Soil characteristic changes and quality evaluation of degraded desert steppe in arid windy sandy areas

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Grassland degradation has been widely observed and is becoming increasingly serious in some areas. It is necessary to quantitatively evaluate grassland degradation and related factors. The study area is the arid windy sandy area in eastern Ningxia. The study is to explore how soil properties change during the process of grassland degradation in arid windy sandy areas and to evaluate soil quality changes in the process of grassland degradation. This study uses undegraded, lightly degraded, moderately degraded, and severely degraded desert steppe as the research object to study the physical, chemical and biological changes at 0-5 cm, 5-15 cm and 15-30 cm soil depths with different degradation degrees, to analyze the correlations among soil factors, to establish the minimum data set, and to use the soil quality index (SQI) to evaluate the soil quality of grassland with different degradation degrees. The results showed that (i) with grassland degradation, soil clay content and moisture content decreased; soil bulk density increased; soil organic matter content and total nitrogen content showed an overall downward trend; and soil available potassium content decreased significantly. With increasing soil depth, soil moisture content decreased, soil bulk density increased, soil organic matter content and available potassium content decreased, and total nitrogen content showed an upward trend in undegraded and lightly degraded grassland. (ii) With grassland degradation, the number of soil bacteria, actinomycetes and fungi, as well as the activity of urease, polyphenol oxidase, protease, phosphatase and sucrase, showed an overall decreasing trend, but the changes were not completely consistent. Microorganisms accumulated in the upper soil of undegraded and lightly and moderately degraded grassland. The activity of the five enzymes generally showed a downward trend as the soil layer deepened. (iii) There was a significant positive correlation between soil clay content, moisture content, organic matter content, total nitrogen content, available potassium content, the activity of

the five enzymes and the number of microorganisms; soil bulk density was significantly negatively correlated with the above factors; total nitrogen content was significantly negatively correlated with available phosphorus content; and available phosphorus content was significantly negatively correlated with fungi quantity. (iv) Based on the minimum data set, the SQI of grassland with different degradation degrees was calculated, indicating that the ranking based on overall soil quality was undegraded >lightly degraded >moderately degraded >severely degraded grassland. The results showed that the degradation of desert steppe in arid windy sandy areas had relatively consistent effects on the physical, chemical and biological traits of the soil. The minimum data set could replace the total data set to evaluate the soil quality of the desert steppe with different degrees of degradation.

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Abstract

Grassland degradation has been widely observed and is becoming increasingly serious in some areas. It is necessary to quantitatively evaluate grassland degradation and related factors. The study area is the arid windy sandy area in eastern Ningxia. The study is to explore how soil properties change during the process of grassland degradation in arid windy sandy areas and to evaluate soil quality changes in the process of grassland degradation. This study uses undegraded, lightly degraded, moderately degraded, and severely degraded desert steppe as the research object to study the physical, chemical and biological changes at 0-5 cm, 5-15 cm and 15-30 cm soil depths with different degradation degrees, to analyze the correlations among soil factors, to establish the minimum data set, and to use the soil quality index (SQI) to evaluate the soil quality of grassland with different degradation degrees. The results showed that (ⅰ) with grassland degradation, soil clay content and moisture content decreased; soil bulk density increased; soil organic matter content and total nitrogen content showed an overall downward trend; and soil available potassium content decreased significantly. With increasing soil depth, soil moisture content decreased, soil bulk density increased, soil organic matter content and available potassium content decreased, and total nitrogen content showed an upward trend in undegraded and lightly degraded grassland. (ⅱ) With grassland degradation, the number of soil bacteria, actinomycetes and fungi, as well as the activity of urease, polyphenol oxidase, protease, phosphatase and sucrase, showed an overall decreasing trend, but the changes were not completely consistent. Microorganisms accumulated in the upper soil of undegraded and lightly and moderately degraded grassland. The activity of the five enzymes generally showed a downward trend as the soil layer deepened. (ⅲ) There was a significant positive correlation between soil clay content, moisture content, organic matter content, total nitrogen content, available potassium content, the activity of the five enzymes and the number of microorganisms; soil bulk density was significantly negatively correlated with the above factors; total nitrogen content was significantly negatively correlated with available phosphorus content; and available phosphorus content was significantly negatively correlated with fungi quantity. (ⅳ) Based on the minimum data set, the SQI of grassland with different degradation degrees was calculated, indicating that the ranking based on overall soil quality was undegraded >lightly degraded >moderately degraded >severely degraded grassland. The results showed that the degradation of desert steppe in arid windy sandy areas had relatively consistent effects on the physical, chemical and biological traits of the soil. The minimum data set could replace the total data set to evaluate the soil quality of the desert steppe with different degrees of degradation.

Key words:

Arid windy sandy area; Desert steppe; Degradation; Soil physical, chemical and biological properties; Minimum data set; Soil quality index.

Introduction

The grassland ecosystem is one of the most extensive vegetation types in the world, covering approximately 25% of the Earth's land area (Liu et al. 2019; Shen et al. 2020). Grasslands have high ecological and economic value and play a vital role in the regional climate, biodiversity protection, provision of ecosystem services and biogeochemical processes (Han et al. 2018; Zhang et al. 2020a). However, grassland degradation has been widely observed in recent years, and it is becoming increasingly serious in some areas (Abdalla et al. 2018; Harris 2010; Liu et al. 2018; Robinson et al. 2017; Schonbach et al. 2011; Wei et al. 2020; Zhang et al. 2014). By 2010, the area of degradation in grasslands accounted for nearly 49.3% of the global grassland area (Yang et al. 2016; Zhang et al. 2020a). Grassland degradation is defined as the process of environmental degradation and desertification caused by overexploitation, poor management, climate warming and drought (Li et al. 2011). It is the overall decline of grassland productivity caused by human activities and natural processes (Belayneh & Tessema 2017; Tiscornia et al. 2019; Yao et al. 2016; Zhang et al. 2018), such as reduced vegetation cover, reduced vegetation cover density, reduced pasture yield, increased unhealthy pasture types, increased soil compaction, changes in plant functional groups and so on (Feng et al. 2009; Li et al. 2013; Lin et al. 2015). Grassland degradation reduces vegetation coverage and species diversity, changes species composition, reduces stored soil organic carbon and nutrients (Gao et al. 2019; Han et al. 2018; Liu et al. 2017; Mchunu & Chaplot 2012), and has adverse effects on the productivity of terrestrial ecosystems, the balance of the regional ecological environment, regional economy and so on (Bai et al. 2008; Batunacun et al. 2018; Shen et al. 2015; Xu et al. 2020). It is necessary to quantitatively evaluate grassland degradation and related factors, which have been subjects of intense research in recent years.

Soil is a complex biological system, the most basic component of human life, and plays a key role in plant growth, organic matter decomposition, nutrient cycling, and water retention (Ritz et al. 2009; Saglam et al. 2015; Zhou et al. 2019). Under the background of global grassland degradation, changes in the soil properties of degraded grasslands have aroused widespread concern. The most direct manifestation of grassland degradation is the reduction of vegetation cover (Babel et al. 2014; Dlamini et al. 2014). With the succession of grassland vegetation degradation, the deterioration of soil physical properties and the infertility of nutrients are also increasing; therefore, the core problem of grassland degradation is soil degradation. Soil degradation weakens the soil structure and reduces the organic matter content, which intensifies soil desertification, and the severe decline in soil organic matter leads to the deterioration of soil structure and reduces soil productivity (Ma et al. 2020). Although grassland degradation is rapidly expanding, quantitative information about the impact of grassland degradation on soil properties is still largely unavailable (Yuan et al. 2019).

Soil quality degradation is an important process of soil degradation. Soil quality is a key aspect of ecosystem function and agricultural sustainability, reflecting abiotic and biotic interactions in the process of maintaining plant and animal productivity (Nabiollahi et al. 2018; Nosrati & Collins 2019; Rahmanipour et al. 2014; Sione et al. 2017). Monitoring soil quality is necessary to assess parameter changes caused by management and to judge whether the soil is improving or degrading (Bilgili et al. 2017; Santos-Frances et al. 2019). Soil quality is a comprehensive reflection of physical, chemical and biological characteristics (Maurya et al. 2020; Zuber et al. 2017). There is no single measurement method that can directly determine soil quality, but it can be assessed by measuring soil physical, chemical and biological characteristics (Imamoglu & Dengiz 2019; Yu et al. 2018). Soil quality assessment is generally performed by selecting a set of soil characteristics that are considered soil quality indicators (Guo et al. 2017; Vasu et al. 2016). Soil organic matter is an important indicator of soil quality. It is a direct product of the biological activities of plants and animals, as well as many biological factors that affect soil functions, and it also affects the physical, chemical and microbiological properties of the soil and the availability of nutrients (Obade & Lal 2014; Raiesi 2017; Sharma et al. 2016). Total nitrogen is a major nutrient for vegetation growth and an important indicator for soil quality evaluation (Pham et al. 2018). Soil microorganisms and enzyme activity are important biological components in the soil. They are early and sensitive indicators for assessing the degree of soil degradation, which are sensitive to soil disturbances and are related to nutrient cycling and organic matter dynamics (Guo et al. 2018; Nosrati & Collins 2019; Pandey et al. 2015). There are many methods for evaluating soil quality that mainly include the comprehensive index method, fuzzy comprehensive evaluation method, principal component analysis method, gray correlation method and soil quality index (SQI) (Zhou et al. 2020). With the importance of soil quality evaluation, the soil quality evaluation of grassland ecosystems has attracted increasing attention. However, there has not been a relatively complete soil quality evaluation system for grasslands thus far, and there have been few research reports on the soil quality evaluation of desert grasslands.

The SQI is an important tool for evaluating and monitoring soil quality changes (Zhao et al. 2019). Because it is simple to calculate and easy to use, the SQI is widely used to quantify soil quality (Nabiollahi et al. 2017). Soil quality indexing involves three steps: (ⅰ) selection of appropriate indicators and determining the minimum data set, which contains the most important variables and can best represent the soil function; (ⅱ) converting the indicators and assigning the weights; and (ⅲ) integrating all indicator scores into a soil quality index (Nabiollahi et al. 2017). The total data set (TDS) and minimum data set (MDS) have been widely used for soil quality assessment (Zhou et al. 2020). The MDS can reduce the workload of data measurement and analysis, reduce the number of indicators used for quality evaluation, and select the most key indicators containing sufficient information for quality evaluation (Jahany & Rezapour 2020). When establishing the MDS, the selection of indicators can be done based on expert opinions or statistical processes (Lima et al. 2013). Principal component analysis is widely used for correlation analysis among soil characteristics (Askari & Holden 2014; Juhos et al. 2019); therefore, it is commonly used for selecting important indicators. In the process of soil quality evaluation, sometimes only physical and chemical indicators are selected, but the more sensitive biological indicators are ignored, which affects the evaluation. Therefore, a data set containing at least one physical, chemical and biological indicator can reflect the soil quality more accurately (Zhou et al. 2020).

The arid windy sandy area in eastern Ningxia is located on the southern edge of the Mu Us Sandy Land. The zonal vegetation is desert steppe. It is an important ecological barrier and animal husbandry base in Ningxia, arid and rainless, with strong wind and much sand, and the ecosystem is extremely fragile. It is one of the largest areas of desertified land and the area most severely damaged by sandstorms in Ningxia. Due to years of overgrazing coupled with harsh natural conditions, the vegetation degraded, the soil deteriorated, and the health of the ecosystem has been seriously threatened.

However, it is necessary to further research the changes in the soil physical, chemical and biological characteristics in the desert steppe where different degrees of degradation has occurred in arid windy sandy areas. There are few reports on soil quality evaluation. To clarify how soil properties change during the process of grassland degradation in arid windy sandy areas and to evaluate soil quality changes in the process of grassland degradation, the desert steppe in the arid windy sandy area in eastern Ningxia was used as the research object. This study discussed the variation in the soil physical, chemical and biological characteristics of grasslands with different degrees of degradation, analyzed the correlations among soil factors, and evaluated the comprehensive condition of soil quality with the help of a minimum data set and SQI to provide the basis for ecological restoration and scientific management of the desert steppe.

Materials & Methods

2.1 Site description

The study area is located in the middle-north region of Yanchi County, east of Ningxia (37°44'-38°10' N, 106°50'-107°40' E), which is a typical arid windy sandy area that is connected with Mu Us Sandy Land to the north and the Loess Plateau to the south. The terrain transitions from Ordos gently sloping hills to loess hills from north to south, and the climate is a typical mid-temperate semiarid continental climate. The average annual temperature is 8.1℃. The annual precipitation is 250-350 mm. The annual evaporation is 2403.7 mm. The climate is dry with little rain and much wind during all four seasons. It is hot in summer, cold in winter and windy in spring. Drought and sandstorms often occur. The zonal soil is light sierozem, and the zonal vegetation is desert steppe mainly composed of xerophytes and mesophytes. The soil is poor and the vegetation is sparse. Due to drought, lack of rain, strong wind erosion, long-term overgrazing, reclamation and other unreasonable developments, the desert steppe in this area has been seriously degraded. Since grazing exclusion in 2003, the grassland ecological environment has improved significantly. The vegetation in this area is mainly composed of semishrubs consisting of *Artemisia ordosica*, *Pennisetum centrasiaticum*, *Glycyrrhiza uralensis*, *Stipa breviflora*, *Sophora alopecuroides*, *Lespedeza potaninii* and other plants.

2.2. Study methods

2.2.1. Plot setting

The study area and sample sites are shown in Fig. 1. Spatial substitution time series is a commonly used research method. Grasslands with consistent terrain and soil conditions but with different degrees of degradation were selected as the research object and 54 sample plots were set up. In each sample plot, five quadrats were set at equal intervals in a diagonal direction for vegetation investigation, and the quadrat sizes of herbaceous plants and shrubs were 1 m×1 m and 10 m×10 m, respectively. According to the "S" shape, five points were arranged in each sample plot for soil moisture content, soil bulk density measurement and soil sample collection. Based on the vegetation survey and measurement data, the cluster analysis method (Zhang et al. 2008) was used to classify the degradation degrees of desert steppe in the study area and undegraded, lightly degraded, moderately degraded and severely degraded grasslands were determined. It determined 7 undegraded grasslands, 39 lightly degraded grasslands, 3 moderately degraded grasslands and 5 severely degraded grasslands. Vegetation profiles of the sample plots with each degradation degree are shown in Table 1.

UD represents undegraded grassland, LD represents lightly degraded grassland, MD represents moderately degraded grassland, and SD represents severely degraded grassland.

2.2.2. Measuring items and methods

(ⅰ) Vegetation investigation: The investigation was conducted during the period of vigorous vegetation growth in August. The geographic coordinates and elevation of each sample plot were recorded during the survey. The species composition in each plot was counted, and the natural height of 30 plants of each species was randomly measured as its average height. In each quadrat of the sample plot, the coverage and the density of vegetation were measured, and then the plants were pruned by species to the ground. The plants were brought back to the laboratory to obtain the aboveground biomass by drying at 65°C to a constant weight.

(ⅱ) Soil moisture content, soil bulk density determination and soil sampling: From April to October for two consecutive years, the TDR probe was used to measure the soil moisture content of the 0-5 cm, 5-15 cm and 15-30 cm soil layers in the middle of each month. While investigating vegetation, the ring knife method was used to measure the soil bulk density of the 0-5 cm, 5-15 cm and 15-30 cm soil layers, and soil samples of the corresponding soil layers were collected. The soil samples for determining microorganisms and enzyme activity were placed into a 4°C incubator and brought back to the laboratory. The soil samples were placed in plastic bags to determine the physical and chemical properties of the soil and brought back to the laboratory for processing.

(ⅲ) Soil physical and chemical properties and microorganism and enzyme activity determination: Soil particle composition was determined by a Microtrac S3500 laser particle size analyzer. Soil organic matter content was determined by the potassium dichromate volumetric method. The soil total nitrogen content was determined by the fully automatic Kjeldahl method. The soil available potassium content and soil available phosphorus content were determined by near-infrared spectroscopy. The number of soil microorganisms was determined by the plate coating culture counting method. Beef extract peptone agar medium was used for aerobic bacteria, Martin medium was used for fungi, and the modified Gao's No. 1 medium was used for actinomycetes. Three dilution gradients (10^{-3}, 10^{-4}, and 10^{-5}) were used for each sample and three replicates were used for each dilution gradient. Soil urease activity was determined by indophenol colorimetry, polyphenol oxidase activity was determined by spectrophotometry, protease activity was determined by the Folin phenol method, phosphatase activity was determined by the phenyl disodium phosphate colorimetric method, and sucrase activity was determined by the 3,5-dinitrosalicylic acid colorimetric method.

2.2.3. Soil quality evaluation

There are many soil physical and chemical properties and biological indicators; while the changes in these factors are different, they exhibit certain correlations. To reflect the comprehensive soil quality situation in the desert steppe with different degrees of degradation more directly, multiple relevant soil factors were transformed into a few comprehensive factors on the basis of the principle of principal component dimensionality reduction. Indicators with high factor loading were selected to establish the MDS, and the SQI was used to evaluate the overall soil quality of grassland with different degrees of degradation.

2.2.3.1. Principal component analysis

Principal component analysis uses the idea of dimension reduction (Bilgili et al. 2017) to transform multiple original variables into several comprehensive indicators (principal component) under the premise of ensuring less information loss (variation) when the original variables are correlated. Because each index has different dimensions, to eliminate the influence of different dimensions on the evaluation results, the soil indicators are processed in a dimensionless manner by calculating the membership values (Jahany & Rezapour 2020), and the corresponding membership function is selected according to the positive or negative principal component factor loading (Nabiollahi et al. 2017). The formulas for calculating the membership values are:

Ascending distribution function: $$Q(x_i) = (x_i - x_{i\min}) / (x_{i\max} - x_{i\min}) \quad (1)$$

Descending distribution function: $$Q(x_i) = (x_{i\max} - x_i) / (x_{i\max} - x_{i\min}) \quad (2)$$

In the formulas, $Q(x_i)$ is the membership value of each soil indicator, x_i is the value of each indicator, and $x_{i\max}$ and $x_{i\min}$ are the maximum and minimum values of the soil indicator i, respectively (Jahany & Rezapour 2020). Among the soil indicators, soil clay content, soil moisture content, soil nutrient content, enzyme activity, and microorganism quantity used the ascending distribution function. Because too high soil bulk density could inhibit root growth and soil porosity (Andrews et al. 2002), soil bulk density used the descending distribution function.

After obtaining the membership value ($Q(x_i)$) of each indicator, principal component analysis was performed. When extracting the principal components, the standard of “characteristic root□1” was used to determine the number of principal components or factors (Juhos et al. 2019), and the accumulated variance contribution rates should reach 85%. According to principal component analysis, the eigenvalue, variance contribution rate, and factor score coefficient matrix of each principal component were obtained. The weight of each indicator (W_i) was calculated by the ratio of the common factor variance of each indicator to the sum of the common factor variances of all indicators obtained by the principal component analysis (Askari & Holden 2014).

2.2.3.2. Selection of the minimum data set

The minimum data set is a method for evaluating soil quality proposed by Larson and Pierce in 1991. The important role of the MDS is to understand the changes in soil by measuring less data. The TDS contained all 15 soil quality indicators, and the MDS was selected by principal component analysis (Zhao et al. 2019). The factor loading of each indicator in each principal component was obtained by principal component analysis. It is generally believed that the greater the absolute value of the factor loading is, the greater the weight of the variable in the corresponding principal component is, and the positive and negative only represent the influence effect. It is assumed that the soil variable with high factor loading can best represent soil quality variation characteristics (Nabiollahi et al. 2018); therefore, the MDS only retains high load attributes in each factor. The high load attribute is defined as an absolute value within 10% of the highest factor load (Nosrati & Collins 2019). When multiple attributes are retained in a single factor, a multivariate correlation coefficient is used to determine whether the variable will be considered redundant and thus eliminated from the MDS (Rahmanipour et al. 2014). Variables with good correlation are considered redundant; therefore, only one is considered for the MDS, and the remaining variables are deleted from the data set. If variables with high weight are not related, each variable is considered to be important and is considered to be a variable in the MDS (Raiesi 2017).

2.2.3.3. Calculation of soil quality index

The SQI is the integration of soil quality evaluation indicators. The range of the SQI is 0-1 (Lima et al. 2013). The larger the SQI is, the better the soil quality. Based on different data sets, the weight of each indicator is obtained by principal component analysis. Principal component analysis was carried out for indicators of different data sets to extract the common factor variance of each indicator. The ratio of the common factor variance of each indicator to the sum of the common factor variances of all indicators is the weight value of each evaluation indicator in each data set (Askari & Holden 2014). The formula for calculating the soil quality index is:

$$SQI = \sum_{i=1}^{n} Q(x_i) \cdot W_i \qquad (3)$$

In the formula, $Q(x_i)$ is the membership value of soil indicator *i*, W_i is the weight of soil indicator *i*, and *n* is the number of soil indicators (Jahany & Rezapour 2020).

2.2.4. Data processing

Excel, DPS7.05 and SPSS26 software were used for data processing and picture making. One-way ANOVA and the LSD method were used for significance tests and multiple comparisons. Pearson correlation analysis was used for correlation analysis of the soil factors. Principal component analysis was used to determine the minimum data set and to calculate the weight values of the indicators.

Results

3.1. Changes in the soil physical and chemical properties of grassland with different degrees of degradation

According to the Kachinsky soil texture classification standard, the soil texture of the grassland in each degradation degree was mainly sandy loam soil, and the main physical and chemical properties of the soil are shown in Table 2. In each layer of the soil that had experienced grassland degradation, soil clay content and moisture content both showed a decreasing trend; soil bulk density showed an increasing trend indicating that the soil had become more compact as a result of grassland degradation; soil organic matter content showed an overall downward trend and in the 5-15 cm soil layer, it decreased significantly (F=3.64, p=0.017); and soil total nitrogen content showed an overall downward trend and in the 15-30 cm soil layer, it decreased significantly (F=4.75, p=0.004). With grassland degradation, soil available potassium content significantly decreased in all layers of the soil ($p < 0.05$), especially in severely degraded grassland; and the change in soil available phosphorus content was not obvious and only in the 5-15 cm soil layer was there a significant difference (F=3.29, p=0.026).

With increasing soil depth, there was no obvious change in soil clay content; soil bulk density showed an increasing trend, indicating that the deeper the soil layer was, the more compact was the soil; and soil moisture content showed an overall downward trend. In grassland with different degrees of degradation, the soil organic matter content decreased with increasing soil depth, and except for the moderately degraded grassland, there was a significant difference ($p < 0.05$) for grassland with other degrees of degradation. With increasing soil depth, the soil total nitrogen content showed an upward trend in the undegraded and lightly degraded grassland; the soil available potassium content showed a downward trend in all grassland with different degrees of degradation, and the difference was significant ($p < 0.05$) except for the undegraded grassland; and the soil available phosphorus content showed a downward trend in the undegraded, lightly degraded and severely degraded grassland, and the difference was significant ($p < 0.05$) for the undegraded and lightly degraded grassland.

3.2. Changes in the soil microorganism quantity of grassland with different degrees of degradation

The changes in the soil microorganism quantity of grassland with different degrees of degradation are shown in Fig. 2. In the horizontal distribution pattern, the number of microorganisms (bacteria, actinomycetes and fungi) increased with grassland degradation, showing the following ranking: undegraded>lightly degraded>moderately degraded>severely degraded. In the undegraded and lightly degraded grassland, the number of bacteria was the largest, followed by the number of actinomycetes, and the number of fungi was the least ($p < 0.05$). In the moderately degraded and severely degraded grassland, the difference in the number of the three kinds of microorganisms was not significant ($p > 0.05$). In terms of the vertical distribution pattern, the number of bacteria, actinomycetes and fungi in the undegraded, lightly degraded and moderately degraded grassland changed in the same order: upper soil>middle soil>lower soil, and there was a significant difference ($p < 0.05$) between the soil layers. In the severely degraded grassland, the number of soil microorganisms in each soil layer was extremely small, and there was no significant difference ($p > 0.05$) between the soil layers.

3.3. Changes in the soil enzyme activity in grassland with different degrees of degradation

The changes in the soil enzyme activity in grassland with different degrees of degradation are shown in Fig. 3. In general, with grassland degradation, the soil enzyme activity (urease, polyphenol oxidase, protease, phosphatase and sucrase) showed a downward trend. Soil phosphatase activity decreased significantly ($p < 0.05$) with degradation; and the activity of urease, polyphenol oxidase, protease and sucrase was significantly different ($p < 0.05$) among the undegraded, moderately degraded and severely degraded grassland, and the activity of urease and polyphenol oxidase was significantly different ($p < 0.05$) between the lightly degraded and severely degraded grassland. In terms of the soil layer distribution, with the deepening of the soil layer, phosphatase activity decreased significantly in the undegraded and lightly degraded grassland; the activity of urease, polyphenol oxidase and sucrase in the upper layer of the undegraded grassland was significantly higher than that in the middle and lower layers, and there was no significant difference in the other degraded grassland; and protease activity was only significantly higher in the upper layer of the lightly degraded grassland than that in the middle and lower layers.

3.4. Correlation analysis between soil factors

The results of the correlation analysis between the soil factors are shown in Table 3. There were some close correlations among the soil factors. Soil clay content had an extremely significantly negative correlation with soil bulk density; an extremely significantly positive correlation with soil moisture content, total nitrogen content, the activity of the five enzymes, bacteria quantity, actinomycete quantity and fungi quantity; and a significantly positive correlation with organic matter content and available potassium content. Soil bulk density had an extremely significantly negative correlation with soil moisture content, organic matter content, available potassium content, the activity of the five enzymes, bacteria quantity, actinomycete quantity and fungi quantity; and a significantly negative correlation with total nitrogen content. Soil moisture content had an extremely significantly positive correlation with organic matter content, available potassium content, the activity of the five enzymes, bacteria quantity, actinomycete quantity and fungi quantity and a significantly positive correlation with total nitrogen content. Soil organic matter content had an extremely significantly positive correlation with available potassium content, the activity of the five enzymes, bacteria quantity, actinomycete quantity and fungi quantity. Soil total nitrogen content had an extremely significantly negative correlation with available phosphorus content; a significantly positive correlation with available potassium content, the activity of the five enzymes and bacteria quantity; and an extremely significantly positive correlation with actinomycete quantity and fungi quantity. The soil available potassium content had an extremely significantly positive correlation with the activity of the five enzymes, bacteria quantity, actinomycete quantity and fungi quantity. The soil available phosphorus content had a significantly negative correlation with fungi quantity. There was a significantly positive correlation between the activity of the five soil enzymes and the number of the three kinds of microorganisms.

3.5. Soil quality evaluation

3.5.1. Principal component analysis of soil factors

To reflect the comprehensive soil quality situation of the desert steppe with different degrees of degradation more directly, multiple relevant soil factors were transformed into a few comprehensive factors on the basis of the principle of principal component dimensionality reduction. First, the soil indicators were processed in a dimensionless manner, and the membership value ($Q(x_i)$) of each indicator was obtained under the different degradation degrees. Then, principal component analysis was performed for the soil indicators, the standard of "characteristic root > 1" was used to determine the number of principal components, and the eigenvalue, variance contribution rate, and factor score coefficient matrix of each principal component were obtained. The weight of each indicator (W_i) was calculated by the ratio of the common factor variance of each indicator to the sum of the common factor variances of all indicators obtained by principal component analysis. The results of the principal component analysis are shown in Table 4.

According to the principal component analysis, the eigenvalues of the first two principal components were all greater than 1, which were 12.2490 and 1.4521, respectively, and their accumulated variance contribution rate reached 91.3409%. Therefore, the first two principal components could represent the original 15 soil indicators, including all information of the original 15 soil indicators, and could better reflect the quality of the soil. The expressions of the first two principal components were:

$$Y_1=-0.015X_1+0.1385X_2+0.0862X_3+0.1539X_4-0.1124X_5+0.1537X_6+0.235X_7+0.0701X_8+0.0613X_9+0.1185X_{10}+0.1558X_{11}+0.1129X_{12}+0.077X_{13}+0.0203X_{14}+0.01X_{15}$$

$$Y_2=0.1786X_1-0.1032X_2+0.0064X_3-0.1402X_4+0.3488X_5-0.1452X_6-0.5379X_7+0.0365X_8+0.0525X_9-0.0562X_{10}-0.1323X_{11}-0.0452X_{12}+0.0225X_{13}+0.1325X_{14}+0.1513X_{15}$$

3.5.2. Selection of the minimum data set

According to the principal component analysis, indicators with high factor loading were selected to establish the MDS. The MDS can reduce the workload of data measurement and analysis, reduce the number of indicators used for quality evaluation, and select the most key indicators containing sufficient information for quality evaluation (Jahany & Rezapour 2020). Based on the results of the principal component analysis, there were two principal components with eigenvalues greater than 1 in the soil quality evaluation indicators of the desert steppe with different degradation degrees, and the accumulated variance contribution rate reached 91.3409%, which could meet the requirement of information extraction. Principal component 1 had several high-weight variables, namely, soil organic matter content, soil available potassium content, soil available phosphorus content and phosphatase activity. Since soil organic matter content was significantly related to soil available potassium content and phosphatase activity, soil available potassium content with the smallest absolute value of factor loading was excluded, and the variables entering the MDS were soil organic matter content, soil available phosphorus content and phosphatase activity. Principal component 2 had several high-weight variables, namely, soil total nitrogen content and soil available phosphorus content. Since soil available phosphorus content had already entered the MDS, soil total nitrogen content was selected to enter the MDS at this time. In summary, the soil indicators of the MDS were soil organic matter content, soil total nitrogen content, soil available phosphorus content and phosphatase activity.

3.5.3. Calculation of soil quality index

The changes in soil physical, chemical and biological properties with different degrees of degradation were different, reflecting the complexity of the changes in soil factors. To reflect the impact of different degrees of degradation on the soil quality of the desert steppe more intuitively, the soil quality comprehensive index of the desert steppe with different degrees of degradation was calculated. The four indicators entering the MDS were soil organic matter content, soil total nitrogen content, soil available phosphorus content and phosphatase activity. After determining the indicators entering the MDS, because of the different dimensions of each indicator, it was necessary to use the membership function to standardize the minimum data set, to recalculate the weights of the four indicators and to obtain the weight coefficients of the different indicators of the MDS. Through the membership values and weight coefficients of the four indicators in the MDS, the SQI values of the undegraded, lightly degraded, moderately and severely degraded grassland were calculated. The results showed that the SQI values of undegraded, lightly degraded, moderately degraded and severely degraded grassland were 0.6230, 0.5454, 0.4587, and 0.3268, indicating that the overall soil quality was ranked as undegraded grassland>lightly degraded grassland>moderately degraded grassland>severely degraded grassland.

3.5.4. Rationality verification of the minimum data set

The rationality verification of the minimum dataset evaluation index system was an important part of soil quality evaluation. The SQI was calculated based on the total data set and the minimum data set (Fig. 4). The SQI of the total data set was represented by SQI_{TDS}, and the SQI of the minimum data set was represented by SQI_{MDS}. A scatter plot of SQI_{TDS} and SQI_{MDS} was made for regression analysis. According to the fitting effect (Fig. 5), SQI_{TDS} was highly correlated with SQI_{MDS}, and the R^2 value was 0.814. This proved that the determined minimum data set could replace the total data set to evaluate the soil quality of the desert steppe with different degradation degrees.

Discussion

4.1. Soil physical and chemical characteristic changes of the desert steppe with different degrees of degradation

Grassland degradation leads to long-term loss of biodiversity and instability in grassland ecosystems (Raiesi & Salek-Gilani 2020), which has a certain impact on soil physical and chemical properties. Soil texture is closely related to the stability of soil organic matter (Yuan et al. 2019). With degradation, plant coverage decreased, which led to an increase in soil bulk density and a decrease in soil structure stability, and the soil clay content showed a decreasing trend. In addition to the reduction of the nutrient input into the soil caused by the reduction of vegetation and litter, with the degradation and sparseness of the vegetation, soil wind erosion increased, soil clay particles blown away by the wind increased, and soil water and fertilizer conservation capacity decreased, resulting in soil degradation. The decrease in soil moisture content in degraded grassland was also related to poor soil water holding capacity because soil clay content was directly related to soil water and fertilizer conservation capacity. With increasing soil depth, there was no obvious change in soil clay content, which might have been due to the relatively stable structure of the soil particles and the lag in soil changes in the deeper layers. With grassland degradation and the increase in soil depth, soil bulk density increased, which was consistent with the results of Yao *et al.* (Yao et al. 2016) and Peng *et al.* (Peng et al. 2018), indicating that grassland degradation was significantly related to the increase in soil compaction. Soil compaction reduced the soil pore volume, and the macropores responsible for the majority of gas and water movements were destroyed, resulting in a decrease in air and water in the soil. With grassland degradation, the soil moisture content decreased, which was consistent with the results of Yuan *et al.* (Yuan et al. 2019) and Yang *et al.* (Yang et al. 2019). Grassland degradation increased the evaporation rate and surface runoff and reduced the soil water infiltration capacity (Tiscornia et al. 2019). With increasing soil depth, the soil moisture content decreased, which was related to the lack of precipitation in the desert steppe in arid windy sandy areas.

In arid and semiarid areas, due to the low availability of rainfall and water, the organic input of plant biomass was low, and the content of soil organic matter was low (Raiesi & Salek-Gilani 2020). With grassland degradation and the increase in soil depth, the soil organic matter content showed a downward trend. This was because the soil organic matter content depended on the balance between the input and output of carbon in the soil (Zhang et al. 2019). The decrease in plant biomass and coverage led to a decrease in the carbon content in the organic carbon pool. The vegetation coverage of severely degraded grassland was poor, and there was no continuous participation of organic matter. Therefore, the decline in soil organic matter was one of the most important indicators of grassland degradation (SY & Korkanc 2016). With the increase in soil depth, the decrease in plant litter accumulation and the amount of roots resulted in the decline in soil organic matter content and the deterioration of soil properties. With grassland degradation, the soil total nitrogen content also showed a downward trend. This was because the carbon, nitrogen and phosphorus elements in grassland soil were mainly from organic matter, such as litter and plant roots, and the change in soil texture, the decrease in vegetation coverage and the change in vegetation composition were all considered to be reasons for the decrease in soil total nitrogen content with grassland degradation (Dong et al. 2012). With increasing soil depth, the soil total nitrogen content showed an upward trend in the undegraded grassland and lightly degraded grassland, which might have been related to the nutrient loss in the surface soil. The changes in soil available potassium and available phosphorus might have been because the changes in soil microorganism composition and enzyme activity affected the mineralization of total nutrients, and the changes in aboveground vegetation affected the absorption of the available nutrients by plants.

4.2. Soil biological characteristic changes of the desert steppe with different degrees of degradation

Some physical and chemical properties of the soil reflect the fertility and structure of the soil and are widely used as indicators of soil quality. However, the physical and chemical properties usually change slowly and cannot reflect the changes in soil quality in the short term. Soil biological characteristics, such as soil microorganism quantity and enzyme activity, are sensitive to soil disturbance and closely related to nutrient cycling and organic matter dynamics (Guo et al. 2018).

The number of microorganisms showed a downward trend with grassland degradation. These differences were attributed to the differences in vegetation characteristics and soil properties of grassland with different degrees of degradation. Research by Li *et al.* found that soil nutrient status was the most important factor controlling the composition changes of bacteria and fungi (Li et al. 2016). Grassland degradation damaged plant growth, soil structure and nutrient status. The disappearance of aboveground plants limited the development and population of soil microbial communities (Zhou et al. 2019), and the decrease in litter input in the soil led to a decrease in the availability of microbial substrates (Wu et al. 2014). In addition, decreasing soil moisture content, decreasing soil nutrients and increasing soil compaction were not beneficial to the growth and reproduction of microorganisms. The composition proportions of the three kinds of microorganisms were different in the grassland with different degrees of degradation. In the undegraded and lightly degraded grassland, the number of bacteria was the largest, the number of actinomycetes was the second largest, and the number of fungi was the lowest. This might have been related to the different biological attributes of the microbial communities. The bacteria are small and reproduce faster than actinomycetes and fungi, which have larger individuals. When the environment was suitable, bacteria were more competitive than actinomycetes and fungi. In the moderately degraded and severely degraded grassland, the vegetation was sparse, and the microbial growth environment was harsh, resulting in a small number of microorganisms, and the difference was not significant. There were also some studies that found in nutrient-deficient soil, fungi were less dependent on *in situ* nutrients than bacteria and could use hyphae to translocate nutrients from one place to another (Sarathchandra et al. 2005). In terms of vertical distribution, the distribution of soil microorganisms was closely related to soil physical structure (Li et al. 2016), soil nutrients, soil respiration and so on. In the undegraded, lightly degraded and moderately degraded grassland, the number of microorganisms in the upper soil was the largest, which is consistent with previous research (Sanaullah et al. 2016), because the upper soil contained various kinds of litter spoilage rich in organic matter, and the structure was loose and porous, providing relatively good living conditions for microorganisms. Moreover, the temperature of the upper soil was higher than that of the lower soil; therefore, the degradation of plant litter was greater, and the soil enzyme activity was higher (van Bruggen & Semenov 2000), which were all helpful for the growth and reproduction of various microorganisms (Pandey et al. 2015). In the severely degraded grassland, the vegetation was sparse, the surface soil was exposed to the air, soil desertification was serious, and the temperature of the surface soil changed greatly. The environment was not conducive to the growth of soil microorganisms, resulting in a small number of microorganisms and the distribution of microorganisms moving down the soil profile; therefore, the vertical difference was not significant.

Soil enzyme activity is a potential indicator of soil quality. It characterizes the biological activity of the soil and participates in biochemical functions and nutrient cycling (Maurya et al. 2020). It can quickly respond to microenvironmental changes in the soil (Pandey et al. 2015) and is highly sensitive to external interference and easy to measure. Urease and protease were closely related to soil nitrogen conversion; polyphenol oxidase was related to the formation of soil organic matter and sensitive to soil environmental changes; phosphatase activity directly affected the decomposition and transformation of soil organic phosphorus and its biological effectiveness; and sucrase played an important role in the soil carbon cycle and organic matter conversion. Pan *et al.* found that soil enzyme activity was negatively correlated with soil electrical conductivity but significantly positively correlated with soil moisture content, organic carbon and total nitrogen concentration (Pan et al. 2013). Yang *et al.* (Yang et al. 2018) and Zhang *et al.* (Zhang et al. 2020b) found that soil organic carbon had the greatest impact on soil enzyme activity. With grassland degradation, soil enzyme activity showed a downward trend because soil enzyme activity was closely related to soil organic matter content and soil physical and chemical properties, and the soil nutrient poorness during the process of grassland degradation caused the decline of enzyme activity. The decrease in enzyme activity was also related to the decrease in microbial biomass and the change in microbial composition in degraded soil. Soil enzyme activity was positively related to microbial biomass because the enzymes involved in carbon, nitrogen, phosphorus and sulfur mineralization were mainly from microorganisms, and microbial biomass was a potential source of enzymes in the soil (Raiesi & Beheshti 2015). The difference in variation of different enzyme activities was due to the situation of soil enzymes involved in soil organic residue transformation that were different, and the important soil nutrient factors affecting soil enzyme activity were also different. Soil enzyme activity decreased with increasing soil depth, which was consistent with the results of Raiesi *et al.* (Raiesi & Beheshti 2015) and Sanaullah *et al.* (Sanaullah et al. 2016). This was because with increasing soil depth, soil organic matter sharply decreased, soil temperature decreased, and soil moisture content decreased, which limited the ability of soil microorganisms to metabolize and produce enzymes.

4.3. Correlations between soil factors of the desert steppe with different degrees of degradation

According to correlation analysis, it was found that soil factors were closely related. Soil bulk density was significantly negatively correlated with soil clay content, soil moisture content, organic matter content, total nitrogen content, available potassium content, the activity of the five enzymes and the number of microorganisms, which was consistent with previous research results. The increase in soil bulk density increased the soil compactness, resulting in a decrease in air and water in the soil, which had a large impact on soil physical and chemical properties and soil microorganisms and enzymes (Peng et al. 2018; Yao et al. 2016). Soil clay content and soil moisture content were significantly positively correlated with soil organic matter content, total nitrogen content, available potassium content, the activity of the five enzymes and the number of microorganisms, which was also consistent with previous research results. Cookson *et al.* found that the increase in soil carbon storage was directly related to the soil clay content (Cookson et al. 2008). Xu *et al.* found that with grassland degradation, the reduction of clay led to a decrease in carbon and nitrogen storage capacity, and the decrease in soil moisture content reduced microbial activity, resulting in a decrease in the mineralization rate and thus a decrease in available nitrogen and phosphorus concentrations (Xu et al. 2019). Yang *et al.* and Maurya *et al.* found that soil moisture content strongly affected soil physical and chemical properties and microbial diversity (Maurya et al. 2020; Yang et al. 2019). All these results proved that soil physical, chemical and biological properties were closely related and together determined the soil quality. The soil organic matter content, total nitrogen content, and available potassium content were significantly positively correlated with the activity of the five enzymes and the number of microorganisms. This was because soil nutrients were an important factor affecting the composition and quantity of microorganisms (Li et al. 2016). Soil organic matter is the fundamental source of soil microbial nutrients, and the large majority of organic matter is also the final product of microbial metabolism (Cookson et al. 2008). Therefore, the changes in microorganism quantity were closely related to the changes in organic matter (Sharma et al. 2016). Pan *et al.* found that soil enzyme activity was significantly positively correlated with soil organic carbon and total nitrogen concentrations (Pan et al. 2013). Yang *et al.* and Zhang *et al.* found that soil organic carbon had the greatest impact on soil enzyme activity (Yang et al. 2018; Zhang et al. 2020b). Furthermore, Raiesi *et al.* found that soil enzyme activity was positively correlated with microbial biomass, and microbial biomass was the potential source of soil enzymes (Raiesi & Beheshti 2015). There was a significantly positive correlation between the activity of the five soil enzymes and the amount of the three kinds of microorganisms, indicating that microorganism quantity and enzyme activity promoted and restricted each other. All these results proved that the higher the soil organic matter content was, the more soil microorganisms, and the higher the enzyme activity, promoting soil nutrient increases and maintaining better physical and chemical properties.

4.4. Soil quality evaluation of the desert steppe with different degrees of degradation

The concept of soil quality integrates various properties of the soil, which are dynamic and sensitive to external environmental changes. Soil quality research cannot directly measure grassland degradation. It needs to be evaluated by combining mathematical logic of certain physical, chemical and biological characteristics (Li et al. 2019). The application of multivariate statistical methods can make the data meaningful (Obade & Lal 2014). When evaluating soil quality, it is impossible to measure only one single feature or to use all features of the soil to evaluate the soil quality (Maurya et al. 2020). The most important variables can be selected to construct a minimum data set, which is able to ideally integrate soil physical, chemical and biological properties and processes (Bilgili et al. 2017). The core of using the MDS method for soil quality evaluation is that it can reduce the workload of data measurement and analysis and can reduce the number of indicators used for quality evaluation. Additionally, the evaluation results of the minimum data set are consistent with the results of the total data set, which proves that this method is feasible, and the minimum data set is able to replace the total data set to evaluate the soil quality of the desert steppe with different degradation degrees.

The ecosystem of the desert steppe in arid windy sandy areas was extremely fragile, and most grasslands were degraded to different degrees. The soil organic matter content was low, soil wind erosion was serious, and the mass reproduction of weeds and poisonous weeds sacrificed high-quality species (Liu & Diamond 2005). With the degradation of plant community structure, the plant height and coverage decreased, the plant flora was simplified, and the biomes decreased (Lu et al. 2017). Changes in plant species composition and coverage changed litter input, root structure, and soil physical, chemical and biological properties (Guo et al. 2018; Wang & Fu

2020; Wang et al. 2014). Vegetation degradation promoted soil degradation, and soil degradation caused vegetation changes, forming a strong feedback mechanism. With grassland degradation, the changes in soil microorganism quantity and enzyme activity were not completely consistent. This result indicated that in the vegetation-soil changing process of the desert steppe, the changes in some soil properties lagged behind the changes in vegetation. The changes in soil physical, chemical and biological properties with different degrees of degradation were different, reflecting the complexity of the changes in soil factors. However, the correlations between grassland soil factors showed that soil physical, chemical and biological properties were connected and interacted with each other and together affected and determined the direction of evolution of desert steppe soil quality. The comprehensive soil quality index illustrated this point. The overall soil quality was undegraded grassland > lightly degraded grassland > moderately degraded grassland > severely degraded grassland, indicating that the degradation of the desert steppe in arid windy sandy areas had relatively consistent effects on the physical, chemical and biological traits of the soil. Soil quality evaluation of the desert steppe in arid windy sandy areas was discussed to provide a basis for ecological restoration and scientific management of the desert steppe, and further research is still needed in the future.

Conclusions

The changes in the soil physical, chemical and biological characteristics of the desert steppe with different degrees of degradation in arid windy sandy areas were studied, and the soil quality was evaluated. With grassland degradation and the increase of soil depth, soil bulk density increased and soil clay content, soil moisture content, soil organic matter content and soil available potassium content decreased; the number of soil bacteria, actinomycetes and fungi, as well as the activity of the five enzymes, showed an overall decreasing trend but the changes were not completely consistent, and microorganisms accumulated in the upper soil of undegraded, lightly and moderately degraded grassland. There was a significant positive correlation among soil clay content, soil moisture content, soil organic matter content, soil total nitrogen content, soil available potassium content, the activity of the five enzymes and the number of microorganisms, while soil bulk density was significantly negatively correlated with the above factors. Based on the minimum data set, the SQI values of undegraded, lightly degraded, moderately degraded and severely degraded desert steppe in arid windy sandy areas were 0.6230, 0.5454, 0.4587 and 0.3268, respectively, indicating that the overall soil quality was undegraded grassland>lightly degraded grassland>moderately degraded grassland>severely degraded grassland. The results showed that the degradation of the desert steppe in arid windy sandy areas had relatively consistent effects on the physical, chemical and biological traits of the soil. Vegetation degradation led to soil degradation, but soil degradation lagged behind vegetation degradation. The minimum data set could replace the total data set to evaluate the soil quality of the desert steppe with different degrees of degradation.

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Figure 1

Study area and sample sites.

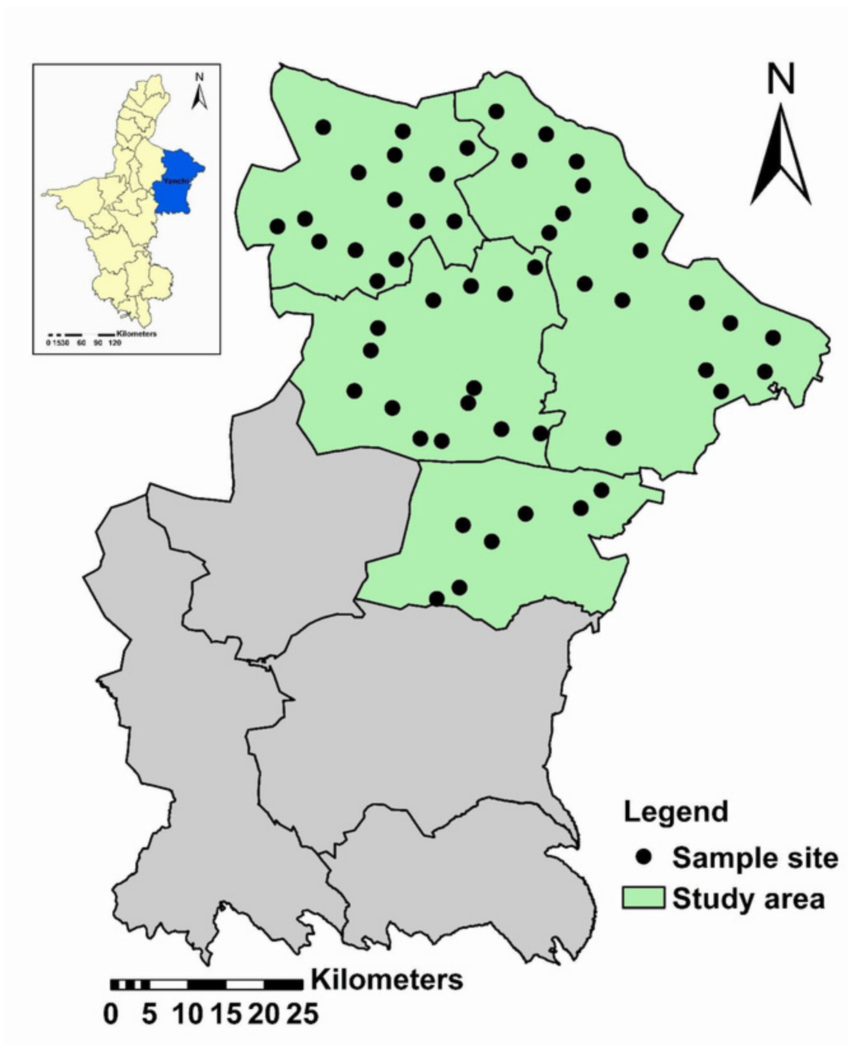

Figure 2

Soil microorganism quantity in grassland with different degrees of degradation.

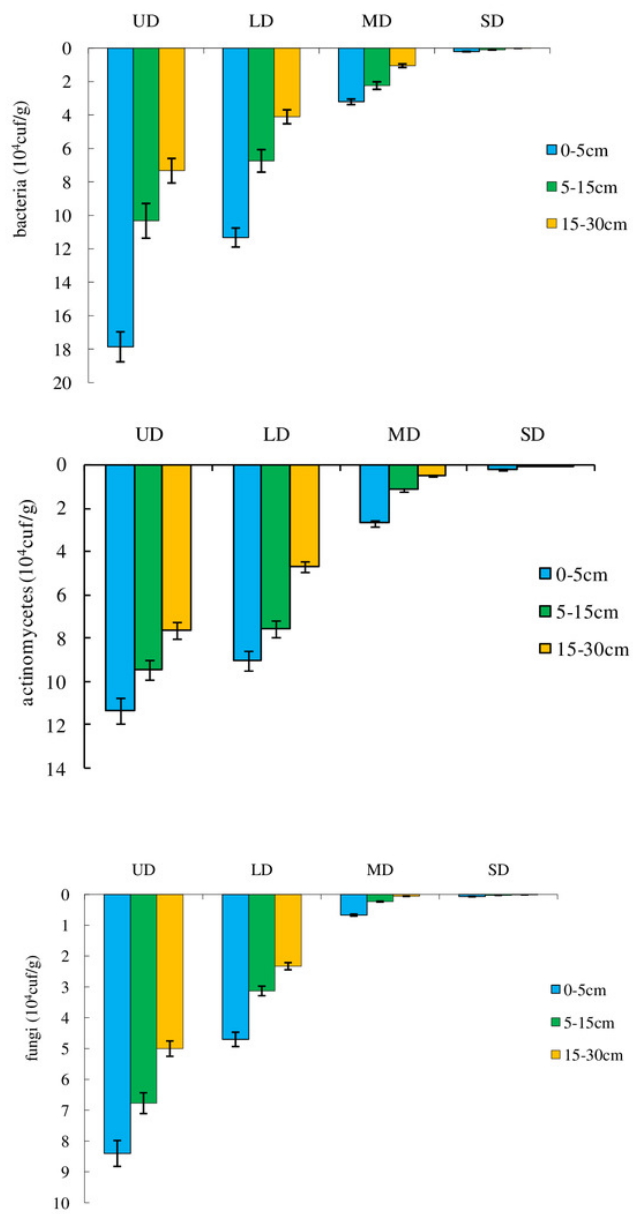
UD
LD
MD
SD
bacteria (10^4cuf/g)
0
2
4
6
8
10
12
14
16
18
20
0-5cm
5-15cm
15-30cm
UD
LD
MD
SD
actinomycetes (10^4cuf/g)
0
2
4
6
8
10
12
14
0-5cm
5-15cm
15-30cm
UD
LD
MD
SD
fungi (10^4cuf/g)
0
1
2
3
4
5
6
7
8
9
10
0-5cm
5-15cm
15-30cm

Figure 3

Soil enzyme activity in grassland with different degrees of degradation.

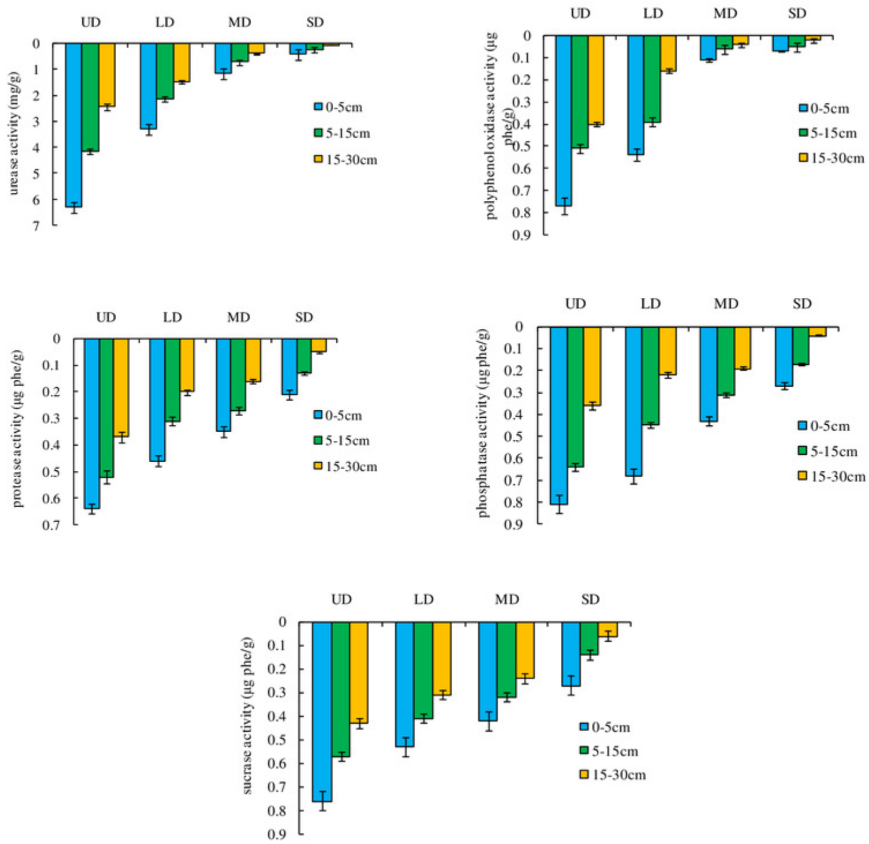
UD
LD
MD
SD
urease activity (mg/g)
polyphenoloxidase activity (μg phe/g)
protease activity (μg phe/g)
phosphatase activity (μg phe/g)
sucrase activity (μg phe/g)
0-5cm
5-15cm
15-30cm

Figure 4

Soil quality index of the TDS and MDS.

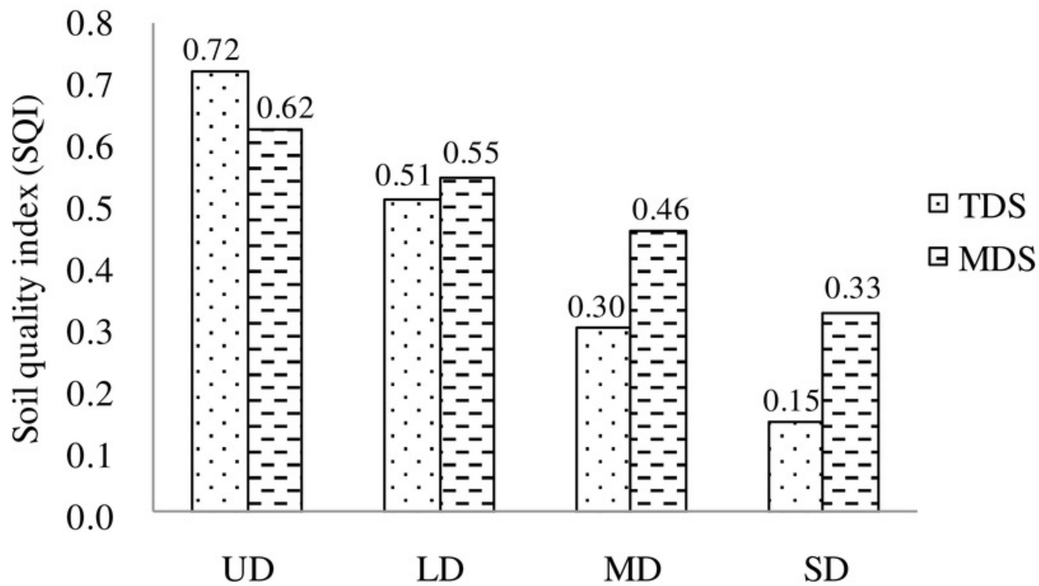

Figure 5

Linear relationship between the SQI values of the TDS and MDS.

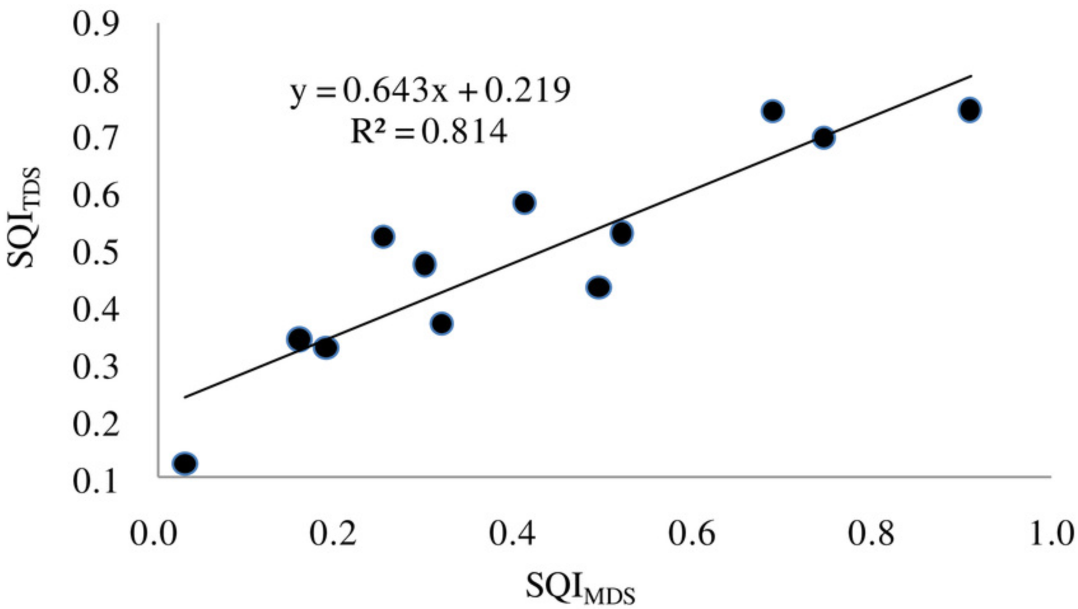

Table 1(on next page)

Vegetation profiles of the sample plots.

Degradation degree	Symbol	Height/cm	Coverage/%	Density/（plant • m^{-2}）	Aboveground biomass/(g • m^{-2})	Species composition
Undegraded	UD	15.22	57.38	87.29	53.83	12-14 species in Gramineae and Asteraceae, 4-6 species in Leguminosae, Chenopodiaceae, etc., species distributed evenly
Lightly degraded	LD	12.19	45.22	72.37	46.17	9-11 species in Gramineae and Asteraceae, 5-7 species in Leguminosae, Chenopodiaceae, Convolvulaceae, etc., species distributed relatively evenly
Moderately degraded	MD	18.25	20.61	41.51	29.11	6-7 species in Gramineae and Asteraceae, 5-6 species in Leguminosae, Chenopodiaceae, Euphorbiaceae, etc., species distributed unevenly
Severely degraded	SD	11.56	12.31	15.33	18.25	2-3 species in Gramineae and Asteraceae, 5-7 species in Leguminosae, Chenopodiaceae, Asclepiadaceae, Zygophyllaceae, etc., more annual plants and a large proportion of poisonous weeds, species distributed unevenly

Table 2(on next page)

The main soil physical and chemical properties of grassland with different degrees of degradation (average±standard error).

Soil layer/cm	Degradation degree	<0.05 mm soil clay/%	Soil bulk density/ （g·cm⁻³）	Soil moisture/%	Organic matter/%	Total nitrogen/ （g·kg⁻¹）	Available potassium/ （mg·kg⁻¹）	Available phosphorus/ （mg·kg⁻¹）
0-5	UD	4.82±0.46aA	1.47±0.03aA	10.27±1.23aA	4.34±0.32aA	0.63±0.07aA	140.00±13.89aA	4.30±0.42bA
	LD	4.56±0.77aA	1.52±0.01aA	9.09±0.59aA	3.65±0.22aA	0.61±0.04aA	129.40±5.18aA	7.25±0.68abA
	MD	3.45±1.86aA	1.55±0.04aA	8.12±0.75aA	3.58±0.51aA	0.59±0.10aA	125.00±9.57aA	6.05±3.31abA
	SD	3.05±0.90aA	1.56±0.03aA	6.79±2.13aA	3.26±0.12aA	0.47±0.05aAB	68.42±3.27bA	8.31±0.59aA
5-15	UD	6.56±0.98aA	1.51±0.03aA	10.02±2.28aA	4.31±0.45aA	0.72±0.05aA	112.50±16.56aA	3.40±0.20bAB
	LD	5.25±0.93aA	1.53±0.02aA	8.43±0.66aA	3.10±0.19bAB	0.62±0.04abA	108.51±5.41aB	5.35±0.47abB
	MD	4.14±1.90aA	1.57±0.06aA	6.37±0.92aA	2.62±0.52bA	0.50±0.05bA	106.25±1.75aB	8.04±2.65aA
	SD	3.40±1.91aA	1.57±0.03aA	6.17±0.03aA	2.30±0.49bAB	0.50±0.03abA	62.14±3.42bA	6.91±0.99aAB
15-30	UD	5.01±1.45aA	1.56±0.03aA	7.75±1.49aA	2.91±0.38aB	0.77±0.08aA	101.25±13.81aA	2.45±0.52aB
	LD	3.63±0.69aA	1.56±0.01aA	7.44±0.62aA	2.58±0.26aB	0.66±0.04aA	76.23±4.62aC	4.33±0.51aB
	MD	3.54±0.53aA	1.59±0.04aA	6.42±0.62aA	2.39±0.47aA	0.59±0.08abA	74.50±2.22abC	5.12±1.65aA
	SD	2.44±1.00aA	1.63±0.05aA	5.83±0.61aA	2.03±0.31aB	0.38±0.03bB	48.56±2.17bB	5.22±0.54aB

Note: Different lowercase letters (a, b) after the same column of data indicate significant differences ($p < 0.05$) between different degrees of degradation; different capital letters (A, B) after the same column of data indicate significant differences ($p < 0.05$) between different soil layers.

Table 3 (on next page)

The correlation between soil factors.

	<0.05 mm soil clay	Soil bulk density	Soil moisture	Organic matter	Total nitrogen	Available potassium	Available phosphorus	Urease activity	Polyphenol oxidase activity	Protease activity	Phosphatase activity	Sucrase activity	Bacteria	Actinomycetes
Soil bulk density	-0.72**													
Soil moisture	0.78**	-0.93**												
Organic matter	0.68*	-0.90**	0.93**											
Total nitrogen	0.78**	-0.59*	0.67*	0.52										
Available potassium	0.66*	-0.83**	0.83**	0.81**	0.57*									
Available phosphorus	-0.49	0.19	-0.41	-0.19	-0.71**	-0.14								
Urease activity	0.73**	-0.90**	0.94**	0.85**	0.62*	0.78**	-0.46							
Polyphenol oxidase activity	0.76**	-0.88**	0.92**	0.80**	0.64*	0.77**	-0.45	0.97**						
Protease activity	0.77**	-0.93**	0.95**	0.93**	0.65*	0.91**	-0.32	0.94**	0.92**					
Phosphatase activity	0.73**	-0.95**	0.95**	0.93**	0.56*	0.91**	-0.19	0.92**	0.91**	0.98**				
Sucrase activity	0.75**	-0.94**	0.95**	0.91**	0.67*	0.91**	-0.34	0.94**	0.91**	0.99**	0.97**			
Bacteria	0.71**	-0.89**	0.93**	0.81**	0.62*	0.81**	-0.43	0.99**	0.98**	0.94**	0.93**	0.94**		
Actinomycetes	0.82**	-0.85**	0.93**	0.77**	0.76**	0.77**	-0.54	0.94**	0.97**	0.89**	0.88**	0.90**	0.95**	
Fungi	0.80**	-0.84**	0.91**	0.79**	0.72**	0.70**	-0.59*	0.97**	0.97**	0.90**	0.86**	0.89**	0.96**	0.97**

Note: * indicates significant correlation at the 0.05 level; ** indicates extremely significant correlation at the 0.01 level.

Table 4 (on next page)

Principal component eigenvalue, variance contribution rate and factor score coefficient matrix.

Evaluation indicator	Principal component	
	1	2
Soil clay (X_1)	-0.0150	0.1786
Soil bulk density (X_2)	0.1385	-0.1032
Soil moisture (X_3)	0.0862	0.0064
Organic matter (X_4)	0.1539	-0.1402
Total nitrogen (X_5)	-0.1124	0.3488
Available potassium (X_6)	0.1537	-0.1452
Available phosphorus (X_7)	0.2350	-0.5379
Urease activity (X_8)	0.0701	0.0365
Polyphenol oxidase activity (X_9)	0.0613	0.0525
Protease activity (X_{10})	0.1185	-0.0562
Phosphatase activity (X_{11})	0.1558	-0.1323
Sucrase activity (X_{12})	0.1129	-0.0452
Bacteria (X_{13})	0.0770	0.0225
Actinomycetes (X_{14})	0.0203	0.1325
Fungi (X_{15})	0.0100	0.1513
Characteristic root	12.2490	1.4521
Variance contribution rates/%	81.6601	9.6808
Accumulated variance contribution rates/%	81.6601	91.3409

1