Responses of grassland vegetation and soil nutrients to desertification in Qilian Mountains of eastern Qinghai-Tibetan Plateau

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Abstract

To explore the change characteristics of vegetation and soil nutrients in grassland desertification, the study intends to using the method of replacing space with time, taking temperate steppe (TS), temperate steppe desert (TSD) and temperate desert (TD) in Qilian mountains as the research objects, and analyze the change characteristics of vegetation and soil nutrients replacing succession of grassland desertification. The study indicated that, from TS, TSD to TD, the total coverage, AGB, Shannon-Weiner index and richness, total porosity, total N, soil organic matter, C/N, C/P, N/P, alkaline phosphatase, catalase, sucrase were decreased, and grass layer height, dominance, soil bulk density and pH were increased. While the total P, total K and available P were first increased and then decreased, and were opposite to evenness and urease enzyme activity change. Meanwhile, the C/N, C/P and N/P of three grassland types ranged from 5.06-17.27, 2.49-71.94 and 0.50-4.19. Correlation analysis showed that, except for available P, available K, and evenness, there was a significant correlation between other vegetation and soil indicators. In conclusion, in the process of grassland desertification, grassland vegetation and soil had undergone significant changes, especially total coverage, AGB, Shannon-Weiner index, soil bulk density, soil organic matter and total nitrogen. Based on N/P, the nitrogen was the main factor limiting the productivity of grassland, and the limitation was more prominent in the process of grassland desertification.

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Keywords: Qilian mountains; desertification; grassland; soil nutrient.

Introduction

"Desertification" refers to land degradation caused by climate change and human activities in arid, semi-arid and semi-humid arid regions (Liu, 1998), which is a global environmental problem that plagues human development, and one of the current ecological research hotspots (Gao et al., 2019). Relevant studies have shown that the global arid area is 6.1×10^8 hm^2, among which China has 2.97×10^8 hm^2, and the arid areas have different degrees of desertification. From 1984 to 1991, the global land desertification accelerated at an annual rate of 3.4% (Office of Desertification Prevention and Control, Ministry of Forestry of the People's Republic of China, 1994). With global warming, the disorderly development of resources and the urbanization process, desertification may become a major ecological problem and challenge in the 21st century (Li et al., 2019; Rong, 2019). Therefore, understanding the rules of desertification, that is, the change characteristics and mutual relationship of vegetation and soil, has important ecological significance for slowing down the desertification process and vegetation restoration and reconstruction in desertified areas.

Qilian Mountain is located on the eastern edge of the Qinghai-Tibet Plateau in China, adjacent to the Mongolian Plateau and the Loess Plateau (Gao et al., 2019). The Qilian mountains is the intersection of the Qinghai-Tibet Plateau, the Loess Plateau and the Inner Mongolia Plateau, with a fragile ecological environment, and is also one of the most sensitive regions for global climate change (Wang et al., 2001). Grassland is the largest vegetation type in Qilian Mountains (Li et al., 2019). Therefore, the health of the grassland ecosystem in the Qilian Mountains is not only related to the water source security in the Hexi region, but also related to the ecological security and social stability in northwest China (Yao et al., 2018). Related studies have found that the climate change in the eastern part of Qilian is warm and humid, while the central and western regions is warm and dry (Rong, 2019). Therefore, climate change poses a serious challenge to the ecology of the Qilian Mountains. The warming and humidification of the climate in the eastern region had caused the degradation of alpine meadows and the shift of the snow line, while the warming and drying of the climate in the central and western regions led to the succession of temperate steppe to temperate desert steppe and temperate desert (Rong, 2019). Succession of grassland desertification will lead to a series of grassland ecological changes, such as changes in vegetation community structure, soil nutrients, microbial composition, etc. (Rong, 2019). Tang et al. (2016) found that the effects of desertification on total phosphorus and available phosphorus were not significant, and desertification decreased productivity in the desert steppe as a result of direct changes to soil physical properties, which can directly affect soil chemical properties. Li et al. (2006) found that soil organic matter is also reduced with desert development, which leads to destruction of the stability of soil physical structure and nutrient content, such as progressive N, P and K loss in surface and subsoil layers, and in response to changes in soil properties, vegetation altered as regards species composition, species diversity, coverage, structure and life-form (Tang et al., 2016). Therefore, a systematic understanding of the vegetation and soil change characteristics in the process of grassland desertification is of great significance to the restoration of desert grassland.

At present, most of the research on grassland desertification focused on the degradation of desert grassland. According to the degradation standard, the desert grassland is divided into several degradation gradients to study the relationship between vegetation community structure and soil nutrients (Rong, 2019; Li et al., 2006; Tang et al., 2016). Because grassland desertification is a process of long-term succession of grassland under warm and dry climate, this study used the method of replacing time with space, and selects three types grassland (temperate steppe, temperate steppe desert and temperate desert) as research objects replacing desertification succession. The characteristics changes and relationship of vegetation and soil factors were analyzed during the succession of temperate steppe to temperate desert, which could provide theoretical basis and data support for curbing grassland desertification and inducing forward succession of desert grassland.

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'-103deg04'E, 35deg50'-39deg19'N). In the horizontal distribution, the vegetation gradually deteriorates from southeast to northwest, which results in the formation of four vegetation zones in an order of forest, shrub, grassland and desert. Vegetation at the vertical belt spectrum, from low altitude to high altitude, was grassland belt, forest belt and alpine meadow grassland belt. The main types of soil were mountain gray cinnamon soil, subalpine meadow soil, alpine meadow soil, alpine cold desert soil. The annual precipitation varied from 100 to 500mm, mostly from June to September, the average annual temperature was -0.6-2.0degC, the average annual relative humidity was 20%-70%, the average annual evaporation was about 1200-1400 mm, the frost-free period was 90-120 days.

1.2 Research methods

1 .2.1 Sample selection

This research area was mainly focused on the Qilian mountain in Gansu province, China. The grassland types were temperate steppe, Temperate Steppe Desert, temperate desert. The utilization of different grassland was shown in Table 1.

1.2.2 Sample collection

The sampling time of this study was from July to August 2019, when the plants were in full bloom. The central area of the typical distribution area of the above 3 types of grassland (TS, TSD and TD) were selected for the sampling site. We established 6 random sampling quadrates (1 m x 1 m) in each site. In each quadrate, plant species, coverage, height, density of the respective species and aboveground biomass were measured and recorded. Aboveground parts of the green plants of the respective species were harvested by clipping to the soil surface, and collecting all litter in each quadrate. All the aboveground plant samples were placed into envelopes and then tagged, respectively. All the green plant samples were immediately dried at 105 for 30 min, then oven-dried at 60for 48 h and weighed. Meanwhile, a 60-meter sample line was set for each sample site and the sample spots were set at a 20-meter interval. Four soil samples were taken around each sample spot using soil drill at the soil layers with a depth of 0-10 cm, 10-20 cm and 20-30 cm respectively, and mixed four soil samples from each layer as one sample respectively. The samples were put into a sample bag and taken back to indoor for air-drying, which were measured for soil organic matter, Total N, Total P, pH and soil enzyme activity.

1.2.3 Sample determination

Soil samples were air-dried at room temperature, and visible roots and other debris in the soil samples were removed. Each composite soil sample was sieved through a 2-mm sieve. SOC was determined by the Walkley–Black method (Nelson & Sommers, 1996). Total N was determined by the Kjeldahl acid digestion method (Foss Kjeltec 8400, FOSS, DK) (Nelson & Sommers, 1996). Total P was measured by Mo-Sb colorimetry (UV-2102C, UNICO, Shanghai, China) (Nelson & Sommers, 1996). Soil pH value: potential method (water/soil ratio: 2.5:1). Urease enzyme activity was measured using the phenol sodium-hypochlorite sodium colorimetric method (Soil Physics institute, 1978). Sucrase enzyme activity was calculated according to the amount of glucose (mg) that was generated in 1 g soil sample after cultivation at 37 for 24h (Soil Physics institute, 1978). Alkaline phosphatase enzyme activity was determined using the method of disodium phenyl phosphate (Soil Physics institute, 1978). Catalase was determined by $KMnO_4$titration (Soil Physics institute, 1978).

1.3 Statistical analyses

The mass ratio was used for the ratio C/N, C/P and N/P. Statistical analyses were performed with SPSS version 19.0 (SPSS Inc., Chicago, IL, USA). All results are presented as mean and standard deviations.

One-way ANOVA and least significant difference (LSD) tests (P¡0.05). The IV of each plant species was calculated by the following formula (Lindsey, 1956):

$$IV = \frac{relative\ coverage\ +\ relative\ height\ +\ relative\ density\ +relative\ dry\ weight}{4}$$

Plant diversity was estimated using the three standard multi-dimensional biodiversity indices, i.e., Pielou Evenness index, Shannon-Weiner (H'), and Simpson diversity index (D) was calculated based on the following equations.

$$H' = -\sum_{i=1}^{s} P\text{i}\ln P\text{i}$$

When H' represents Shannon-Weiner index, P_i the total number of individual species proportion of ith species in the community and S represents encountered species number. the number of species encountered, P_i the proportion of the total number of individual species belonging to I th species in the community, $\ln P_i$ means the natural logarithm of P_i.

$$D=1-\sum_{i=1}^{S} P\text{i}2$$

Where D reprensets Simpson diversity index, S represents encountered species number. Pi the total number of individual species proportion of i th species in the community.

$$J=H'/\ln S$$

Where J represents Pielou evenness index, H' represents Shannon-Weiner index, S means the number of species

R=S

Where R represents richness index, S means the number of species.

2 Result

2.1 Vegetation characteristics

From TS, TSD to TD, the total coverage, AGB, Shannon-Weiner index and richness were decreased (Table2). There were significant differences among different treatments. Compared with TS, the coverage under TSD and TD decreased by45.31% and 60.41%, respectively, and the AGB decreased by 58.90% and 70.24%, respectively, and the Shannon-Weiner index decreased by 38.94% and 55.43%, respectively, and the richness decreased by 51.08% and 58.77%, respectively. The changes in dominance was the opposite of total coverage. The grass layer height was in order of TSD>TD >TS and evenness was in order of TD >TS >TSD.

2.2 Soil physical and chemical characteristics

Soil bulk density, total porosity and pH for various treatments were shown in Table3. The soil bulk density gradually increased in TS and increased in TSD and TD with the increase of soil depth. Compared with TS, the TSD and TD significantly increased the soil bulk density in the 0-30 cm soil depth. Soil bulk density was in order of TS < TSD < TD in same soil layers. The soil total porosity showed the opposite trend as changes in soil bulk density, and the pH showed the same trend as changes in soil bulk density except the pH in 10-20cm soil layer (TS < TD < TSD). Except TS, the total N gradually increased with the increase of soil depth. From Table4, compared with TS, the TSD and TD significantly decreased the soil total N in the 0-30 cm soil depth, and soil total N in same soil layers was in order of TD < TSD < TS. The SOC showed the same trend as changes in total N (Table4). The total P in same soil layers was in order of TSD < TD < TS (Table4), and the TSD and TD significantly decreased the total P in the 0-30 cm soil depth compared with TS. Available P showed the same trend as changes in total P (Table3). The available K in same soil layers was in order of TSD < TS < TD, except in 0-10cm soil layers (Table3).

2.3 Soil Stoichiometric characteristics

Soil C/N, C/P and N/P for various treatments were shown in Table4. Compared with TS, the TSD and TD significantly decreased the C/N in the 0-30 cm soil depth. The C/N was in order of TD < TSD < TS in same soil layers. The C/P and N/P showed the same trend as changes in C/N.

2.4 Soil enzyme activity

Soil enzyme activity for various treatments were shown in Fig.1. With the increase of soil depth, the Urease, alkaline phosphatase and sucrase enzyme activity was decreased, and catalase enzyme activity was increased. Compared with TS, the TSD increased and TD significantly decreased the Urease enzyme activity in the 0-30 cm soil depth. The Urease enzyme activity was in order of TD < TS < TSD in 10-20cm and 20-30cm soil layers, but was in order of TD < TSD < TS in 0-10cm soil layers. The alkaline phosphatase enzyme activity in same soil layers was in order of TD < TSD < TS, and the TSD and TD significantly decreased the alkaline phosphatase enzyme activity in the 0-30 cm soil depth compared with TS. The catalase (except in 20-30cm soil layers) and sucrase enzyme activity showed the same trendas changes in alkaline phosphatase enzyme activity.

2.5 Correlation

Correlation analysis showed that, except for available P, available K and evenness, there was a significant correlation between other vegetation and soil indicators (Table 5).

3 **Discussion**

3.1 Vegetation characteristics

Species diversity is an important feature of ecosystem stability maintenance and function operation, and vegetation productivity is an important indicator to characterize the plant ecological function stability and regional ecological carrying capacity (Pennekamp et al., 2018; Campos-Herrera, et al., 2013). Tang et al. (2016) found that, with the succession of grassland to desert, species richness, total vegetation coverage, dominant abundance, richness index and aboveground organisms all showed a downward trend. In this study, compared with TS, the coverage, AGB, Shannon-Weiner index and richness decreased, which was similar to the results of the Meng et al. (2018) study. Due to the suitable water and heat conditions in the temperate steppe distribution area, it was mainly composed of perennial herbs. The Temperate Steppe Desert was used for water limitation, and part of the herbaceous plants were degraded and formed mainly herbaceous and semi-shrub vegetation. However, due to extremely rare rainfall, dwarf shrubs and subshrubs with strong drought resistance were mainly found in temperate desert (Zhang et al., 2015). Evolving from temperate steppe to temperate desert, the vegetation structure gradually becomes uniform and the stability of the ecosystem decreases (Sharma et al., 2009).

3.2 Soil nutrient and stoichiometric characteristics

Soil degradation was one of the important characteristics of desertification. With the development of desertification, the degradation of soil physical and chemical factors had gradually increased (Wang et al., 2018). Related studies have found that, with the succession and development of desertification, and the content of soil organic matter and total N decrease significantly (Meng et al., 2018). In this study, from TS, TSD to TD, the total porosity, total N and soil organic matter were significant decreased, and soil bulk density and pH were significant increased. But the total P, total K and available P were in order of TSD < TD < TS. Due to the long-term warming and drying of the climate, the succession of temperate steppe to Temperate Steppe Desert has been induced. The vegetation type had evolved from herbaceous to semi-shrub (Wu et al., 2017). The decrease in vegetation litter amount and the decrease in decomposition rate (decomposing bacteria activity decreased) were co-leading of the reduced soil carbon, nitrogen, and phosphorus nutrients, which turned the changes of soil pH, porosity and bulk density. At the same time, soil changes had a negative effect on vegetation, which was caused the heterogeneity absorption of trace elements by vegetation (Tao et al., 2019). Soil ecological stoichiometric characteristics (C/N, C/P and N/P) have a strong regulatory effect on the carbon fixation process in terrestrial ecosystems (Zhang et al., 2016), which is an important parameter to measure soil quality (Liu et al., 2021), reflecting the ability of soil to release nitrogen and phosphate mineralized nutrients. The optimal C/N required for microbial life activities was 25 (Tessier and Raynal, 2019), which is the most favorable ratio for the conversion of organic carbon. In this study, from TS, TSD to TD, C/N rate was decreased, and C/N of TS, TSD to TD was 15.70, 10.13 and 5.80, respectively. That was, TS was good for microbial life activities, but TSD and TD was bad for microbial life activities. Soil C/P ratio was an important indicator of soil phosphorus mineralization capacity, which could measure the potential of soil organic matter mineralization to release phosphorus or absorb phosphorus fixation (Zhang et al., 2018). In this study, from TS, TSD to TD, C/N was decreased, and C/P of TS, TSD to TD was 63.17, 10.04 and 2.98, respectively. The N/P ratio was used as an index for determining the nutrient factors that limit productivity, and N/P¡10 and N/P>20 were used as indicators to evaluate the productivity of vegetation limited by nitrogen or phosphorus(Li et al., 2018). In this study, from TS, TSD to TD, C/N was decreased, and N/P of TS, TSD to TD was 4.02, 1.00 and 0.53, respectively. That was, productivity was increasingly limited by soil nitrogen from TS, TSD to TD.

3.3 Soil enzymes characteristics

Soil enzymes decomposed complex organic compounds into smaller organic compounds and inorganic nutrients (Grandy et al., 2007). As the most active and sensitive components in soil, soil enzymes played an important role in the nutrient cycle of soil and the supply of nutrients needed for plant growth, and were an important index for evaluating soil quality of different grassland types (Veronica et al., 2007). Its activity and mainly affected by soil physical and chemical properties, soil microorganisms and vegetation litters (Cui et al., 2019). In ours research, with the increase of soil depth, urease, alkaline phosphatase and sucrase enzyme activity decreased and catalase enzyme activity increased. From TS, TSD to TD, the alkaline phosphatase, catalase and sucrase enzyme activity were decreased. Because the soil surface layer accumulates more litter and humus than the depth soil layer, the organic matter content was high and the nutrient source was sufficient, which was conducive to the growth and reproduction of microorganisms. meanwhile water and heat in topsoil better and ventilation conditions, plant hair root and litter turnover rapid, which further accelerated the microbial growth and metabolism, making the soil Urease, Alkaline phosphatase and Sucrase enzyme activity decreased with the increase of soil depth, but the Catalase enzyme activity increased.

3.4 The evolution mechanism of grassland desertification succession

This research used space instead of time to analyze the evolution of grassland vegetation and soil in the process of grassland desertification, in the western Qilian Mountains- eastern Qinghai-Tibet Plateau during the global warming process. Based on the steppe spatial distribution pattern, the evolution from temperate steppe to temperate desert, rainfall decreased and temperature raised, that was, climate change was "warming and drying" (Rong, 2019). The complex of altitude as a regional hydrothermal factor also showed a decreasing trend (from temperate steppe to temperate desert was from 2800m to 1500m) (Xu et al., 2021). In the grassland ecosystem, above-ground vegetation was a sensitive indicator of climate change (Zhou et al., 2020), and prioritized the perception of climate change and adjusted its growth characteristics to adapt to environmental changes. For example, in the process of grassland desertification, grassland vegetation coverage, biomass and diversity index decreases, and the height of the grass layer increased (Fig.2), and plant species evolved from herbaceous plants to lignified shrubs to reduce water evaporation and adapt to rising temperatures, which was a survival strategy for plants (Zhou et al., 2020). When vegetation changed, soil, as a substrate and nutrient donor for plants, would also change, such as physical structure (increased bulk density, decreased porosity), decreased chemical nutrients (carbon, nitrogen, and phosphorus), and decreased soil enzyme activities (Fig2) (Wang et al., 2018). Meanwhile, changes in soil physical structure, nutrient content and enzyme activity will adversely affect plants and affect their growth. The "coordination" and "antagonism" of grassland plants and soil promote the flow of material and energy in the grassland ecosystem to adapt to changes in the environment (He et al., 2021). The results could provide theoretical basis and data support for curbing grassland desertification and inducing forward succession of desert grassland.

4 Conclusion

The research used the method of replacing space with time, and analyzed the change characteristics of vegetation and soil nutrients in succession of grassland desertification found that, grassland vegetation and soil had undergone significant changes, especially total coverage, AGB, Shannon-Weiner index, soil bulk density, soil organic matter and total nitrogen. Based on N/P, the nitrogen was the main factor limiting the productivity of grassland, and the limitation was more prominent in the process of grassland desertification. The results could provide theoretical basis and data support for curbing grassland desertification and inducing forward succession of desert grassland.

Conflicts of interest

The authors declare no conflicts of interest.

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Data availability statement

The dataset that associated with this study is available. When the paper is accepted for publication, we store the data to the specified platform according to the requirements of the journal.

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