Soil fertility evaluation and spatial distribution of grassland in Qilian mountain nature reserve-Tibetan Plateau

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The study assessed the overall soil characteristics of Qilian mountain grasslands and rated the soil nutrient status with Classification Standard of the second national soil Survey of China. The Nemerow index method was used to evaluate the soil fertility of different grassland types. GIS was used to analyze the spatial distribution of the soil nutrients and provided a database for the grassland's ecological protection and restoration. The study graded the soil organic matter (SOM), total N, and available K at level 2 (high) or above for most regions, available soil-P at level 4, while the soil bulk density, total porosity and pH were 0.77-1.32 g cm^{-3}, 35.36-58.83% and 7.63-8.54, respectively. The soil comprehensive fertility index was in a ranking order of Temperate steppe (TS) >Alpine meadow (AM) > Alpine steppe (AS) >Upland meadow (UM) >Alpine desert (AD)> Lowland meadow (LM)> Temperate Desert Steppe (TDS)> Temperate Desert (TD). The areas with high, medium and low soil fertility accounted for 63.19%, 34.24% and 2.57% of the total grassland area of Qilian mountain. Soil fertility of different grassland types had different main limiting factors, for instance, the pH, total N and SOM were the main factors limiting soil fertility in LM, while pH and available P were the main factors limiting soil fertility in UM, AM, TS and AS. In summary, the grassland soil fertility of Qilian mountain was generally at the mid-upper level, and the main limiting factors were found in the different types of grasslands and their spatial distributions. Our findings also indicated the typical grasslands and meadows may demand for acidic phosphate fertilizers, while desert grasslands may demand for compound fertilizers of nitrogen and phosphorus to improve their comprehensive soil fertility and grassland productivity .

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Abstract: The study assessed the overall soil characteristics of Qilian mountain grasslands and rated the soil nutrient status with Classification Standard of the second national soil Survey of China. The Nemerow index method was used to evaluate the soil fertility of different grassland types. GIS was used to analyze the spatial distribution of the soil nutrients and provided a database for the grassland's ecological protection and restoration. The study graded the soil organic matter (SOM), total N, and available K at level 2 (high) or above for most regions, available soil-P at level 4, while the soil bulk density, total porosity and pH were 0.77-1.32 g cm^{-3}, 35.36-58.83% and 7.63-8.54, respectively. The soil comprehensive fertility index was in a ranking order of Temperate steppe (TS) >Alpine meadow (AM) > Alpine steppe (AS) >Upland meadow (UM) >Alpine desert (AD)> Lowland meadow (LM)> Temperate Desert Steppe (TDS)> Temperate Desert (TD). The areas with high, medium and low soil fertility accounted for 63.19%, 34.24% and 2.57% of the total grassland area of Qilian mountain. Soil fertility of different grassland types had different main limiting factors, for instance, the pH, total N and SOM were the main factors limiting soil fertility in LM, while pH and available P were the main factors limiting soil fertility in UM, AM, TS and AS. In summary, the grassland soil fertility of Qilian mountain was generally at the mid-upper level, and the main limiting factors were found in the different types of grasslands and their spatial distributions. Our findings also indicated the typical grasslands and meadows may demand for acidic phosphate fertilizers, while desert grasslands may demand for compound fertilizers of nitrogen and phosphorus to improve their comprehensive soil fertility and grassland productivity.

Keywords: grasslands; soil fertility; Qilian natural reserve; spatial distribution;

Introduction

The Qilian mountain natural reserve is one of the most sensitive regions under global warming and an important ecological security barrier in northwestern of China (Wang et al., 2001). Grassland ecosystem is the largest ecological system in Qilian mountain natural reserve, which accounts for 74.3% of the total area and plays an important role in maintaining biodiversity, water conservation and ecological balance of the natural reserve (Li et al., 2019). In last few decades climate change, human activities and mismanagement have severely damaged the Qilian mountain grassland ecosystem. Understanding the current status of grassland soil in Qilian mountain is of great significance to the health and sustainable development of grassland ecosystems. There are many types of grasslands in Qilian mountain. Due to differences in terrain, rainfall and temperature, the distribution of the same type of grassland is very patchy and has discontinuities and irregularities. Previous studies found that different grassland types have large differences in soil nutrients due to the differences in vegetation types and utilization methods (Grazing, water conservation and sand fixation) (Fayiah et al., 2019; Chen et al., 2020).

Soil fertility has a directly impact on the health of grasslands and is also influenced by grassland vegetation (Hao et al., 2020). Without human disturbance, the growth and distribution of grassland vegetation is strongly affected by soil fertility apart from climate (Wang et al., 2016; Harpole et al., 2007). Soil fertility not only affects the growth of grassland vegetation, but also affects the grassland ecosystem health (Ma et al., 2019). Therefore, good understanding and objective evaluation of soil fertility characteristic is of great significance to restoration of regional vegetation, and improvement of fragile grassland ecosystem (Su et al., 2019; Jin et al., 2018).

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Grassland soil fertility plays a key role in supporting grassland ecosystem services (Clanet, 1980; Hu et al.,2018; Qu et al.,2016). Soil organic matter, available nitrogen, available phosphorus, available potassium, soil bulk density and pH are important components of soil fertility, while their content directly affect grassland vegetation productivity (Wuest, 2015; Li et al., 2014). Many methods have been used for soil fertility evaluation, including Nemerow index method (Hua et al., 2018; Shahab et al., 2013), AHP (Keshavarzi et al., 2020; Sousa et al., 2012), Subordinate function value method, etc. The Nemerow Index originates from professor N. L. Nemerow's book "Scientific Stream Pollution Analysis", which is used to evaluate water quality for pollutants (N. L. Nemerow., 1974), and modified and improved by Chinese scholars (Hua et al., 2018; Shahab et al., 2013; Zhou et al., 2017; Zhou et al., 2018). The Nemerow Index is used to evaluate the comprehensive soil fertility, meanwhile the Modified Nemerow Index can determine the minimum limiting factor of soil fertility. Among those evaluation methods, Nemerow index method has been well recognized due to the fact it can avoid the influence of subjective factors, which could highlight the influence of the worst factor of soil attribute factors on soil fertility (Bao et al., 2012). Also Nemerow comprehensive index method reflects the law of the limiting factor of plant growth in ecology, which can improve the credibility of the evaluation results (An et al., 2015; Zhou et al., 2017). Comprehensive evaluation of soil fertility combining with geographic information system (GIS) has been widely used to assess spatial distribution characteristics of soil nutrients, which is helpful to explore the relationship between soil nutrients and environmental factors (Wang et al., 2007; Peng et al., 2013; Nie et al., 2016; Brevik et al. 2016; Miller et al. 2016).

Many studies have been carried out on the soil of degraded grassland in Qilian mountain (Cheng et al., 2019; Wang et al., 2018; Chen et al., 2016). However; there are few studies on grassland soil fertility and its spatial distribution characteristics in Qilian mountain. Therefore, the aims of this study were to investigate the soil of different type grasslands in Qilian mountain natural reserve, 1) to analyze the distribution characteristics of soil fertility index, and 2) to determine the limiting factors of grassland soil fertility in Qilian mountain nature reserve, which can be of great help to provide scientific insight for improving grassland ecological services.

1 Materials and methods

1.1 Study area

The study sites were located in the Qilian mountain nature reserve in Gansu province, China (94°10′-103°04′E, 35°50′-39°19′N). From southeast to northwest at horizontal direction, there are four vegetation zones in the following order of forest, shrub, grassland and desert. At vertical direction, from low to high altitude (3000-5564 mm), there are three vegetation belts: grassland belt, forest belt and alpine meadow grassland belt. The main types of soil are Aridisols, Inceptisols and Entisols. The precipitation varies from 100 to 500 mm, mostly occurring during June to September. The average annual temperature is from -0.6 to 2.0°C; the average annual relative humidity is from 20% to 70%; the annual evaporation is about 1200-1400 mm; and the frost-free period is about 90-120 days (http://www.qilianshan.com.cn).

1.2 Sites selection and Sample collection

This study sites were mainly located on the Qilian mountain natural reserve in Gansu province, China. The grassland types were Temperate steppe (TS), Alpine meadow (AM), Alpine steppe (AS), Upland meadow (UM), Alpine desert (AD), Temperate desert steppe (TDS), Lowland meadow (LM), Temperate desert (TD) (Table 1) (NY/T 2997-2016, 2016).

The sampling time of this study was from July 23 to August 5, 2019, when the plants were in full bloom. The central points (Table 1) of the typical distribution area of the above 8 types of grasslands (AM, TS, LM, AS, UM, TDS, AD and TD) were selected as the sampling sites. A 60-meter sample line was randomly set for each sample site and the sample spots were set for every 20-meter interval. Four soil samples were taken at each sampling sites using soil drill (an auger drill) at a depth of 0-30 cm. The four soil samples were mixed to compose one sample. The samples were put into a sample bag and taken back to a laboratory for air-drying for further test. Three soil samples were taken. Meanwhile, Soil bulk density was measured by a stainless steel cutting ring (5 cm diameter and 5 cm high) after aboveground material was harvested for a total of 10 cores in each site.

1.3 Sample analyses

Soil bulk density was determined by Core method (Dong et al., 2012). Total porosity was determined by water immersion weighing method (Soil Physics institute, 1978). Soil samples were air-dried at room temperature, and visible roots and other debris in the soil were removed. Each soil sample was sieved through a 2-mm sieve. Soil organic matter was determined by the Walkley–Black method (Nelson and Sommers, 1996). The measurement of total soil N was determined using a micro Kjeldahl digestion procedure (Nelson and Sommers, 1996). Briefly, a small amount of dried soil (passing 0.25 mm sieves) mixed with H_2SO_4, $CuSO_4{\cdot}H_2O$ and K_2SO_4, heated and then made up with ammonium-free distilled water. The solution was mixed with 4 ml 40% NaOH and distilled using a Kjeldahl apparatus to release NH_3 for the determination of N content. Available P was extracted with sodium bicarbonate, and then determined by the molybdenum blue method. Available K was extracted with ammonium acetate, and then determined by flame photometry.

1.4 Evaluation of soil fertility

1.4.1 Evaluation of individual indicators of soil fertility

This study used the China second soil census standard (National Geographic Resource Science Sub Center, http://gre.geodata.cn) (Table 2) to rank the grassland soil organic matter, total N, available P, available K, pH, bulk density and total porosity indicators of Qilian mountain grassland, and to compare the differences between different grassland types (Zhou et al., 2017).

1.4.2 Comprehensive soil fertility evaluation

The Nemerow Index originates from professor N. L. Nemerow's book "Scientific Stream Pollution Analysis", which is used to evaluate water quality for pollutants (Nemerow. N. L., 1974). The Nemerow formula is as follows:

$$F=\sqrt{\frac{Fi^2+Fimax^2}{2}}$$

Where F is the Composite pollution index, F_i is the average value of each sub-pollution index, F_{imax} is the minimum value of each sub-pollution index, and i is the number of the sampling point.

The Nemerow index is used to evaluate the impact of the maximum pollutant on water quality. After modified and improved by Chinese scholars (Hua et al., 2018; Shahab et al., 2013; Zhou et al., 2017; Zhou et al., 2018), the Nemerow Index is used to evaluate the comprehensive soil fertility, meanwhile the improved Nemerow Index can determine the minimum limiting factor of soil fertility. The improved Nemerow formula is as follows:

$$F=\sqrt{\frac{Fi^2+Fimin^2}{2}}\cdot\left(\frac{n-1}{n}\right)$$

Where F is the soil comprehensive fertility index, F_i is the average value of each sub-fertility index, F_{imin} is the minimum value of each sub-fertility index, and n is the number of participating indicators.

To improve the Nemerow comprehensive index, the minimum value of F_i is used to replace the maximum value of F_i in the original Nemerow comprehensive index, which highlights the impact of the soil worst attribute on soil fertility and can reflect the minimum factor law of plant growth. In addition, the addition of the correction item $\left(\frac{n-1}{n}\right)$ improves the credibility of the evaluation, that is, the more soil sub-fertility index in the evaluation, the greater the value of $\left(\frac{n-1}{n}\right)$ and the higher of credibility. Meanwhile, correction item $\left(\frac{n-1}{n}\right)$ also reflects the difference in evaluation results when the evaluation indicators are not equal.

According to the grading standards of soil properties in the China second soil census standard (Table 3), the selected index parameters were standardized to eliminate numerical size differences between selected index parameters. The standardized treatment methods are as follows:

When the attribute value belongs to the level low, $c_i \leq x_a$, $Fi=c_i / x_a$ $(F_i \leq 1)$ (1)

When the attribute value belongs to the level upper, $x_a<c_i\leq x_c$, $F_i =1+(c_i-x_a)/(x_c-x_a)$ $(1<Fi\leq 2)$ (2)

When the attribute value belongs to the level high, $xc<ci \leq xp$, $Fi =2+(ci-xc)/(xp-xc)$ $(2< Fi \leq 3)$ (3)

When the attribute value belongs to the level very high, $ci>x$, $Fi=3$ (4)

In the above formulas, F_i is the attribute division coefficient, c_i is the measured value of the attribute, and x_a, x_c, and x_p are the classification indexes.

The improved Nemerow index method was then used to comprehensively evaluate the grassland soil fertility in Qilian mountain.

1.5 Soil comprehensive fertility index spatial distribution

Analysis method based on multiple regression and residues (AMMRR) had been widely used in many studies for grassland spatial interpolation (Liu et al., 2012; Guo et al., 2011). This method is more accurate than many other interpolating methods and can also effectively avoids systematic errors (Liu et al., 2012; Guo et al., 2011). In this paper, based on the comprehensive fertility index determined by the improved Nemerow index method, the ArcGIS10.2.2 (Nistor, M.M., 2016) was used to conduct the spatial analyses including extracting the center points of different grassland types (Fig.1), assigning values for grassland types, performing AMMRR interpolation, and drawing the Qilian mountain grassland soil fertility index spatial distribution. The comprehensive fertility index was divided into low (<1.50), medium (1.50-2.00), and high (> 2.00) (Zhou et al., 2017; Zhou et al., 2018).

1.6 Statistical analyses

Statistical analyses were conducted using SPSS (version 19.0 SPSS Inc., Chicago, IL, USA). All results were presented as mean and standard deviations. One-way ANOVA and least significant difference (LSD) tests were declared at $P<0.05$.

2 Results

2.1 Characteristics of grassland soil fertility indexes

The soil bulk density, total porosity, pH, total N, available P, available K and soil organic matter were 0.77-1.32 g cm^{-3}, 35.36-58.83%, 7.63-8.54, 0.63-4.97 g kg^{-1}, 6.79-24.27 mg kg^{-1}, 0.21-1.06 g kg^{-1} and 4.99-131.52 g kg^{-1} respectively (Table 4), and the corresponding Coefficient of variation (CV) of each index was greater than 10%.

2.2 Soil physical and chemical features in different type grasslands

The soil fertility indexes for different type grasslands are shown in Table 5, a significant difference ($P < 0.05$) was observed between different grassland types. Soil bulk density and total porosity were in a ranking order of desert type > meadow type > steppe type. The pH was in a ranking order of TD > LM > TDS > UM > AD > AS> AM > TS. Total N was in a ranking order of AM > TS > AS > UM > AD > TDS > LM > TD. The soil organic matter was in a ranking order of TS > AM > AS > UM > AD > TDS > LM > TD. The available P was in a ranking order of LM > TS > AM > AS > UM > TD > TDS > AD. The available K was in a ranking of LM > UM > AS > TD >TS > AM > AD > TDS.

2.3 Soil physical and chemical spatial distribution

The soil physical and chemical spatial distributions were shown in Fig.2. Soil bulk density of most areas was 0.75-0.94 g cm^{-3}. Total porosity of most areas was 50-60%. pH of most areas was 8-9. The SOM of most areas was 30-134 g kg^{-1}. The total N of most areas was 2.0-5.0 g kg^{-1}. The available P of most areas was 10-20 mg kg^{-1}. The available K of most areas was 0.3-1.5 g kg^{-1}.

2.4 Soil comprehensive fertility index

The soil comprehensive fertility indexes of different type grasslands ranged from 1.01 to 2.24 (Table 6). The soil comprehensive fertility index was significantly higher in AM, UM, AS and TS than in AD, significantly higher in AD than in LM and TDS, and significantly higher in TDS than in TD, but no significant difference was found among others. The soil comprehensive fertility index was in a ranking order of TS > AM > AS > UM > AD >LM > TDS > TD.

The soil fertility of Qilian mountain grassland was at a moderate or high level (Fig.3). In terms of spatial distribution, the soil comprehensive fertility index was at a high level in eastern and western of Qilian mountain, and the soil fertility in the central region was at a moderate level. There are only a few areas where the soil fertility of the grassland was at a low level, and distributed in the marginal regions of the western and central regions. The areas with the high, medium and low soil fertility accounted for 45.60%, 41.92% and 12.46% of the total grassland area of Qilian mountain respectively.

2.5 Limiting factors for grassland soil comprehensive fertility

The soil fertility of different types of grasslands had different major limiting factors (Table 6). For example, the pH, total N and SOM were the main factors limiting soil fertility in LM, and pH and available P were the main factors limiting soil fertility in UM, AM, TS and AS. The Soil bulk density, pH, total N, SOM and available P were the main factors limiting soil fertility in TD and TDS. Soil bulk density and available P were the main factors limiting soil fertility in AD. The limiting factors for the comprehensive soil fertility of Qilian mountain grasslands were shown in Fig.3.

3 Discuss

Soil organic matter content is closely related to soil fertility and soil health. The nitrogen, phosphorus, and potassium provide essential nutrients for plant growth and development, and are the main components of soil nutrients (Zhang et al.,2013; Zhou et al., 2016). The contents of SOM and available K were graded as level 2 (high) or above for Qilian mountain grasslands according to the classification of China second soil census standards (National Geographic Resource Science SubCenter, http://gre.geodata.cn). Available P was graded as level 4 with the content of 6.79-24.27 mg kg^{-1}. Soil density suitable for plant growth is generally within 1.14 to 1.26 g cm^{-3}. In ours research, the average soil bulk density of grasslands in Qilian mountain was 1.01 g cm^{-3}, with a value of between 0.75-1.14 g cm^{-3} in most of the Qilian mountain area. The grassland soil comprehensive fertility index of Qilian mountain decreases from east to west. The spatial distribution and succession of grassland types decided the grassland soil fertility. From west to east in Qilian mountain, the grassland types are desert, typical grassland and meadow grassland mainly. As an indicator of degree of dispersion of the sample, CV <10% means weak variation, 10-100% means medium variation and > 100% means strong variation. The results of our studies indicated that, except for soil pH, which were weak variations, all the nutrient indicators were moderately variable.

Grassland type is decided by climate, vegetation and soil (Hu et al., 1978). Soil as the substrate of grassland, its physical and chemical properties of different types of grasslands provide important insight to understand grassland evolution (Gou et al., 2019; Li et al., 2019). Zhang et al (2019) found that the contents of total N, organic carbon and soluble organic carbon of different alpine types of grasslands were in an order of alpine meadow> alpine meadow grassland> alpine grassland> alpine desert, and the differences between various alpine types of grasslands were significant. This study observed that the ranking of the different types of grasslands was desert type > meadow type > steppe type for soil bulk density, the ranking of total porosity were opposite to that of soil bulk density. Furthermore, the total N, SOM and soil comprehensive fertility index in different grassland types had significant differences. Since soil nutrients were mainly derived from the decomposition of animals, plants, microbial residues, litters, root exudates and soil parent materials, spatial heterogeneity of soil fertility distribution in different types of grasslands observed in this study indicated these grasslands were influenced through the different climate and vegetation (Wei et al., 2018). Soil organic matter mainly came from the decomposition of residual organic matter, but moisture and temperature were the dominant factors controlling the decomposition rate of organic matter. This was why Ren and Hu (2008) used rainfall and temperature accumulated as a first-class classification index to classify grassland types in Comprehensive and Sequential Classification System (Ren and Hu., 2008).

Evaluation factors affect the rationality and objectivity of evaluation results to a certain extent (Chen et al., 2019; Science - Soil Science, 2019). In many studies, the evaluation indicators of soil fertility mainly focused on nutrients such as soil organic matter, nitrogen, phosphorus and potassium (Chen et al., 2019; Science-Soil Science, 2019; Yu et al., 2018). The soil bulk density and total porosity can reflect the status of soil fertility from different angle as soil compactness, permeability, infiltration performance and water holding capacity (Garrigues et al., 2012). The modified Nemerow formula highlights the effect of the minimum factor on soil fertility, reflecting the law of the smallest factor of plant growth in ecology (An et al., 2015), and the soil minimum factor can be judged according to the minimum value of the Fi in the Nemerow formula. In ours study, the soil fertility of different types of grasslands had different main limiting factors. Such as pH, total N and SOM were the main factors limiting soil fertility in LM, and pH and available P were the main factors limiting soil fertility in UM, AM, TS and AS. The Soil bulk density, pH, total N, SOM and available P were the main factors limiting soil fertility in TD and TDS. Soil bulk density and available P were the main factors limiting soil fertility in AD. The Nemerow index method can objectively reflect the comprehensive fertility characteristics of grassland soil, but many studies have not analyzed the spatial distribution characteristics of soil fertility in depth (Bao et al., 2012; Fan, et al., 2012). Ours research combined GIS and soil science to draw a spatial distribution map of grassland soil fertility in Qilian mountain, which more intuitively reflected the distribution of grassland soil fertility. In ours study, the areas with high, medium and low soil fertility accounted for the total grassland area of Qilian mountain was 45.60%, 41.92% and 12.46%.

Grassland was an important foundation for the construction of the Qilian mountain ecosystem. Based on the research results, the actual distribution of grassland types, and reasonable management could promote benign and sustainable development of grassland ecosystems.

4 Conclusions

The results of soil fertility indexes and their spatial distribution of grasslands in Qilian mountain showed that, except for the low-available P content, all the soil fertility indexes had reached level 2 and above according to China's second soil census standard, while soil bulk density was relatively low and pH was relatively high. The soil comprehensive fertility index was in a ranking order of TS > AM > AS > UM > AD >LM > TDS > TD, and the areas with high, medium and low soil fertility accounted for 63.19%, 34.24% and 2.57% of the total grassland area respectively. The main limiting factors found in the different types of grasslands and spatial distribution, the typical grasslands and meadows may need to apply acidic phosphate fertilizers, and desert grasslands to apply compound fertilizers of nitrogen and phosphorus to improve comprehensive soil fertility and grassland productivity

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Table 1 (on next page)

nformation of the sample sites, Classification criterion of soil nutrients, Grading criterion for various soil properties in the Nemerow grading method, Criteria for determining the organic matter, total nitrogen and bulk density of grassland soi

nformation of the sample sites, Classification criterion of soil nutrients,Grading criterion for various soil properties in the Nemerow grading method, Criteria for determining the organic matter, total nitrogen and bulk density of grassland soils with different degradation degrees,Descriptive statistics in various studied parameters of grassland soil in Qilian Mountain Nature Reserve

Table 1 Information of the sample sites (NY/T 2997-2016, 2016)

Type Grassland	Altitude m	longitude and latitude	Main plant species	Coverage %
Lowland meadow (LM)	1364	39°40′35.02″N 99°8′45.09″E	*Phragmites australis* (Cav.) Trin. ex Steud, *Achnatherum splendens, sophora alopecuroides* L.	48.33
Upland meadow (UM)	3114	37°11′36.47″N 102°43′42.73″E	*Potentilla anserina* L., *Poa annua* L., *Elymus nutans griseb., Melissilus ruthenicus*(L.) Peschkova, *Artemisia annua* L..	81.67
Alpine meadow (AM)	2977	37°10′48.66″N 102°47′13.83″E	*Polygonum viviparum* L., *Kobresia myosuroides* (Villars) Fiori, *Melissilus ruthenicus*(L.). *Peschkova, artemisia annua* Linn., *Saussurea japonica* DC.	85.00
Temperate steppe (ST)	2817	37°22′13.68″N 102°40′44.93″E	*Poa annua* L., *Kobresia myosuroides* (Villars) Fiori, *Stipa capillata* Linn., *Potentilla anserina* L., *Artemisia annua* Linn.	85.00
Alpine steppe (AT)	3735	39°16′32.99″N 97°42′52.57″E	*Stipa purpurea, kobresia myosuroides* (Villars) Fiori, *Poa annua* L., *Potentilla anserina* L., *Androsace umbellate*	85.00
Temperate desert Steppe (TDS)	2139	38°57′57.23″N 99°47′41.95″E	*Sympegma regelii* Bunge, *Salsola collina* Pall., *Allium polyrhizum* Turcz, *Stipa capillata* Linn., *Ajania nematoloba*	43.75
Temperate Desert (TD)	1358	39°29′29.11″N 99°18′45.00″E	*Nitraria tangutorum* Bobr, *Nitraria sphaerocarpa* Maxim, *Suaeda glauca* (Bunge) Bunge, *Sympegma regelii* Bunge	31.67
Alpine desert (AD)	4290	39°15′34.39″N 97°45′6.70″E	*Rhodiola rosea* L., *Saussurea japonica* DC., *Kobresia myosuroides* (Villars) Fiori	28.33

Table 2(on next page)

Table 2. Classification criteria used for soil index

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Grades	SOM g kg^{-1}	Total N g kg^{-1}	Available P mg kg^{-1}	Available K g kg^{-1}	Interpretation
1	> 40	> 2.0	> 40	> 0.20	Very high
2	30-40	1.5-2.0	20-40	0.15-0.20	High
3	20-30	1.0-1.5	10-20	0.10-0.15	Upper
4	10-20	0.75-1.0	5-10	0.05-0.10	Mid-low
5	6-10	0.5-0.75	3-5	0.03-0.05	Low
6	< 6	< 0.5	< 3	< 0.03	Very low

Table 3(on next page)

Table 3 Grading criterion for various soil properties in the Nemerow grading method

Table 3 Grading criterion for various soil properties in the Nemerow grading method

Soil properties		Soil bulk density	total porosity	pH	SOM	Total N	Available P	Available K
Classification index of Nemorow	x_p	0.95	0.50	7	30	2.00	20	0.20
	x_c	1.10	0.40	8	20	1.50	10	0.10
	x_a	1.25	0.30	9	10	0.75	5	0.05

x_a, x_c, and x_p are the classification indexes

Table 4 (on next page)

(on next page)

Table 4. Descriptive statistics of grassland soils in Qilian mountain nature reserve

Table 4. Descriptive statistics of grassland soils in Qilian mountain nature reserve

Item	MIN	MAX	Mean	SD	CV%
Soil bulk density g cm^{-3}	0.77	1.32	1.01	0.18	17.88
Total porosity %	35.36	58.83	48.25	7.90	16.38
pH	7.63	8.54	8.07	0.38	4.71
Total N g kg^{-1}	0.63	4.97	2.38	1.8	75.49
Available P mg kg^{-1}	6.79	24.27	12.81	5.52	43.09
Available K g kg^{-1}	0.21	1.06	0.40	0.27	68.00
SOM g kg^{-1}	4.99	131.52	51.23	48.83	95.32

Table 5(on next page)

Table 5 Soil physical and chemical properties in different Grassland types in Qilian mountain Nature Reserve

1 Table 5 Soil physical and chemical properties in different Grassland types in Qilian mountain Nature Reserve

Grassland Type	Soil bulk density g cm^{-3}	Total porosity %	pH	Total N g kg^{-1}	Available P mg kg^{-1}	Available K g kg^{-1}	SOM g kg^{-1}
LM	1.05± 0.09bc	43.65±4.83cd	8.51±0.04a	0.64±0.10d	24.27±3.55a	1.06±0.91a	12.67±1.63cd
UM	0.95±0.07cd	48.73±2.06bc	7.97±0.24b	2.01±0.51c	12.34±2.97b	0.45±0.06b	36.87±16.45c
AM	0.83± 0.09de	51.59±5.45b	7.76±0.26d	4.81±0.13a	13.73±7.54ab	0.30±0.15bc	116.46±28.35a
TS	0.77± 0.03df	54.98±1.92ab	7.63±0.10e	4.97±0.78a	14.94±5.69ab	0.30±0.06c	131.52±14.33a
AS	0.91± 0.05d	58.83±2.50a	7.83±0.03bc	3.36±0.35b	13.65±6.95ab	0.35±0.08bc	65.56±20.49b
TDS	1.14± 0.09b	52.53±1.06b	8.50±0.03a	0.77±0.12d	7.96±0.65b	0.21±0.03c	13.18±1.94cd
TD	1.32± 0.06 a	35.36±4.69e	8.54±0.05a	0.63±0.08d	8.81±2.22b	0.32±0.05bc	4.99±0.99d
AD	1.11± 0.06b	40.32±2.18de	7.84±0.04bc	1.88±0.07c	6.79±0.97b	0.24±0.04c	28.65±1.90cd

2 Note: Data are presented as the mean±SD; Different small letters in the same column mean significant difference at 0.05 level. TS, Temperate steppe; AM, Alpine meadow; AS,
3 Alpine steppe; UM, Upland meadow; AD, Alpine desert; TDS, Temperate Desert Steppe; LM, Lowland meadow; TD, Temperate Desert.
4

Table 6(on next page)

Table 6 Comprehensive evaluation of different Grassland Types in Qilian mountain Nature Reserve soil fertility using Nemerow index

Table 6 Comprehensive evaluation of different Grassland Types in Qilian mountain Nature Reserve soil fertility using Nemerow index

rassland Type	F_i							$\overline{Fi}$	F
	Soil bulk density	Total porosity	pH	Total N	Availa-ble P	Availa-ble K	SOM		
LM	2.67	2.37	1.49	0.85	3.00	3.00	1.27	2.09	1.37c
UM	3.00	2.87	2.03	3.00	2.23	3.00	3.00	2.73	2.06a
AM	3.00	3.00	2.24	3.00	2.37	3.00	3.00	2.80	2.17a
TS	3.00	3.00	2.37	3.00	2.49	3.00	3.00	2.84	2.24a
AS	3.00	3.00	2.17	3.00	2.37	3.00	3.00	2.79	2.14a
TDS	1.73	3.00	1.50	1.03	1.59	3.00	1.32	1.88	1.30c
TD	1.06	2.54	1.46	0.84	1.76	3.00	0.50	1.59	1.01d
AD	1.93	2.03	2.16	2.76	1.36	3.00	2.87	2.30	1.62b

Note: TS, Temperate steppe; AM, Alpine meadow; AS, Alpine steppe; UM, Upland meadow; AD, Alpine desert; TDS, Temperate Desert Steppe; LM, Lowland meadow; TD, Temperate Desert.

Figure 1

Fig.1 The simulated samples of different grassland type patches spatial distribution

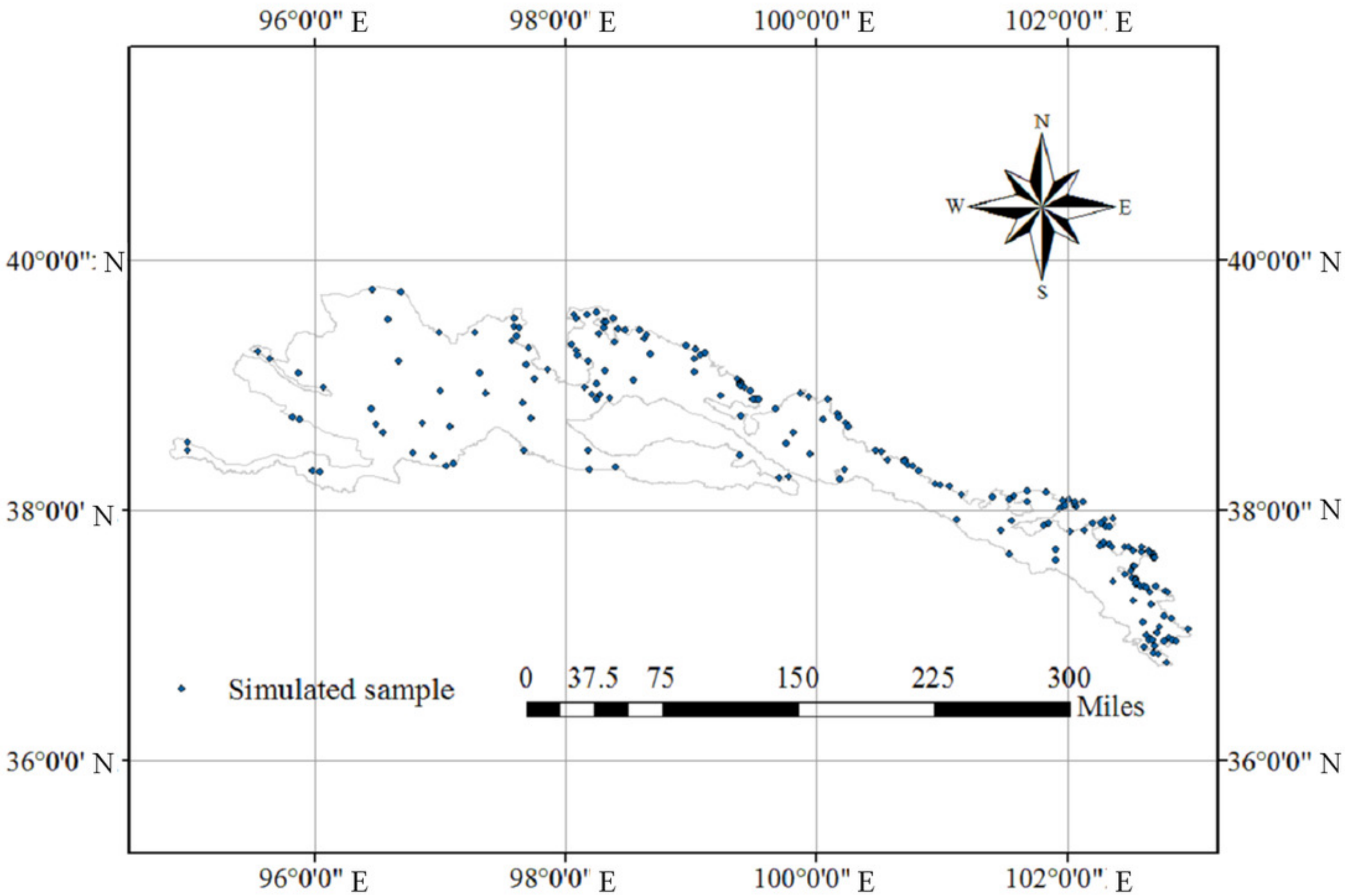

Figure 2

Fig.2 Soil physical and chemical spatial distribution

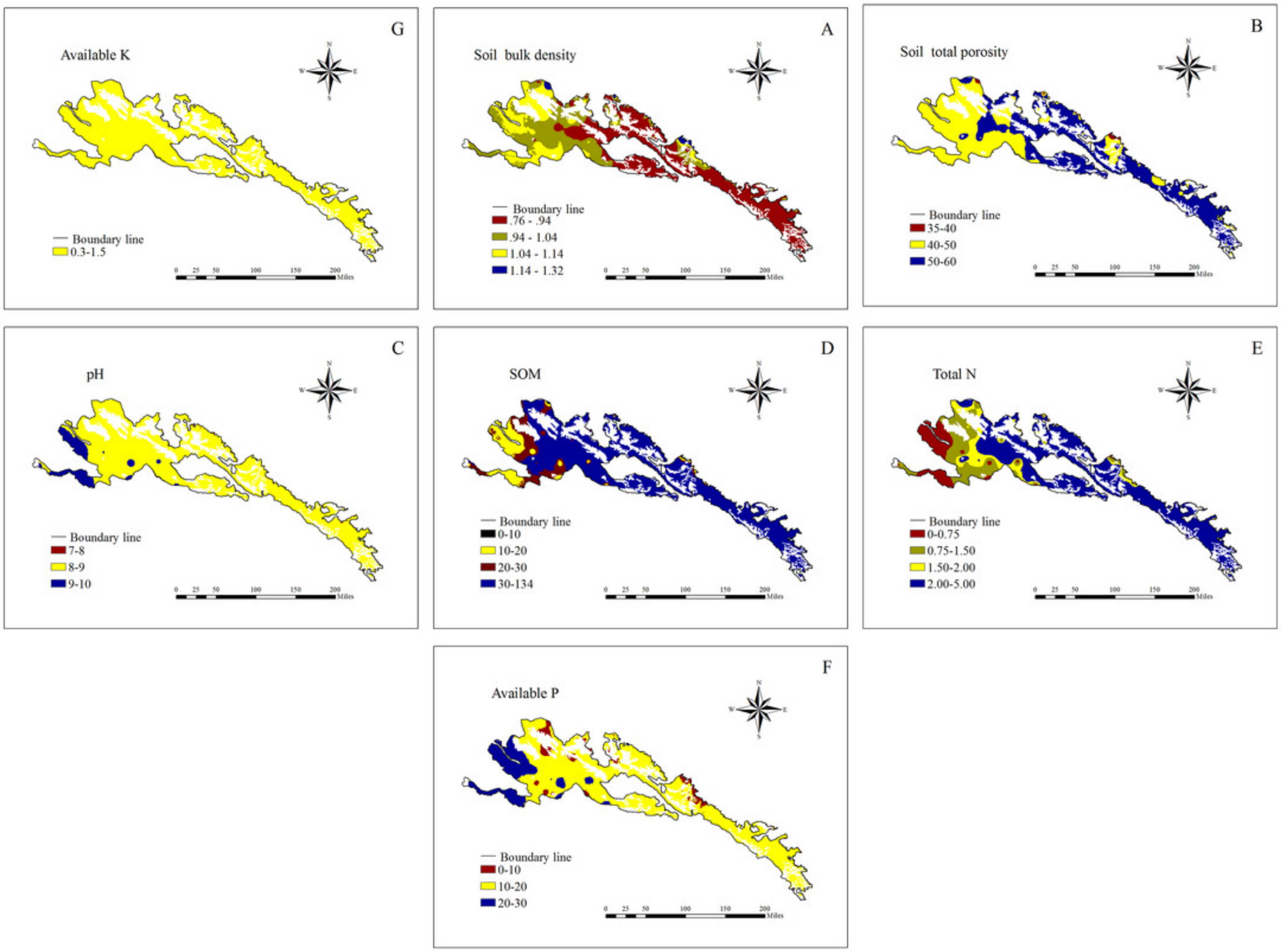

Figure 3

Fig.3 Spatial distribution of grassland soil comprehensive fertility index and limiting factors for grassland soil comprehensive fertility.