Heterogeneity of soil structure and fertility during desertification of alpine grassland in northwest Sichuan

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Abstract. The variations of soil structure and soil physical-chemical properties in the process of alpine grassland desertification were revealed, and the indicators of grassland desertification were put forward in order to deepen the understanding of the law of degradation succession and development of alpine grassland. It was used to provide scientific basis for ecological restoration and improvement of ecological service function of alpine grassland. With severe desertification alpine grassland as the core in the Hongyuan County, Tibetan Qiang Autonomous Prefecture of Ngawa, Sichuan Province, China, along both the directions of wetland and arid grassland, the heterogeneity of soil structure and soil fertility in both directions was studied by the analysis of the mean weight diameter (MWD), geometric mean diameter (GMD), >0.25 mm aggregate content (R_{0.25}), fractal dimension (D), soil bulk density, soil moisture content, and soil nutrients. Our results showed that MWD, GMD, and R_{0.25} all gradually increased, but the D decreased with the reduction in the degree of desertification in the arid grassland and wetland, resulting in the strong stability of soil structure. The decreasing rate of the D in the direction of arid grassland was faster than that of wetland. Therefore, soil structure stability and erosion resistance in the direction of arid grassland were stronger than that of wetland soil; the D had different response to aggregates with different particle sizes. The aggregate less than 0.25 mm (r = 0.981, P < 0.01) and 1–2 mm (r = −0.79, P < 0.01) had the largest responses in the direction of the arid grassland and wetland, respectively; the aggregate more than 1 mm and 1–2 mm can be used as indicators to evaluate desertification of the soil in the direction of the arid grassland and wetland, respectively. The higher the content of the indicating aggregates, the weaker the degree of the desertification.

Key words: deterioration of alpine grassland; fractal dimension; soil physical-chemical properties; soil water-stable aggregates.

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INTRODUCTION

Grassland degradation is a process of reverse succession of grassland ecosystem, which is mainly manifested as vegetation degradation and soil degradation. Although the vegetation degradation and soil degradation affect and feedback each other, it is showed that soil degradation lags behind vegetation degradation (Gad and Abdelsamie 2000, Gomes et al. 2003). In the process of grassland degradation, soil degradation is mainly manifested as the destruction of soil structure, significant reduction in soil erosion resistance, serious loss of organic and mineral nutrients, and weakening of soil fertility (Yuan et al. 2019), among which soil structure degradation is the core of soil degradation (Cai et al. 2013).
Soil aggregates are soil structural units composed of soil organic matter and inorganic mineral particles through the function of the adhesion, cementation, and agglomeration (Yan et al. 2016). They are the matrix of the substance–energy transformation and metabolism in soil. Soil aggregates can significantly affect the soil porosity, water-holding capacity, and corrosion resistance and played an important role in conditioning soil fertility and improving soil tillage. In addition, soil aggregates are directly related to soil erosion and degradation, which are one of the important parameters for the characterization of soil physical property (Veiga et al. 2009).

The stability and quantity of soil aggregates have a great impact on soil physical properties and soil nutrient reserves. Those two properties of soil aggregates can not only keep soil structure stable and reduce soil erosion, but also protect soil organic matter and improve soil fertility. Soil particle distribution can characterize soil structure, nutrient status, nutrient conversion degree, and conversion rate. The ideal particle composition and nutrient conditions can provide suitable soil environment such as water, fertilizer, gas, and heat for vegetation growth and reproduction (Suding et al. 2004, Slimani et al. 2010). In recent years, the fractal dimensions of soil aggregates, particles, and porosity have been calculated by the fractal model to quantitatively describe the physical structure characteristics of soil (Yan et al. 2013, Li et al. 2019a).

The alpine grassland in the northwest Sichuan is one of the five pastoral areas in China. It is also the wetland source area of the Tibetan Plateau with important ecological value. In addition, it is the most important water supply area in the upstream of the Yellow River. However, due to the influence of natural and human factors, the grassland desertification in this area was increased by 307.7% during the 34 yr from 1966 to 2000, and the average annual grassland desertification area was increased by 816.0 hm². Vegetation coverage and root distribution density of degraded grassland gradually decrease. As a result, soil moisture evaporation increased, soil moisture content decreased (Andry et al. 2009, Chen et al. 2017), soil porosity and compactness reduced, and soil bulk density increased. It probably has directly or indirectly affected the composition of soil particles, the size and distribution of the soil, and soil water-holding performance, and leads to soil infiltration capacity and soil erosion resistance. Especially, reduced organic carbon input results in lower soil aggregation effect, and soil aggregate disintegration occurred, by the larger particles to smaller particles’ group changes (Li et al. 2004). Polysaccharide and active organic matter are the main factors affecting the decomposition of large aggregates, while clay particles and inert organic matter mainly affect the decomposition of microaggregates. The variation of soil environment after alpine grassland degradation has greatly changed the structure and functional stability of soil aggregates formed by long-term adaptation and evolution of microorganisms. It leads to the enhancement of decomposition ability of microorganisms to soil organic carbon and total nitrogen of different grain grades. In addition, it also results in the decrease in the proportion of large soil aggregates with the degradation degree of grassland.

Previous studies on soil aggregates and nutrient characteristics during grassland degradation mainly focus on grasslands in arid and semiarid areas, while only a few reports have been reported on alpine grasslands (Luo et al. 2016, Li et al. 2019a, Erdem et al. 2019). Moreover, because of the soil texture and climatic factors such as water and heat in different types of grasslands, the distribution and stability of soil aggregates are also different (Lorenz et al. 2008, An et al. 2010, Zhou et al. 2012, Chen et al. 2017). Many intensive studies concerning the effects of desertification control and restoration methods on protection benefits have been carried out in desertification lands (Cortina et al. 2011, Angeles et al. 2013, Hu et al. 2016), but only a few have focused on soil structure and physical and chemical properties in the desertification process of alpine grassland.

In this paper, we reported detailed investigations of distribution and stability of soil aggregates in desertification of alpine grasslands. We proposed that the soil aggregates and soil nutrients of the wetland and arid grassland on both sides of severe desertification patches repeatedly examined three main predictions: (1) Desertification soil in alpine grassland has more small aggregates and lower large aggregates, which could be the significant characteristics of grassland desertification; (2) the comparison of MWD, GMD, $R_{0.25}$, and fractal dimension ($D$) in the
desertification process of arid and wet grasslands indicates that the stabilities of soil aggregates in different types of grassland desertification are different; and (3) the aggregates with different particle sizes are correlated with soil organic matter, alkali-soluble nitrogen, available phosphorus, and soil desertification degree. Therefore, the soil aggregates can be used as one of the indicators of grassland desertification.

**MATERIALS AND METHODS**

**Study site**

The study area was located in the Hongyuan County, Tibetan Qiang Autonomous Prefecture of Ngawa, Sichuan Province, China. The longitude and latitude are 101°51′–103°23′ E and 31°51′–33°19′ N. The terrain sloped from southeast to northwest with an elevation of 3210–4857 m. It belonged to the cold temperate monsoon climate of the continental plateau with a short spring and autumn, and a long winter, without summer. Annual average rainfall is 791.95 mm, and the rainfall is mainly concentrated from May to October. The average temperature of a year is 1.1°C, −10°C for the coldest month and 10.9°C for the hottest month. It has annual average snow period of 76 d, without absolute frost-free period. Sunshine is sufficient with strong solar radiation. Annual average sunshine time was 2158.7 h.

It is dominated mainly by grassland, accompanying with a relatively large area of marshland and sandy land. The soil type is mainly subalpine meadow soil, and the alpine cold desert soil, marshy meadow soil, rock-forming soil, and wind sandy soil are also distributed. The middle sandy lands are mainly distributed in Qiongxi Town and Wachi Town with total area of about 6915.4 hm². The dominant vegetation species of the grassland are mainly Sichuan Song grass and small Song grass, with companion species of Potentilla, Aster alpinum, Elymus sibiricus, and Festuca.

**Soil sampling and analytical methods**

The sampling experiments were carried out in the study area in September 2018. Taking the severe desertification plaques as the core, along the direction of wetland and arid grassland on both sides, there was an obvious decreasing gradient of desertification, followed by severe desertification, the moderate desertification, mild desertification, and no desertification of grassland.

The soil sampling was taken by the following method: (1) According to a severe desertification grassland patches as a starting point, there were two different sides which were dealt with separately. One was in the direction of wetland up to the edge of the river. Another one was along the direction of arid grassland without desertification; (2) the grid sampling method was used here. The sampling belts were set in every 50 m starting with the severe desertification grassland. There were totally 10 sampling belts. In each sampling belt, three sampling points were selected with the interval of 10 m. A soil profile at a depth of 20 cm was taken in each sampling point. A total of 30 soil samples were taken with the soil box to prevent from the failure of aggregates and the ring sampler with 100 cm³ was used for an intact soil core to test the soil bulk density and soil moisture content. Soil samples naturally dried indoor were used for determinations of organic matter, alkali-hydrolyzed nitrogen, and available phosphorus.

The content of soil moisture (SM): Drying and weighing methods were used.

The soil bulk density: The unstirred natural soil sample was cut with a ring knife (generally 100 cm³) with a certain volume, and the soil sample was filled with it. After drying, the dried soil weight per unit volume was measured and calculated (Nanjing Agriculture Institute 1985).

The content of organic matter in the soil (TOM): After being processed by using 0.25-mm sieves, the soil sample was determined using the law of K_2Cr_2O_7 capacity (Nanjing Agriculture Institute 1985).

The content of alkali-hydrolyzed nitrogen in the soil (AN): After being processed by using 0.25-mm sieves, the soil sample was determined using the law of alkali diffusion (Nanjing Agriculture Institute 1985).

The content of available phosphorus in the soil (AP): After being processed by using 0.25-mm sieves, the soil sample was determined using the law of Olsen (Nanjing Agriculture Institute 1985).

The above indices were tested thrice.

**Mechanical stability aggregates**

Dry sieving method: Gently break the soil sample into small lumps with a diameter of
about 10 mm and air-dried in the lab after get rid of small stones, animal and plant residues. 100 g of dried soil was placed on the soil sample sieves, of which pore diameters were 2, 1, and 0.25 mm from top to bottom. Then, the soil mechanical stability aggregates of >2, 1–2, 0.25–1, and <0.25 mm were successively isolated by vibrating sieve machine for 10 min (rotating speed: 1400 r/min) and were weighed to calculate the aggregate percentage at all levels; each sample was measured for three times.

**Water-stable aggregates**

Wet sieving method: 100 g of air-dried soil samples was prepared according to the composition ratio of mechanical stability aggregates obtained by dry sieving method and was soaked in the aggregate analyzer for 5 min, and then oscillated for 30 min (TTF-100 model: rotating speed 30 times/min, upper and lower amplitude 40 mm). Thus, soil water-stable aggregates of >2, 1–2, 0.25–1, and <0.25 mm were isolated. After drying and weighing at 50°C, the percentage of aggregates at all levels was calculated, and each sample was measured for two times.

**Stability of soil aggregates**

The index of soil aggregate stability was indicated by mean weight diameter (MWD), geometric mean diameter (GMD), >0.25 mm aggregate content (R<0.25), and fractal dimension (D) of soil water-stable aggregates. The calculation of fractal dimension adopted the fractal theory to establish the fractal model of soil aggregate structure (Tyler and Wheatcraft 1992, Yang and Luo 1993). The calculation formulas are as follows:

\[
\text{MWD} = \sum_{i=1}^{n} \overline{x}_i W_i
\]

(1)

\[
\text{GMD} = \exp\left(\sum_{i=1}^{n} W_i \ln \overline{x}_i \right)
\]

(2)

\[
R_{>0.25} = \frac{[1-M_{x<0.25}/M_T]}{3-D}
\]

(3)

\[
M_{x<0.25}/M_T = \left[\frac{\overline{x}_i}{x_{max}}\right]^{3-D}
\]

(4)

In the formula, \( \overline{x}_i \) is the average particle size of two adjacent sieve grades (mm). In this study, the average diameter of the aggregates is 3.5 mm for large aggregates, 1.5 mm for relatively larger aggregates, 0.625 mm for the microaggregates, and 0.125 mm for sticky powder. \( W_i \) is the percentage of level \( i \) aggregates, \( M_{x<0.25} \) is the mass of aggregates with particle size <0.25 mm (g), \( M_T \) is total mass of each grain grade (g), \( M_{x<\overline{x}} \) is the cumulative soil quality of particle size less than \( x_i \) (g), \( x_{max} \) is the size of the maximum soil particle (it is 5 mm in this study), and \( D \) is fractal dimension. After plotting \( \lg(M_{x<\overline{x}}/M_T) \) with respect to \( \lg(x_i/x_{max}) \), the parameter of 3-D is obtained from the slope of the plotted curve, and the \( D \) can be determined by the regression analysis.

**Statistical analysis**

All results were reported as the mean ± standard deviations (SD). All the analyses were carried out using SPSS 20.0 for Windows (SPSS, Chicago, Illinois, USA). We used one-way ANOVA to determine the effect of the grassland desertification on stability of soil aggregates. Pearson’s correlation coefficients were calculated to determine whether different particle sizes of aggregates were related to desertification degree of grassland, fractal dimension, soil bulk density, soil moisture content, and soil nutrients in arid grassland and wetland, respectively. Multiple comparison tests were also performed to compare the least significance difference (LSD) at \( P = 0.01 \) and \( P = 0.05 \).

**RESULTS AND DISCUSSION**

**Response of soil structure to grassland desertification process**

*Distribution of mechanical stability aggregates.*—With the decrease in grassland desertification, soil mechanical stability aggregates in alpine grassland showed a trend of changing from small size to large size (Fig. 1). The <0.25 mm aggregates’ fractions in the direction of arid grassland and wetland decreased from 98.83% to 21.87% and 68.27%, respectively, but it has gone in the opposite way for the 0.25–1, 1–2, and >2 mm fractions. However, for 0.25–1 mm fraction, it conversely increased from 0.94% to 29.52% and 14.29% with the average value of 15.24% and 8.68%, respectively. The 1–2 and >2 mm aggregates’ fractions increased from 0.23% to 67.48% and 20.45%, respectively.

*Distribution of soil water-stable aggregates.*—For the mass distribution of soil water-stable aggregates with different particle sizes (Fig. 2), the
similar condition occurred, but the variations were lower than that of the mechanical stability aggregates. The <0.25 mm aggregates’ fractions in arid grassland and wetland decreased from 76.88% to 17.06% and 32.05%, respectively. However, for 0.25–1 mm aggregates’ fractions, it conversely increased from 22.3% to 54.47% and 54.59%, respectively. The 1–2 and >2 mm aggregates’ fractions increased from 0.82% to 53.34% and 15.01%, respectively.

The formation of soil aggregates is a complex process involving physical, chemical, and biological interactions. Soil water-stable aggregates are structural units against hydraulic dispersion formed by soil particles through various natural processes, and are important to keep soil structure stable and are one of the indexes to measure soil erosion resistance (An et al. 2010, Mai et al. 2010, Ma et al. 2010).
GMD, and \( R_{0.25} \) is the fractal dimension.

\[
\begin{array}{c|c|c|c|c}
\text{Distance (m)} & \text{MWD (mm)} & \text{GMD (mm)} & \text{\( R_{0.25} \) (%)} & \text{\( D \)} \\
\hline
0 & 0.25 \pm 0.003 & 0.18 \pm 0.02 & 23.12 \pm 1.66 & 2.60 \pm 0.005 \\
50 & 0.22 \pm 0.010 & 0.17 \pm 0.02 & 18.32 \pm 0.64 & 2.62 \pm 0.004 \\
100 & 0.18 \pm 0.004 & 0.15 \pm 0.03 & 10.54 \pm 0.79 & 2.66 \pm 0.006 \\
150 & 0.28 \pm 0.003 & 0.20 \pm 0.01 & 28.73 \pm 0.76 & 2.57 \pm 0.007 \\
200 & 0.48 \pm 0.070 & 0.27 \pm 0.02 & 81.52 \pm 6.29 & 2.51 \pm 0.003 \\
250 & 0.63 \pm 0.040 & 0.41 \pm 0.03 & 69.67 \pm 3.07 & 2.33 \pm 0.022 \\
300 & 1.12 \pm 0.040 & 0.55 \pm 0.02 & 64.01 \pm 3.23 & 2.42 \pm 0.025 \\
350 & 1.59 \pm 0.240 & 1.00 \pm 0.09 & 81.52 \pm 6.29 & 2.27 \pm 0.200 \\
400 & 1.08 \pm 0.120 & 0.59 \pm 0.07 & 67.52 \pm 3.07 & 2.38 \pm 0.130 \\
450 & 1.31 \pm 0.220 & 0.79 \pm 0.10 & 79.82 \pm 4.12 & 2.22 \pm 0.029 \\
500 & 1.70 \pm 0.099 & 1.02 \pm 0.08 & 83.94 \pm 3.44 & 2.20 \pm 0.093 \\
\end{array}
\]

Notes: Data are from a total of 30 soil samples from the alpine grassland of Hongyuan County, Tibetan Qiang Autonomous Prefecture of Ngawa, Sichuan Province, China. Distance is the length of distance from severe desertification plaques; MWD is the mean weight diameter; GMD is the geometric mean diameter; \( R_{0.25} \) is the percentage of water-stable aggregates >0.25 mm; \( D \) is the fractal dimension.
Generally speaking, with the reduction in the desertification, $D$ in arid grassland and wetland directions was decreased from 2.60 to 2.20 and 2.40, respectively. Thus, the $D$ decreased gradually with the reduction in desertification, and the soil structure, stability, and corrosion resistance increase gradually (Liu et al. 2013, Chen et al. 2017). Within the same research filed, the decrease in $D$ in the direction of the arid grassland was greater than that of wetland. This may be due to the fact that the arid grassland has a thicker hay layer, which can effectively reduce the splash erosion of rainfall, and can reduce the destruction of the large aggregates in soil. However, the wetland soil was affected by the surface runoff, and the large aggregates in soil were affected by a decrease in water erosion. This indicated that the average agglomeration degree and the mechanical stability of soil aggregates increase with the decrease in desertification. Therefore, the soil structure stability of the arid grassland was stronger than that of wetland.

**Effects of grassland desertification on soil bulk density and water content**

It was found that the soil bulk density and moisture content presented a similar variation trend in both directions of arid grassland and wetland (Fig. 3). It seemed that the soil moisture content increases, but the bulk density decreased with the reduction in desertification degree.

The moisture content (4.38–55.39%) of the soil in the direction of arid grassland was higher than that of wetland (4.38–20.03%). Because <0.25 mm aggregates mainly consist of microsand grains (73.06–98.83%) in the direction of wetland, the soil water-holding capacity decreased when soil particles in wetland became finer (Zeng et al. 2018).

However, the bulk density (1.33–0.79 g/cm$^3$) of the soil in the direction of arid grassland was lower than that of wetland (1.33–1.14 g/cm$^3$). Generally, the looser and more porous the soil is, the smaller the bulk density is, and the better the soil structure is (Six et al. 2000), so the soil structure of arid grassland is better than that of wetland.

**Effects of grassland desertification on soil fertility**

Soil nutrient is a significant index of soil fertility and a core element of soil structure. With the decrease in desertification, the contents of organic matter and available nitrogen in the surface soil in the direction of the arid grassland and wetland both increased gradually (Figs. 4, 5). It can be found that the contents in the direction of arid grassland were significantly higher than that of wetland ($P < 0.05$), and the contents of the organic matter in each direction were 37.45–154.86 g/kg and 37.45–47.53 g/kg, and for the available nitrogen, they were 14.85–57.59 mg/kg and 14.85–27.65 mg/kg, respectively. However, with the decrease in desertification, the soil available phosphorus decreased firstly and then increased for both the directions of the arid grassland and wetland, with the contents of 5.98–54.6 and 15.8–54.6 mg/kg, respectively (Fig. 6).

Table 2. Stability (MWD, GWD, $R_{0.25}$, $D$) of soil water stability aggregates found in the process of desertification reduction in alpine wetland (from near to far from severe desertification plaques).

| Distance (m) | MWD (mm)   | GMD (mm)   | $R_{0.25}$ (%) | $D$     |
|-------------|------------|------------|----------------|---------|
| 0           | 0.25 ± 0.003 | 0.18 ± 0.02 | 23.12 ± 1.66   | 2.60 ± 0.005 |
| 50          | 0.25 ± 0.020 | 0.18 ± 0.01 | 22.20 ± 2.28   | 2.61 ± 0.031 |
| 100         | 0.20 ± 0.010 | 0.16 ± 0.01 | 15.12 ± 0.46   | 2.64 ± 0.002 |
| 150         | 0.24 ± 0.010 | 0.18 ± 0.03 | 20.28 ± 2.23   | 2.62 ± 0.006 |
| 200         | 0.66 ± 0.040 | 0.34 ± 0.09 | 49.74 ± 3.11   | 2.48 ± 0.027 |
| 250         | 0.34 ± 0.090 | 0.21 ± 0.02 | 28.39 ± 3.11   | 2.58 ± 0.002 |
| 300         | 0.54 ± 0.030 | 0.28 ± 0.03 | 42.00 ± 1.92   | 2.52 ± 0.006 |
| 350         | 0.58 ± 0.060 | 0.34 ± 0.09 | 39.18 ± 1.87   | 2.55 ± 0.018 |
| 400         | 0.74 ± 0.100 | 0.34 ± 0.08 | 47.03 ± 5.97   | 2.51 ± 0.050 |
| 450         | 0.53 ± 0.070 | 0.29 ± 0.03 | 44.59 ± 3.87   | 2.50 ± 0.004 |
| 500         | 0.71 ± 0.060 | 0.44 ± 0.08 | 67.95 ± 5.75   | 2.40 ± 0.170 |

*Note:* See notes of Table 1 for details.
The results showed that grassland degradation had a great impact on the inorganic nitrogen content of surface soil. The total nitrogen content of soil mainly came from the accumulation and decomposition of soil organic matter. When soil organic matter decreased, soil nitrogen content also decreased (Zhao et al. 2009, Jiang et al. 2016).

Fig. 3. Comparisons of soil moisture content and soil bulk density (±standard error [SE]) in alpine arid grassland (A) and wetland (B) in the process of desertification reduction (from near to far from severe desertification plaques). The soil moisture content and soil bulk density in alpine arid grassland are denoted as white column shapes and black squares in (A), respectively. The soil moisture content and soil bulk density in alpine wetland are denoted as white column shapes and black squares in (B), respectively.
This may be mainly due to the decrease in vegetation coverage after the alpine grassland degradation, which greatly changed the structure and functional stability formed by the long-term adaptation and evolution of microorganisms, and lead to the enhanced decomposition ability of microorganisms to soil organic carbon and total nitrogen of different particle sizes (Haynes and Swift 1990). Therefore, it appears that the proportion of soil large aggregates decreased with the aggravation of grassland degradation.

Soil structure and soil physical–chemical properties during deterioration of alpine grassland

The fractal dimension (D) and soil water-stable aggregates.—The existing studies had shown that the D of soil aggregates was related to their physical and chemical properties. It was reported that the D of soil aggregates had a significant positive correlation with organic matter, available phosphorus, and available nitrogen (Veiga et al. 2009). However, in this study it was shown that the correlation between soil structure and soil physical–chemical properties was not completely consistent in the direction of the arid grassland and wetland (Tables 3, 4).

The D of soil particles was negatively correlated with the length of the patch from severe desertification patches in the direction of the arid grassland and wetland; the correlation coefficients were −0.926 and −0.805 (P < 0.01), respectively.

The D was significantly correlated with water stability aggregates of different particle sizes (Tables 3, 4). However, their correlations were not completely consistent and the response of D to the content of particle size distribution was different in arid grassland and wetland. In the direction of the arid grassland, the <0.25 mm aggregates had the largest response ($r = 0.981, P < 0.01$), followed by the 1–2 mm aggregates ($r = −0.903, P < 0.01$), the >2 mm aggregates ($r = −0.852, P < 0.01$), and the 0.25–1 mm aggregates ($r = −0.622, P < 0.05$). In the direction of

![Fig. 4. A comparison of soil organic matter (±standard error [SE]) in alpine arid grassland and wetland in the process of desertification reduction (from near to far from severe desertification plaques). TOM is the content of soil organic matter. The content of soil organic matter in arid grassland and wetland is denoted as black squares and black circles, respectively.](image-url)
the wetland, the largest response occurred on the 1–2 mm aggregates \((r = -0.798, P < 0.01)\), followed by 0.25–1 mm \((r = -0.648, P < 0.05)\) and <0.25 mm \((r = 0.632, P < 0.05)\). But it seemed that there was no significant correlation between \(D\) and the contents of the >2 mm aggregates.

This indicated that the larger the \(D\), the finer the soil, which was consistent with the research results of Zhou et al. (2015). It is also reported that the \(D\) can be used to characterize soil structure and change trend (Zhang 2002), and it is feasible to use it as an indicator to reveal soil desertification (Li et al. 2017). Hou pointed out that the \(D\) of soil particles has an indicative effect on soil nutrients, which may have strong spatial specificity (Hou et al. 2010).

The fractal dimension (\(D\)) and soil physical–chemical properties.—Opposite results occurred for the relationships between \(D\) and bulk density, and water content in arid grassland and wetland. The correlation coefficients were 0.876 and -0.760 \((P < 0.01)\) with bulk density, but were -0.907 and 0.785 \((P < 0.01)\) with water content. In addition, except for the significant negative correlation between \(D\) and available nitrogen \((r = -0.914, P < 0.01)\) in arid grassland, there was no significant correlation between \(D\) and other nutrients in the study area.

Soil aggregates composition and soil physical–chemical properties.—The contribution of soil aggregates is to balance the water, fertilizer, air, and heat, to maintain the activity of microorganisms and enzymes, and to support enough porosity of soil surface (Haynes & Swift, 1990). Soil swelling, shrinkage, dispersion, and agglomeration are not only processes of structural change, but also closely related to the transformation of the water, gas, thermal movement, and material in soil (such as carbon and nitrogen). Changes in soil structure can affect the physical, chemical, and biological properties of soil (Six et al. 2000).

In arid grassland, similar trends occurred for the correlation relationships between >1 mm aggregates and other factors, such as <0.25 mm \((-0.871 < r < -0.923, \ P < 0.01)\) aggregates,
Fig. 6. A comparison of soil available phosphorus (± standard error [SE]) in the process of desertification reduction in alpine arid grassland and wetland (from near to far from severe desertification plaques). The content of soil available phosphorus in arid grassland and wetland is denoted as black squares and black circles, respectively.

Table 3. Correlation between soil structure (>2, 1–2, 0.25–1, <0.25 mm, D) and physical–chemical properties (bulk density, moisture content, TOM, AN, AP), the extent of grassland desertification (distance) in arid grassland.

| Variable | D  | GD1  | GD2  | GD3  | GD4  | LD  | BD  | MC  | TOM  | AN  |
|----------|----|------|------|------|------|-----|-----|-----|------|-----|
| GD1      |    | 0.852**|     |      |      |     |     |     |      |     |
| GD2      |    | 0.903**| 0.881**|      |      |     |     |     |      |     |
| GD3      |    | 0.622*| 0.193| 0.369|      |     |     |     |      |     |
| GD4      |    | 0.981**| 0.871**| 0.923**| 0.630*|     |     |     |      |     |
| LD       |    | 0.926**| 0.854**| 0.926**| 0.475| 0.929**|     |     |      |     |
| BD       |    | 0.876**| 0.844**| 0.934**| 0.312| 0.859**| 0.926**|     |      |     |
| MC       |    | 0.907**| 0.898**| 0.977**| 0.355| 0.918**| 0.948**| 0.953**|     |     |
| TOM      |    | 0.938**| 0.836**| 0.933**| 0.462| 0.916**| 0.954**| 0.966**| 0.963**|     |
| AN       |    | 0.914**| 0.787**| 0.898**| 0.511| 0.900**| 0.952**| 0.952**| 0.934**| 0.973**|
| AP       |    | −0.815| 0.464| 0.372| −0.317| −0.225| 0.121| −0.292| 0.410| 0.251| 0.166|

Notes: D is the fractal dimension; GD1 is the percentage of water-stable aggregates >2 mm; GD2 is the percentage of water-stable aggregates 1–2 mm; GD3 is the percentage of water-stable aggregates 0.25–1 mm; GD4 is the percentage of water-stable aggregates smaller than 0.25 mm; LD is the length of distance from severe desertification plaques; BD is soil bulk density of soil; MC is moisture content of soil; TOM is the content of organic matter in the soil; AN is the content of alkali-hydrolyzed nitrogen in the soil; AP is the content of available phosphorus in the soil.

*The correlation was significant at the 0.05 level (bilateral).

**The correlation was significant at the 0.01 level (bilateral).
distance ($0.854 < r < 0.926$, $P < 0.01$), bulk density ($-0.844 < r < -0.934$, $P < 0.01$), water content ($0.898 < r < 0.977$, $P < 0.01$), organic matter ($0.836 < r < 0.933$, $P < 0.01$), available nitrogen ($0.787 < r < 0.898$, $P < 0.01$). This was similar to the research results of Chen et al. (2013), which reported that the 1–2 mm aggregates were the most suitable for nutrient accumulation. This phenomenon may be due to the different physical properties and microstructural characteristics of aggregates with different particle sizes (Denef and Six 2010).

There was no significant relationship between 0.25 and 1 mm and soil physical–chemical properties. The <0.25 mm fractions were significantly positively correlated with bulk density ($r = 0.859$, $P < 0.01$), and significantly negatively correlated with distance ($r = -0.929$, $P < 0.01$), water content ($r = -0.918$, $P < 0.01$), organic matter ($r = -0.916$, $P < 0.01$), and available nitrogen ($r = -0.900$, $P < 0.01$).

In the wetland, the >0.25 mm aggregates' fractions showed a significant positive correlation with the bulk density (0.618 < $r$ < 0.864, $P < 0.05$), while the <0.25 mm aggregates' fractions showed a significant negative correlation with bulk density ($r = -0.877$, $P < 0.01$).

Meanwhile, there was an obvious correlation between aggregates with different soil particle sizes and the degree of desertification. It seemed that the lower the degree of desertification, the higher the 0.25–2 mm fractions (0.672 < $r$ < 0.814, $P < 0.05$), and the lower the <0.25 mm fractions ($r = -0.677$, $P < 0.05$). However, there were no correlations between other particle size aggregates and physical–chemical properties.

Therefore, the results indicate that >1 and 1–2 mm aggregates can be used as indicators to evaluate desertification of arid grassland and wetland, respectively. That is, the higher the contents of the indicators were, the weaker the degree of the desertification was. It is also found that with an increase in the content of >1 mm aggregates, the soil bulk density decreased, but the water content increased.

**Conclusion**

Overall, our study showed that MWD, GMD, and $R_{0.25}$ of water-stable aggregates in arid grassland and wetland increased gradually as desertification decreased. However, with the reduction in the desertification, the fractal dimension decreased, leading to the strong stability of soil structure. The decreasing rate of the $D$ in the direction of arid grassland was faster than that of wetland. Therefore, soil structure stability and erosion resistance in the direction of arid grassland were stronger than that of wetland soil. Furthermore, the larger the $D$ of soil particles, the finer the soil granulation. The $D$ had different response to aggregates with different particle sizes. The aggregates <0.25 mm ($r = 0.981$, $P < 0.01$) and 1–2 mm ($r = -0.79$, $P < 0.01$) had the largest responses in the direction of the arid grassland and wetland, respectively. It was found that aggregates larger than 1 mm and 1–2 mm can be used as indicators to evaluate desertification of the soil in the direction of the arid grassland and wetland, respectively.
arid grassland and wetland, respectively. The higher the content of the indicating aggregates, the weaker the degree of the desertification. In the future, we look for more studies on the influence of micro-topography (such as slope, slope direction, altitude) on soil structure in the process of alpine grassland desertification.

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