Changes in Soil Aggregates Composition Stabilization and Organic Carbon during Deterioration of Alpine Grassland

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Abstract: The stability of alpine grassland ecosystem is closely related to the stability of soil structure. The objectives of this study were to analyze the characteristics of soil aggregates and organic carbon in different degradation stages of alpine grassland in northwest Sichuan, and to build the relationship between soil organic carbon and aggregates. The results showed that the non-degraded grassland was dominated by macro-aggregates (>0.25 mm), while the degraded grassland was dominated by micro-aggregates. Both soil aggregate stability and soil organic carbon content were significantly reduced with the intensification of grassland degradation. The soil organic carbon content in degraded grassland was significantly lower than that in non-degraded grassland, and the fastest decline stages of the soil organic carbon occurred in the transformation processes from non-degraded to lightly degraded. The highest value of the soil aggregate organic carbon appeared in the 0.5-2 mm size, and the organic carbon content of each aggregate also decreased with the grassland degradation. The soil organic carbon and soil aggregate organic carbon were significantly correlated with the stability index of soil aggregate (P<0.01).

1. Introduction

Soil aggregates are the basic structural units formed by soil components such as mineral particles and organic matter during natural physical processes[1], which directly or indirectly affecting soil erosion resistance, biodiversity and carbon sequestration potential[2]. Luna et al. have shown that different restoration techniques have significant effects on the stability of degraded soil aggregates and organic carbon [3]. Meanwhile, Zheng et al. believe that the land use pattern is correlated with the stability of soil aggregates [4]. Feng et al. studied the alpine grassland with different degrees of degradation in the river source area and found that >0.25 mm particle size water-stable aggregates decreased significantly with the increase of degradation degree [5]. At present, domestic and foreign studies on soil aggregates mainly focus on soils with better agglomeration structure, but less related to soils with poor agglomeration structure, especially lack of stability of sandy soils in alpine grasslands.

Under the combined action of natural and human factors, the alpine grassland in northwestern Sichuan has serious desertification, low vegetation coverage, severe soil structure damage and difficult ecological restoration. At present, the research on grassland degradation in this area mainly focuses on soil nutrient change, desertification influencing factors and ecological management patterns [6-8], and lacks attention to soil aggregate stability and organic carbon. In this study, the dry sieve method and
the wet sieve method were used to analyze the soil aggregate stability and soil organic carbon in different degraded stages of the alpine grassland in northwestern Sichuan, as well as the relationship between them.

2. Materials and methods

2.1. Experimental site
The research area is located in Hongyuan County, Aba Tibetan and Qiang Autonomous Prefecture, Sichuan Province, on the eastern edge of the Qinghai-Tibet Plateau. It belongs to the plateau continental cold temperate monsoon climate, with an average annual average of 1.1°C, an average annual rainfall of 791.9 mm. The soil type is dominated by subalpine grassy soil, some areas are swamp soil, and some are desert soil.

In the region with the same natural environment conditions, four kinds of non-degraded grasslands, lightly degraded grasslands, moderately degraded grasslands, and severely degraded grasslands were selected (33°10′35.977″-33°10′47.555″N, 102°37′27.476″-102°37′34.172″E), and the vegetation coverage respectively are 95%, 70~80%, 40~50%, 10%. Select two squares for each plot, the sample size is 10 m×10 m, and each sample square randomly selects three sampling points. Soil aggregate samples were separately collected in layers of 0-10, 10-20, 20-30, 30-40 cm and three soil samples from the same layer were mixed into one soil sample. A total of 32 mixed soil samples were collected for the determination of soil aggregate content, soil organic carbon and aggregate organic carbon.

2.2. Sample determination
The soil sample is broken into small clods with a diameter of about 10 mm, and the animal and plant debris and small stones are removed and then laid flat in the room to dry naturally. The aggregate was measured by dry sieve method and wet sieve method [9], and each sample determined twice. Soil organic carbon and agglomerate organic carbon were determined by potassium dichromate external heating method.

2.3. Method of calculation
The formula for calculating the specific gravity of large aggregates (R₀.25), the average weight diameter (MWD) and geometric mean diameter (GMD) of the agglomerates and the agglomerate destruction rate (PAD) is shown in reference [10].

2.4. Statistical analysis
The discrepancy of soil organic carbon in different soil layers and grain size fractions were studied by one-way variance. Correlation analysis was used to study the correlation between soil organic carbon and aggregate stability.

3. Results

3.1. Soil Aggregate Stability
The soil aggregates and organic carbon data at the study site were explained in detail by Jiang et al. (2018) in the study of the effects of alpine grassland degradation on soil aggregates[11], however, some brief analyses are necessary. There were significant differences in soil aggregates at different degradation stages (Table 1). The mechanical-stable aggregates and water-stable aggregates of non-degraded grassland are dominated by macro-aggregates (>0.25 mm), while degraded grassland is composed of micro-aggregates (<0.25 mm). Meanwhile, for the indicators of R₀.25, MWD and GMD, non-degraded > lightly degraded > moderately degraded > severely degraded, while PAD is reversed, with the most obvious change from non-degraded to lightly degraded. These results indicate that the stability of soil aggregates is significantly reduced with the degradation of alpine grassland.
3.2. Distribution characteristics of soil organic carbon

3.2.1. Soil organic carbon. The distribution of soil organic carbon is shown in Figure 1. Soil organic carbon content decreased with increasing grassland degradation, showing non-degraded > lightly degraded > moderately degraded > severely degraded. The total organic carbon content of degraded grassland was significantly lower than that of non-degraded grassland \((P<0.05)\), however, the difference between lightly, moderately and severely degraded grassland was not significant.

![Figure 1. Soil organic carbon distribution.](image)

From the soil profile (0-40 cm), the soil organic carbon content of grassland with different degrees of degradation showed a trend of decreasing from the surface layer to the lower layer. For non-degraded grassland, the difference of total organic carbon content between the soil layers was significant \((P<0.05)\). For lightly and moderately degraded grassland, the soil organic carbon content in the surface layer (0-10 cm) was significantly higher than that in the 10-40 cm soil layer \((P<0.05)\). The differences between 10-20, 20-30, and 30-40 cm soil layers are relatively small. There was no significant difference in total organic carbon content in the soil of severely degraded grassland.
3.2.2. Soil aggregate organic carbon. The distribution characteristics of organic carbon in soil aggregates are shown in Table 2. The highest organic carbon content of soil aggregates appeared at 0.5–2 mm, followed by >2 mm and 0.25–0.5 mm, <0.25 mm size aggregates have the lowest organic carbon content. The organic carbon content of >2 mm, 0.5–2 mm and 0.25–0.5 mm granular aggregates generally decreased with the increase of soil depth. For <0.25 mm grain-aggregated organic carbon, the performance of the non-degraded grassland decreased from the surface layer to the lower layer, while the degraded grassland did not show a uniform trend.

The content of organic carbon in soil aggregates of degraded grassland was significantly lower than that of non-degraded grassland (P<0.05). The content of organic carbon in each aggregate was significantly decreased with the increase of grassland degradation (P<0.05). The organic carbon content of 0.5–2 mm aggregates in 0-10 cm lightly degraded grassland was significantly higher than that of moderately and severely degraded grassland (P<0.05). The organic content of the >2 mm and <0.25 mm granular aggregates in the 10-20 cm soil layer was significantly higher than that of the moderately and severely degraded grassland (P<0.05). The content of organic carbon in the aggregates of lightly degraded grassland with 20-30 cm and 30-40 cm soil layers was significantly higher than moderately and severely degraded grassland (P<0.05). The organic carbon content of the aggregates of the granular aggregates in moderately and severely degraded grassland was not significant difference in the 0-40 cm soil layer.

### Table 2. Distribution characteristics of organic carbon in soil aggregates.

| Soil layer (cm) | Degradation degrees | Agglomerate classification (mm) | >2 | 0.5–2 | 0.25–0.5 | <0.25 |
|-----------------|----------------------|---------------------------------|-----|-------|----------|-------|
| 0-10            | Non-degraded         | 50.61±5.39 a                    | 139.83±7.99 a | 89.27±2.66 a | 43.85±3.43 a |
|                 | Lightly degrade      | 22.95±2.78 b                    | 55.82±3.76 b | 17.45±0.75 b | 12.58±0.16 b |
|                 | Moderately degraded  | 16.07±2.67 b                    | 36.14±2.61 c | 12.82±2.49 b | 8.39±1.80 b |
|                 | Severe degraded      | 3.38±0.88 c                     | 21.24±1.62 c | 3.74±0.83 c | 3.46±0.25 c |
| 10-20           | Non-degraded         | 30.60±1.05 a                    | 57.51±1.25 a | 37.84±2.70 a | 21.04±1.76 a |
|                 | Lightly degrade      | 12.63±1.90 b                    | 19.47±2.29 b | 13.39±1.29 b | 8.02±1.34 b |
|                 | Moderately degraded  | 4.47±1.13 c                     | 16.17±1.85 b | 5.89±0.01 b | 3.52±0.91 c |
|                 | Severe degraded      | 3.26±0.71 c                     | 9.93±1.68 b | 2.21±0.64 b | 1.76±0.13 c |
| 20-30           | Non-degraded         | 19.88±0.25 a                    | 26.61±4.20 a | 25.30±1.06 a | 21.41±1.02 a |
|                 | Lightly degrade      | 10.29±2.90 b                    | 17.53±0.32 b | 11.65±0.27 b | 8.89±1.05 b |
|                 | Moderately degraded  | 5.50±1.00 c                     | 10.40±0.54 c | 6.63±2.95 c | 2.96±0.46 c |
|                 | Severe degraded      | 2.74±0.02 c                     | 7.02±1.00 c | 1.32±0.31 d | 1.20±0.20 c |
| 30-40           | Non-degraded         | 19.28±1.16 a                    | 23.29±0.38 a | 17.67±4.38 a | 16.39±0.22 a |
|                 | Lightly degrade      | 8.87±0.56 b                     | 13.59±1.95 b | 11.29±2.80 ab | 7.50±0.81 b |
|                 | Moderately degraded  | 5.36±0.85 c                     | 8.01±0.63 c | 5.78±2.15 bc | 4.20±2.75 bc |
|                 | Severe degraded      | 2.71±0.07 c                     | 7.40±0.60 c | 2.26±0.39 c | 2.28±0.31 c |

Note: different lowercase letters in the same column indicate significant differences in P<0.05 levels for the same fractional aggregate organic carbon.

3.3 Relationship between soil aggregate stability and organic carbon

The correlation between soil organic carbon, aggregate organic carbon and aggregate stability index is shown in Table 3. Total organic carbon and aggregate organic carbon were significantly correlated with mechanical-stable aggregates and water-stable aggregates Rₐ₂₂₅, MWD and GMD, and negatively correlated with PAD. Overall, the higher the soil organic carbon content, the stronger the stability of soil aggregates. The significant correlation between soil organic carbon and water-stable aggregates is higher than that of mechanical-stable aggregates, indicating that soil water-stable aggregates can better reflect soil erosion resistance and are more closely related to soil organic carbon.
4. Discussion

With the degraded alpine grassland, the aggregates $R_{0.25}$, MWD and GMD were significantly decreased ($P<0.05$), and the PAD was significantly increased ($P<0.05$), which indicating that the stability of soil aggregates was significantly increased with the degree of degradation, which is similar to previous studies [12]. The organic carbon in the small-grained aggregates is mainly chemically protected, and is less interfered by external factors, and the rate of change is slow. The organic carbon in the large-scale aggregates is mainly protected by physical protection, sensitive to vegetation changes and management measures, and turnover is fast. Organic carbon is an important cementing material for aggregates. Therefore, as the degree of grassland degradation increases, the decrease in soil organic matter leads to a significant decrease in the content of macro-aggregates. Studies have shown that vegetation reduction and soil degradation are mutually causal and interaction. In this study area, under the over-feeding of livestock, the growth and development of herbaceous plants are inhibited, vegetation coverage is reduced, and vegetation litter is reduced while soil organic matter content decreases, soil bulk density increases and water holding capacity declines. At this time, macro-aggregates disintegrate and soil erosion resistance decreases, eventually leading to a significant decrease in agglomerate stability.

During the degradation of alpine grassland, the composition and stability of soil aggregates were most significant in the period of non-degraded to lightly degraded and of lightly degraded to moderately degraded. However, the changes in moderate to severe degradation were small, which indicated that the light degradation stage was an important turning point of grassland degradation. This is different from Cai et al. (2009) and other studies on grassland in the northern Tibetan Plateau[8]. It is considered that the soil aggregates of lightly degraded grassland are better than those of non-degraded grassland. Compared with the northern Tibetan Plateau, the study area is slightly shorter, the annual average temperature is about 1℃, and the average annual precipitation is nearly 500 mm. Under good natural conditions, the soil microbial activity is strong, due to natural and artificial effects on the grassland. In the early stage of grassland degradation, the soil organic matter rapidly decomposed and lost, and the macro-aggregates also disintegrated rapidly, and the stability of the aggregates was significantly reduced. When the grassland enters the moderate and severe degradation stage, the soil organic matter content is already low, and the aggregate stability index changes the least. Therefore, when the alpine grassland in Northwest Sichuan is facing light degradation, great attention should be paid to it and desertification control work should be carried out in time.

The results of this study showed that the total organic carbon content of grassland with different degrees of degradation decreased from the surface layer to the lower layer. For the non-degraded and lightly degraded grassland, the surface layer (0-10 cm) received more litter and the organic carbon aggregate provided the binder, which can significantly increase the total amount of macro-aggregates and the degree of association between the aggregates, in the meanwhile, increase the structural stability. So the aggregate stability and organic carbon content are reduced from the surface layer to

| AOC | mechanical-stable aggregates | water-stable aggregates | PAD |
|-----|-----------------------------|------------------------|------|
|     | $R_{0.25}$ | MWD | GMD | $R_{0.25}$ | MWD | GMD |       |
| >2 mm | 0.845** | 0.827** | 0.864** | 0.858** | 0.860** | 0.910** | -0.718** |
| 0.5–2 mm | 0.668** | 0.636** | 0.710** | 0.692** | 0.691** | 0.784** | -0.548** |
| 0.25–0.5 mm | 0.777** | 0.764** | 0.828** | 0.789** | 0.795** | 0.881** | -0.636** |
| <0.25 mm | 0.844** | 0.828** | 0.876** | 0.844** | 0.843** | 0.902** | -0.686** |
| Total organic carbon | 0.787** | 0.767** | 0.834** | 0.801** | 0.803** | 0.886** | -0.651** |

Note: ** indicates a correlation significance $P < 0.01$. 
the lower layer. When the grassland enters the moderate and severe degradation stage, due to overgrazing, combined with the excavation of caves to expose the soil to the surface, the surface soil lacks vegetation protection. Frequent dry and wet cycles lead to the breakdown of large aggregates of soil, the weakening of carbon fixation and the reduction of aggregate stability [3]. Followed by the alternating shrinkage and expansion of freezing and thawing to change the structure and composition of soil aggregates, accelerate the mineralization decomposition rate of soil organic carbon, reduce the water stability of soil aggregates [4], and further promote grassland degradation. These effects mainly occur in the soil surface 0-10 cm, and the influence is weakened with the increase of soil depth.

5. Conclusions
The mechanical-stable aggregates and water-stable aggregates of non-degraded grassland are dominated by macro-aggregates (>0.25mm), while degraded grassland is dominated by micro-aggregates (<0.25 mm), with the degree of grassland degradation. Meanwhile, the R0.25, MWD and GMD indicators are significantly reduced, while the PAD is reversed, and the stability of the aggregates is most obvious in the non-degraded to lightly degraded stage. Grassland degradation significantly reduced the content of soil organic carbon, and the highest value of aggregate organic carbon agglomerates appeared in 0.5~2 mm size. The content of organic carbon in macro-aggregates was significantly higher than that of micro-aggregates. During the process of grassland degradation, the organic carbon of soil aggregate and the stability index of soil aggregate were significantly correlated (P<0.01). These results indicated that with the intensification of alpine grassland degradation, the soil structure is destroyed, the carbon sequestration effect is weakened, and the soil organic carbon content and aggregate stability are significantly reduced.

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