

Article

Effects of Long-Term Fenced Enclosure on Soil Physicochemical Properties and Infiltration Ability in Grasslands of Yunwu Mountain, China

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Abstract: Fenced enclosures, a proven strategy for restoring degraded grassland, have been widely implemented. However, recent climate trends of warming and drying, accompanied by increased extreme rainfall, have heightened soil erosion risks. It is crucial to assess the long-term effectiveness of fenced enclosures on grassland restoration and their impact on soil physicochemical properties and water infiltration capacity. This study investigated the effects of enclosure duration on soil organic matter, aggregate composition and stability, and infiltration capacity in Yunwu Mountain Grassland Nature Reserve, comparing grasslands with enclosure durations of 2, 14, 30, and 39 years. Results showed that grasslands enclosed for 14, 30, and 39 years had infiltration rates increased by 20.66%, 152.03%, and 61.19%, respectively, compared to those enclosed for only 2 years. After 30 years of enclosure, soil quality reached its optimum, with the highest root biomass, soil organic matter, aggregate stability, and a notably superior infiltration rate. The findings suggest that long-term fenced enclosures facilitate grassland vegetation restoration and enhance soil infiltration capacity, with the most significant improvement observed at the 30-year enclosure milestone, followed by a gradual decline in this effect.

Keywords: vegetation restoration; soil infiltration capacity; aggregate stability



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1. Introduction

Grasslands are an important component of natural ecosystems and are among the most widely distributed types of vegetation [1]. As an ecological and productive complex, grasslands have been significantly impacted by human activities. Extensive grazing on grasslands has led to a reduction in plant cover and aboveground biomass [2,3], causing significant changes in plant community composition and structure and a decline in the regenerative capacity of the grasslands [4], ultimately leading to grassland degradation [5]. Additionally, trampling by livestock also causes soil compaction, reducing the infiltration capacity of grassland soils [6]. With the increasingly noticeable trend of warming and drying in recent years [7], the duration of droughts has increased, and extreme rainfall events have become more frequent, significantly contributing to soil erosion [8]. Therefore, it is crucial to maximize the infiltration capacity and erosion resistance of the soil [9].

Since 2004, a series of comprehensive ecological protection and construction projects have been implemented by the nation to improve the grassland ecological environment. Among these, the fenced enclosure is a grassland management strategy that uses mesh fences to exclude livestock, preventing grazing and trampling and allowing vegetation to recover naturally [4,10,11]. The implementation of fenced enclosures has facilitated the recovery of grassland vegetation, ultimately yielding a more abundant assortment of

community types. With the prolongation of enclosure duration, the extent of vegetation coverage enlarges, and the vegetation and its underground root systems incrementally exert a beneficial impact on the soil, thereby contributing to an improvement in soil quality [1,12]. Recent research efforts are centered on investigating the efficacy of long-term fenced enclosures in restoring degraded grasslands and boosting soil organic carbon stocks. Li et al. [13] conducted an investigation on grassland enclosures of 5, 6, and 8 years, along with grazing lands, and it was observed that the enclosed grasslands experienced a marked increase in vegetation cover. Moreover, a significant augmentation in soil organic carbon levels was observed. By comparing soil data from grazed grasslands, grasslands enclosed for restoration for 15 years, and grasslands enclosed for restoration for 30 years, Zhang et al. [1] arrived at similar conclusions. The study by Wu et al. [10] on the Qinghai–Tibet Plateau revealed that implementing long-term enclosure measures can rehabilitate the soil's carbon and nitrogen storage capacity in alpine meadows. Nonetheless, studies on the impact of long-term enclosure on soil structure and infiltration capacity in grasslands remain scarce.

A well-structured soil, being both developed and stable under the combined effects of water and external mechanical stress, is also considered the most desirable soil characteristic for maintaining environmental quality [14]. The process of vegetation restoration induces changes in soil structure as a result of vegetation growth, ultimately affecting soil infiltration capacity as well [15]. The soil infiltration capacity plays a crucial role in determining the quantity of rainfall that is converted into soil water, constituting one of the significant indicators for evaluating soil water retention and erosion resistance [16,17]. Due to the reduced infiltration capacity of degraded grassland, there is an increase in surface runoff during rainfall events, subsequently elevating the risk of soil erosion [9]. Fenced enclosures, recognized as a crucial measure for restoring degraded grassland [10], have demonstrated significant improvement in plant and soil recovery through numerous related studies [18]. Nonetheless, the continuous effect of long-term fenced enclosures on grassland restoration is worthy of further study. This study compares the soil property changes, specifically soil organic matter, soil aggregate composition and stability, and soil infiltration characteristics, across four grasslands with varying fenced enclosure periods (2 years, 14 years, 30 years, and 39 years). The primary goal is to enhance our understanding of the impacts of fenced enclosure measures of different durations on grassland soil and to elucidate the primary factors influencing soil infiltration capacity changes subsequent to grassland vegetation restoration.

2. Materials and Methods

2.1. Study Sites

The experiment was conducted in September 2020 at the Yunwu Mountain Grassland Nature Reserve (106°24′–106°28′ E, 36°13′–36°19′ N), located in Guyuan City, Ningxia Hui Autonomous Region, in the northwestern part of the Loess Plateau (Figure 1). This region is characterized by a typical semi-arid climate, featuring drought, low and concentrated rainfall from June to September, large temperature variations, and long sunshine duration. The annual mean temperature is 5 °C in the region, with the hottest month being July, where temperatures range between 22 °C and 25 °C. The coldest month is January, with an average minimum temperature of approximately −14 °C. The annual average precipitation is 445 mm. The region, with an elevation ranging from 1700 to 2120 m, is a typical low mountain and hill region covered by loess. The soil types, according to the FAO classification system, include Calcaric Cambisols, Calcic Luvisols, and Chernozem [19]. These included plots enclosed for 2 years (G_{2a}), 14 years (G_{14a}), 30 years (G_{30a}), and 39 years (G_{39a}). Basic information about the sample plots is presented in Table 1.

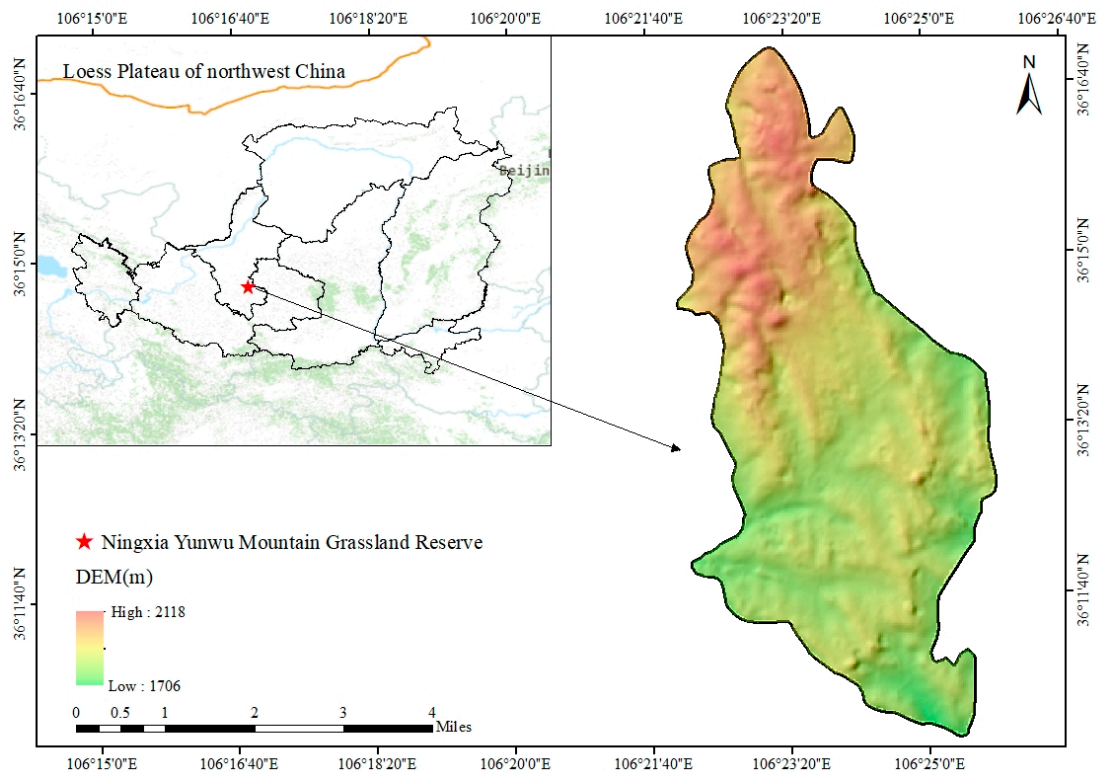


Figure 1. Location of the study area.

Table 1. Basic information of the sample site.

Sample Plot	Dominant Species	Coverage	Longitude and Latitude
G _{2a}	<i>Stipa przewalskyi</i> <i>Stipa grandis</i> <i>Artemisia stechmanniana</i>	0.70	36°21' N 106°20' E
G _{14a}	<i>Stipa przewalskyi</i> <i>Stipa grandis</i> <i>Artemisia stechmanniana</i> <i>Thymus mongolicus</i>	0.75	36°22' N 106°18' E
G _{30a}	<i>Stipa grandis</i> <i>Stipa przewalskyi</i> <i>Artemisia stechmanniana</i> <i>Chrysanthemum lavandulifolium</i>	0.90	36°21' N 106°20' E
G _{39a}	<i>Stipa grandis</i> <i>Artemisia stechmanniana</i> <i>Stipa przewalskyi</i>	0.80	36°15' N 106°23' E

2.2. Measurements of Soil Properties

Soil samples were collected in September 2020. In each sample plot, three sampling points were randomly selected. Given that shallow soil (0–10 cm) is typically subjected to direct influences from plant roots, microbial activities, and external environmental factors such as rainfall, it accumulates a relatively rich amount of organic matter. As soil depth increases, the intensity of these influencing factors gradually diminishes, resulting in corresponding changes in soil physicochemical properties. To further ascertain the impact of these enclosed grasslands on soil properties, soil samples were collected at three depth intervals: 0–10 cm, 10–20 cm, and 20–30 cm, to reflect the vertical variations in soil properties. Soil samples were collected in layers from the sampling points using a soil auger and a cutting ring with a volume of 100 cm³. The soil bulk density (BD) and

initial water content were determined using the cutting ring method. Soil organic matter (SOM) was quantified by the K_2CrO_7 titration method, while soil textural composition was analyzed using a Master sizer 2000 laser particle analyzer. Root samples were collected using a large cutting ring with a diameter of 100 mm and a height of 63.7 mm. After passing through a 1 mm sieve and being washed, the root samples were placed into kraft paper bags. They were then dried in an oven at 60 °C until a constant weight was achieved, followed by the measurement of root biomass.

2.3. Measurements of Soil Aggregate Traits

Undisturbed soil samples were collected in layers at each sampling point using aluminum boxes (20 cm × 12.5 cm × 6 cm) and air-dried in a cool, shaded area. A 50 g sample of the air-dried soil was placed on the top of a 5 mm sieve, beneath which were sieves of 5–2 mm, 2–1 mm, 1–0.5 mm, and 0.25 mm, respectively. The soil sample and sieves were immersed in water and shaken vertically at a rate of 30 times per minute for 2 min. The mass of soil retained on each sieve was subsequently recorded, enabling the determination of the composition of water-stable aggregates across the particle size ranges of >5, 2–5, 1–2, 0.5–1, 0.25–0.5, and <0.25 mm. The following formula is employed to compute key indicators, including the mean weight diameter (MWD), geometric mean diameter (GMD), and fractal dimension (D), which serve to describe the stability characteristics of soil aggregates [20].

Below are the specific calculation formulas for each index presented:

$$m_i = M_i / M_T \times 100\% \quad (1)$$

$$MWD = \sum_{i=1}^n (\bar{R}_i m_i) / \sum_{i=1}^n m_i \quad (2)$$

$$GMD = \exp \left\{ \sum_{i=1}^n m_i \ln \bar{R}_i \right\} \quad (3)$$

$$\frac{M(r < \bar{R}_i)}{M_T} = \left(\frac{\bar{R}_i}{R_{max}} \right)^{3-D} \quad (4)$$

$$\lg \left[\frac{M(r < \bar{R}_i)}{M_T} \right] = (3 - D) \lg \left(\frac{\bar{R}_i}{R_{max}} \right) \quad (5)$$

where m_i is the percentage of the mass of the i th-class aggregate; M_T is the mass of the i th-class water-stable aggregate; $\bar{R}_i$ is the average diameter of the i th-class aggregate; R_{max} is the maximum particle size of water-stable aggregates; $M(r < \bar{R}_i)$ is the mass of aggregates with a particle size smaller than $\bar{R}_i$.

2.4. Measurements of Soil Water Infiltration Rate

Measurement of soil infiltration was executed through the utilization of a disc infiltration instrument. In the experiment, a flat sample plot was chosen, and the procedure was conducted sequentially as follows: before the commencement of each measurement, the water temperature was noted down, the pressure head was adjusted accordingly, and the water level in the storage pipe was recorded. Fine quartz sand was laid on the contacted surface. Throughout the infiltration process, data were recorded at intervals of 10 s for the initial 1.5 min, followed by recordings every 30 s from the 1.5 min mark until the 3 min mark, and subsequently, recordings were made every minute after the 3 min mark. The process was repeated five times. The experimental procedure followed Bodner et al. [21,22].

The calculation formula of stable infiltration rate (f_s) is as follows:

$$f_s = \frac{\Delta h D_2^2}{\Delta t D_1^2 C_T} \quad (6)$$

$$C_T = 0.7 + 0.03T \quad (7)$$

where f_s is the soil infiltration rate (mm/min) observed at a standard water temperature of 10 °C; D_1 is the effective diameter (cm) of the base plate of the disc infiltration instrument, while D_2 is the diameter (cm) of its storage tube; Δt is the time interval (min); Δh is the difference in readings (mm) of the storage tube within a specified time interval Δt ; C_T is the temperature correction coefficient; and T is the average water temperature (°C) during a particular time period.

2.5. Statistical Analysis

In this study, one-way ANOVA was used to compare soil bulk density, porosity, mechanical composition, organic matter, root biomass, and soil aggregate composition and characteristics among different treatments. The Duncan post-test was used to compare the initial infiltration rate, stable infiltration rate, and average infiltration rate of soil between different treatments. Pearson correlation analysis was used to evaluate the relationship between the soil water infiltration rate and soil bulk density, porosity, soil organic matter, and soil aggregate composition and characteristics. All statistical evaluations were performed in IBM SPSS Statistics 20.0 with significance assumptions of $p \leq 0.05$ or $p \leq 0.01$.

3. Results

3.1. Soil Properties of Grassland with Different Enclosure Years

The soil bulk density measured in various sample plots lies within the range of 0.83 to 1.21 g·cm^{−3} (Table 2), with an evident trend of increment corresponding to soil depth. In the 0 to 10 cm soil layer, the order of bulk density is $G_{2a} > G_{14a} > G_{30a} > G_{39a}$. A notable decrease of 24.58% ($p < 0.05$) in soil bulk density was recorded as the closure duration increased from 14 to 30 years. Contrary to this trend, the total porosity and water content of the soil displayed a progressive decrease with increasing soil depth. In the 0–10 cm soil layer, the total porosity was measured at 66.34% and 68.82% after 30 and 39 years of grassland enclosure and restoration, respectively. These values were significantly higher than the porosity levels of 55.34% and 55.16% recorded in G_{2a} and G_{14a} ($p < 0.05$). Similarly, at this depth, soil water content exhibited an analogous trend, ascending with the prolongation of enclosure duration. However, in the soil below a depth of 10 cm, the soil water content exhibited the following trend: $G_{30a} > G_{39a} > G_{2a} > G_{14a}$ (Table 2). A marked reduction in water content was evident in the grassland following 14 years of enclosure, particularly as soil depth increased. Specifically, at depths below 20 cm, the water content of G_{14a} was notably lower than that recorded in the other sample plots ($p < 0.05$).

Table 2. Soil physical properties (mean $\pm$ standard deviation) of grassland with different depths and different enclosure years.

Soil Depth (cm)	Plots	BD (g/cm ³)	Porosity (%)	Soil Separates		
				Sand (>0.02 mm)	Silt (0.02–0.002 mm)	Clay (<0.002 mm)
0–10	G_{2a}	1.19 $\pm$ 0.03 a	55.14 $\pm$ 1.22 b	59.57 $\pm$ 1.44 a	26.68 $\pm$ 1.23 c	13.74 $\pm$ 0.67 b
	G_{14a}	1.18 $\pm$ 0.06 a	55.36 $\pm$ 2.21 b	59.33 $\pm$ 2.54 a	26.92 $\pm$ 1.61 bc	13.75 $\pm$ 0.95 b
	G_{30a}	0.89 $\pm$ 0.03 b	66.34 $\pm$ 4.65 a	49.19 $\pm$ 3.02 b	32.17 $\pm$ 3.78 a	18.64 $\pm$ 2.55 a
	G_{39a}	0.83 $\pm$ 0.04 b	68.82 $\pm$ 1.51 a	52.22 $\pm$ 0.70 b	30.98 $\pm$ 0.68 ab	16.80 $\pm$ 0.53 a
10–20	G_{2a}	1.19 $\pm$ 0.02 a	55.08 $\pm$ 0.64 b	62.56 $\pm$ 1.84 a	25.51 $\pm$ 3.02 b	11.93 $\pm$ 2.18 b
	G_{14a}	1.21 $\pm$ 0.03 a	54.42 $\pm$ 0.99 b	51.78 $\pm$ 3.35 b	31.51 $\pm$ 1.94 a	16.72 $\pm$ 2.05 a
	G_{30a}	0.94 $\pm$ 0.05 b	64.35 $\pm$ 2.01 a	48.70 $\pm$ 1.60 b	33.79 $\pm$ 0.98 a	17.50 $\pm$ 0.62 a
	G_{39a}	0.90 $\pm$ 0.07 b	66.21 $\pm$ 2.67 a	51.45 $\pm$ 2.45 b	31.77 $\pm$ 0.68 a	16.78 $\pm$ 2.00 a
20–30	G_{2a}	1.21 $\pm$ 0.05 a	54.41 $\pm$ 2.05 b	61.88 $\pm$ 2.83 a	27.03 $\pm$ 2.04 b	11.09 $\pm$ 0.80 c
	G_{14a}	1.21 $\pm$ 0.02 a	54.34 $\pm$ 0.60 b	49.69 $\pm$ 1.01 b	31.99 $\pm$ 0.67 a	18.32 $\pm$ 0.36 ab
	G_{30a}	1.06 $\pm$ 0.03 b	59.82 $\pm$ 0.95 a	47.38 $\pm$ 2.80 b	33.38 $\pm$ 2.03 a	19.25 $\pm$ 0.76 a
	G_{39a}	1.01 $\pm$ 0.07 b	63.29 $\pm$ 3.42 a	51.28 $\pm$ 0.68 b	31.71 $\pm$ 0.61 a	17.01 $\pm$ 0.98 b

Note: Different lowercase letters indicate the significant differences between different depths of each plot ($p < 0.05$).

The textural composition of the soil in the enclosed grassland is illustrated in Table 2. The clay content (<0.002 mm) in the four grasslands with varying enclosed durations ranged between 11% and 19%. It is noteworthy that within the 20–30 cm soil layer, G_{30a} showed significantly higher clay content compared to G_{39a} and G_{2a} ($p < 0.05$). The silt content ($0.02\sim0.002$ mm) ranged between 25% and 33%, with G_{2a} exhibiting significantly lower silt content in comparison to the other sampling locations ($p < 0.05$). The sand content (>0.02 mm) was between 47% and 62%. Specifically, in the soil layer of 10–20 cm, the sand content followed the trend $G_{2a} > G_{14a} > G_{39a} > G_{30a}$. In the soil layers of 10–20 cm and 20–30 cm, the sand content of G_{2a} was 62.56% and 61.88%, respectively, both of which were significantly higher than that of other grasslands with varying enclosure durations ($p < 0.05$).

Figure 2 shows the soil organic matter content in grasslands with different enclosure durations. The soil organic matter content in the grassland under 2 years of enclosure decreased from $39.71 \text{ g}\cdot\text{kg}^{-1}$ in the top 0–10 cm soil layer to $33.99 \text{ g}\cdot\text{kg}^{-1}$ in the deeper 20–30 cm soil layer. In contrast, the grassland with 30 years of enclosure showed values of $60.21 \text{ g}\cdot\text{kg}^{-1}$ and $39.34 \text{ g}\cdot\text{kg}^{-1}$ in the respective layers, indicating significant increases of 78% and 16% when compared to G_{2a} ($p < 0.05$). At a depth of 20–30 cm, the organic matter content of G_{39a} was lower than that of G_{2a} . Nevertheless, in the soil layer exceeding 20 cm, the organic matter content of G_{39a} was notably higher than that of G_{2a} ($p < 0.05$). At a soil depth of 0–10 cm, the organic matter content followed the order $G_{30a} > G_{39a} > G_{2a} > G_{14a}$ ($p < 0.05$). Across other soil depths, G_{14a} consistently exhibited the lowest organic matter content ($p < 0.05$).

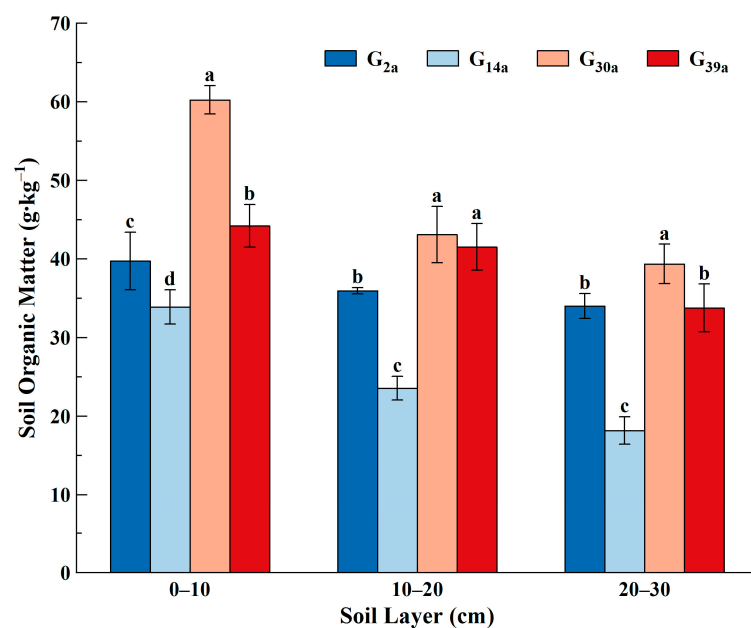


Figure 2. Soil organic matter content of grassland in different depths and different enclosure years. G_{2a} , enclosure of grassland for 2 years; G_{14a} , enclosure of grassland for 14 years; G_{30a} , enclosure of grassland for 30 years; G_{39a} , enclosure of grassland for 39 years. Note: Different lowercase letters indicate the significant differences between different depths of each plot ($p < 0.05$).

As illustrated in Figure 3, the root biomass of all sample plots exhibited an overall decreasing trend with increasing soil depth. In the soil depth ranging from 0 to 10 cm, the root biomass was determined to follow the order $G_{30a} > G_{14a} > G_{2a} > G_{39a}$, which was statistically significant ($p < 0.05$). Within the 0–10 cm soil layer, the root biomass of G_{30a} was measured to be $1833.50 \text{ g}\cdot\text{m}^{-2}$, representing a 1.22-fold increase compared to that of G_{39a} at the same depth ($p < 0.05$). However, no significant difference was observed between G_{30a} and G_{14a} . At a soil depth ranging from 20 to 30 cm, the root biomass of G_{30a} experienced a reduction of 84.82%, while that of G_{39a} decreased by 74.44%. At this particular soil depth,

the root biomass of G_{2a} was determined to be $119.96 \text{ g} \cdot \text{m}^{-2}$, indicating an 89.66% decrease in comparison to the 0–10 cm soil layer and being notably lower than the root biomass recorded for the other sample plots at this depth.

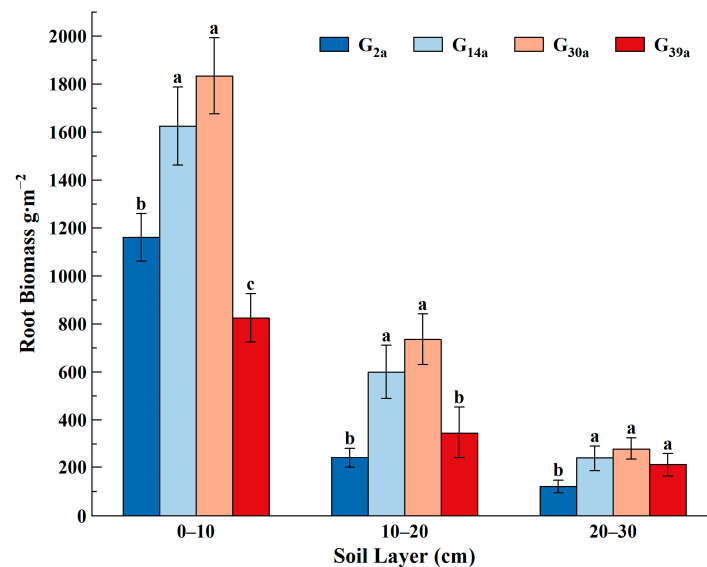


Figure 3. Soil root biomass of grassland at different depths and different enclosure years. G_{2a} , enclosure of grassland for 2 years; G_{14a} , enclosure of grassland for 14 years; G_{30a} , enclosure of grassland for 30 years; G_{39a} , enclosure of grassland for 39 years. Note: Different lowercase letters indicate the significant differences between different depths of each plot ($p < 0.05$).

3.2. Characteristics of Soil Aggregates in Grasslands with Different Enclosure Years

Figure 4 illustrated the distribution of aggregates of different sizes in the soil of the enclosed grassland after it has been wet sieved. In the 0–30 cm soil layer, aggregates of less than 0.25 mm particle size dominated, with average proportions of 52.62% for G_{2a} , 36.97% for G_{14a} , 26.03% for G_{39a} , and 24.97% for G_{30a} . In the soil of G_{2a} , the majority of macro-aggregates were found in the particle size fraction exceeding 5 mm, displaying a decreasing pattern with increasing soil depth. In the soil of G_{14a} , macro-aggregates were primarily concentrated within the 1–2 mm and 2–5 mm particle size fractions, with aggregate contents spanning from 15.25% to 15.68% and 16.55% to 18.83%, respectively. Both G_{39a} and G_{30a} manifested high overall macro-aggregate contents. The aggregate contents exceeding 0.25 mm in the soil of G_{30a} and G_{39a} exhibited a significantly higher level compared to G_{14a} and G_{2a} across all soil layers (Figure 5a). Notably, in the 0–10 cm soil layer, the trend was as follows: $G_{30a} > G_{39a} > G_{14a} > G_{2a}$, with G_{30a} and G_{39a} being 1.55 and 1.54 times the content of G_{2a} , respectively ($p < 0.05$). The mean weight diameter (MWD), geometric mean weight (GMW), and fractal dimension (D) are key metrics utilized to describe the stability of soil aggregates. According to Figure 5b, the MWD of soil aggregates in the 0–10 cm and 20–30 cm soil layers displayed a consistent trend of $G_{30a} > G_{39a} > G_{14a} > G_{2a}$, with G_{30a} showing significantly higher values compared to G_{2a} and G_{14a} ($p < 0.05$). In contrast, within the 10–20 cm soil layer, the MWD of soil aggregates in G_{14a} was significantly larger than that in G_{2a} ($p < 0.05$). Figure 5c indicates the GMD of soil aggregates in grasslands subject to different enclosure durations. It is noteworthy that G_{2a} consistently exhibits lower GMD values across all soil layers, while G_{14a} shows significantly higher GMD values when compared to G_{2a} ($p < 0.05$). Additionally, the D of soil aggregates in G_{2a} and G_{14a} is significantly higher than that in G_{30a} and G_{39a} ($p < 0.05$), with this pattern remaining consistent across different soil layers (Figure 5d).

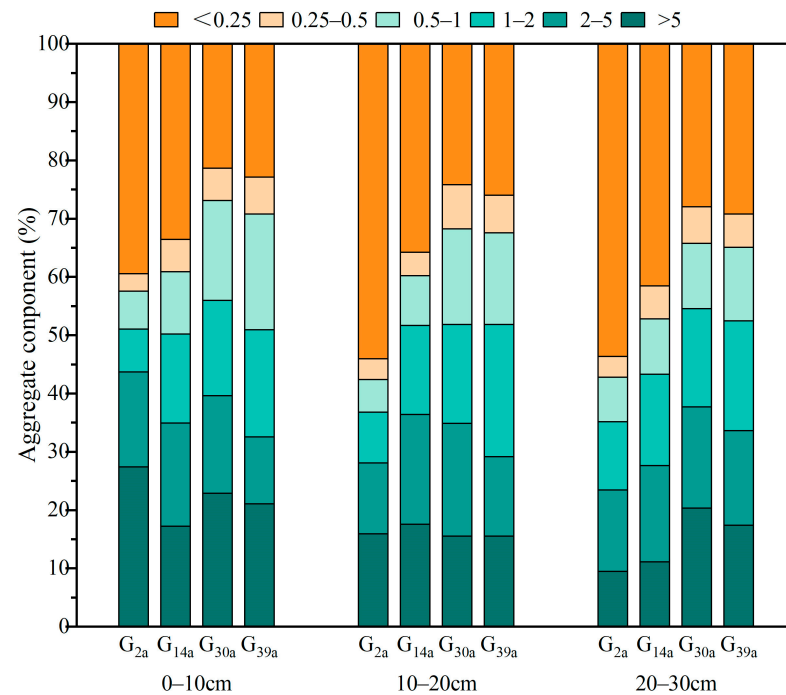


Figure 4. Composition of soil aggregates in grasslands with different enclosure years. G_{2a} , enclosure of grassland for 2 years; G_{14a} , enclosure of grassland for 14 years; G_{30a} , enclosure of grassland for 30 years; G_{39a} , enclosure of grassland for 39 years.

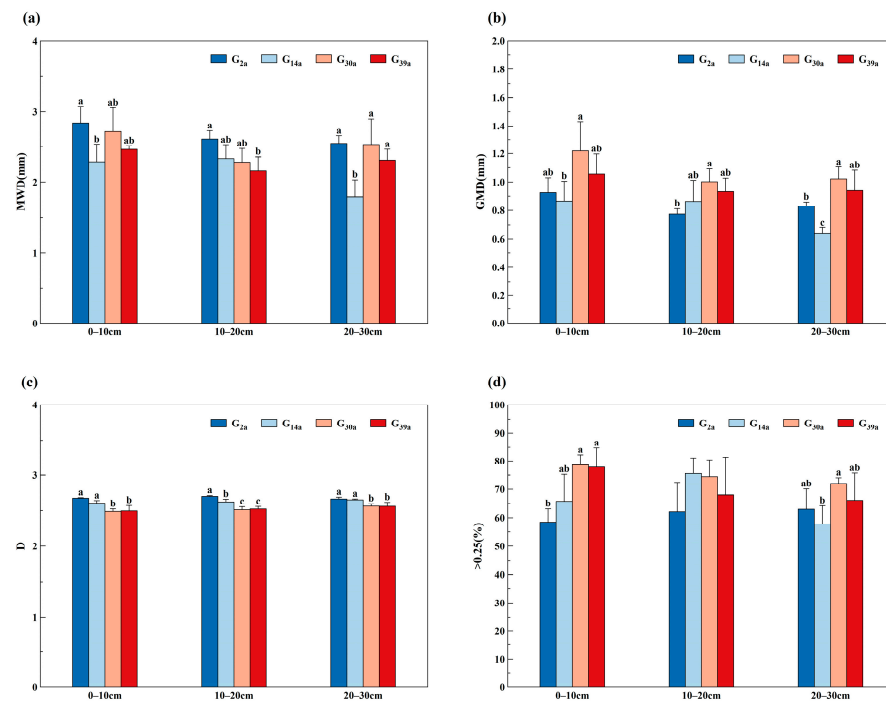


Figure 5. Characteristics of soil aggregates in grasslands with different depths and different enclosure years. G_{2a} , enclosure of grassland for 2 years; G_{14a} , enclosure of grassland for 14 years; G_{30a} , enclosure of grassland for 30 years; G_{39a} , enclosure of grassland for 39 years. Note: (a) presents the Mean Weight Diameter (MWD) of soil aggregates. (b) displays the Geometric Mean Diameter (GMD) of soil aggregates. (a,c) illustrates the Fractal Dimension (D) of soil aggregates. (d) shows the content of water-stable soil aggregates with a particle size greater than 0.25 mm. Different lowercase letters indicate the significant differences between different depths of each plot ($p < 0.05$).

3.3. Soil Water Infiltration Characteristics of Grassland with Different Enclosure Years

Figure 6 indicates the curves of soil infiltration rate varying with time in grasslands with different enclosure years. In the initial stages of infiltration, there was a sharp decrease. One minute after the infiltration started, the rate decreased by 32–51%. It gradually leveled off after five minutes and reached a stable infiltration state after 20 min. Significant differences exist in the infiltration characteristics across grasslands subjected to varying enclosed durations (Figure 7). The initial infiltration rates for the sample plots are as follows: $G_{30a} > G_{39a} > G_{14a} > G_{2a}$ ($p < 0.05$), with corresponding rates of 7.77 mm/min, 6.19 mm/min, 5.90 mm/min, and 4.93 mm/min, respectively. The stable infiltration rate follows a similar trend to the initial infiltration rate, where G_{30a} exhibits a significantly higher stable infiltration rate of 3.81 mm/min compared to other grasslands with varying enclosed durations ($p < 0.05$). G_{39a} 's stable rate stands as the second highest, with a value of 2.44 mm/min. It is noteworthy that G_{2a} possesses the lowest stable infiltration rate among all sample plots. In comparison to G_{2a} , grasslands enclosed for 14 years, 30 years, and 39 years exhibit respectively elevated infiltration rates of 20.66%, 152.03%, and 61.19%. In general, the average infiltration rate of G_{30a} is significantly greater than that of other sample plots, indicating that the infiltration ability of the grassland exhibits an upward trend with increasing enclosure duration. Specifically, when the enclosed duration reaches 30 years, the infiltration capability reaches a relatively high level, after which it begins to decrease.

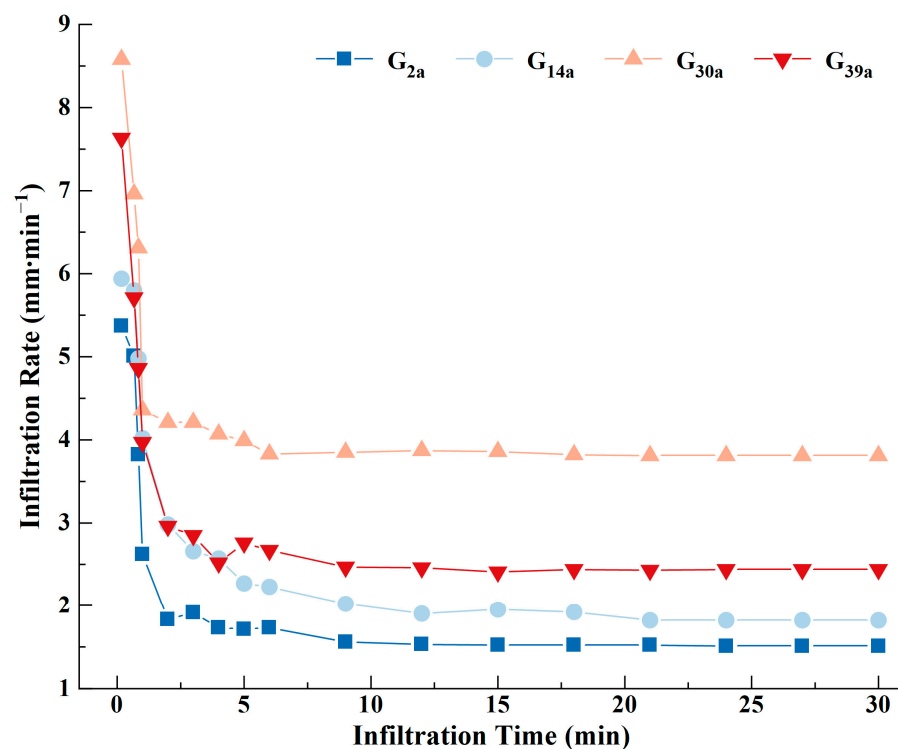


Figure 6. Soil infiltration process of grassland with different enclosure years. G_{2a} , enclosure of grassland for 2 years; G_{14a} , enclosure of grassland for 14 years; G_{30a} , enclosure of grassland for 30 years; G_{39a} , enclosure of grassland for 39 years.

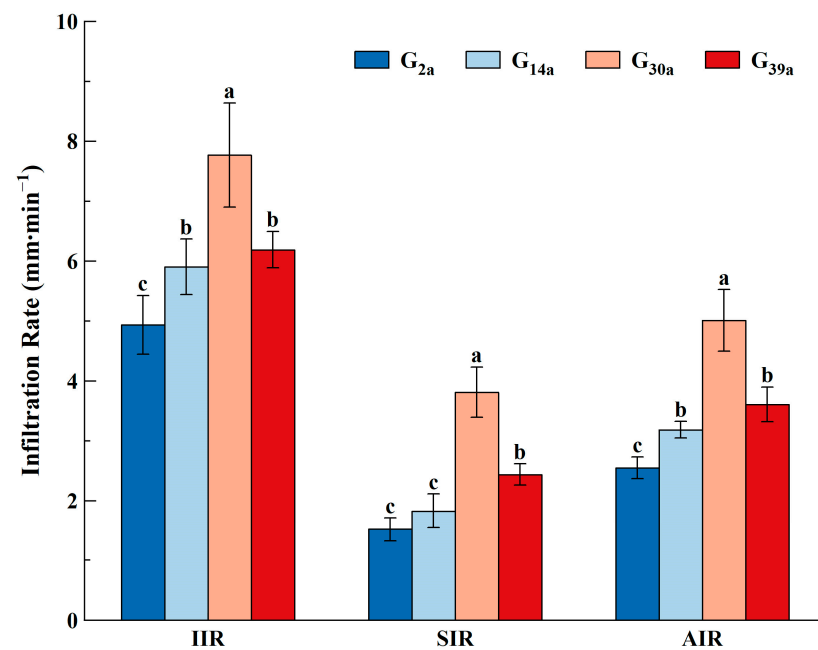


Figure 7. Soil infiltration characteristics of grassland with different enclosure years. G_{2a}, enclosure of grassland for 2 years; G_{14a}, enclosure of grassland for 14 years; G_{30a}, enclosure of grassland for 30 years; G_{39a}, enclosure of grassland for 39 years. IIR: initial infiltration rate; SIR: steady infiltration rate (10–30 min); AIR: average infiltration rate (0–30 min). Note: Different lowercase letters indicate the significant differences between different depths of each plot ($p < 0.05$).

3.4. Analysis of Influencing Factors of Soil Water Infiltration Capacity

A highly significant positive correlation is found between soil infiltration rate and physicochemical properties, including total porosity and soil organic matter content ($p < 0.01$) (Table 3). Conversely, bulk density exhibits a highly significant negative influence on soil infiltration rate ($p < 0.01$). Furthermore, the content of soil aggregates across different particle sizes is intimately linked to the soil infiltration rate. The initial infiltration rate is significantly positively correlated with the content of soil aggregates with a particle size of 2–5 mm ($p < 0.05$), and the content of aggregates with a particle size of 0.25–2 mm is significantly positively correlated with the stable soil infiltration rate ($p < 0.01$). In general, the indicators of soil aggregate stability, notably the large aggregates exceeding 0.25 mm and the GMD, exhibit a significant positive correlation with the stable soil infiltration rate, whereas they indicate a negative correlation with the D ($p < 0.01$).

Table 3. Correlation analysis of soil infiltration performance and influencing factors.

	IIR	SIR	AIR
Bulk Density	−0.597 **	−0.671 **	−0.668 **
Porosity	0.597 **	0.671 **	0.668 **
SOM	0.455 **	0.584 **	0.528 **
>5 mm	0.436 **	0.441 **	0.442 **
2–5 mm	0.377 *	0.29	0.341 *
1–2 mm	0.505 **	0.446 **	0.486 **
0.5–1 mm	0.639 **	0.638 **	0.645 **
0.25–0.5 mm	0.638 **	0.600 **	0.627 **
<0.25 mm	−0.797 **	−0.748 **	−0.783 **
GMD	0.659 **	0.626 **	0.650 **
D	0.796 **	0.758 **	0.786 **

Note: Spearman correlations for soil physical properties and infiltration rates. BD: bulk density; SOM: organic matter; D: fractal dimension; GMD: geometric mean diameter; IIR: initial infiltration rate; SIR: steady infiltration rate (10–30 min); AIR: average infiltration rate (0–30 min). The significance levels: * $p < 0.05$, ** $p < 0.01$.

Principal component analysis (PCA) was conducted on soil water infiltration capacity, and the results are presented in Table 4. Three principal components were extracted from 11 factors that significantly influenced the infiltration rate, with a cumulative contribution rate of 88.46%, encompassing most of the information. The first principal component, with a contribution rate of 63.47%, was determined by water-stable aggregates and soil bulk density. Among them, the 1–2 mm water-stable aggregates had the highest loading (0.91), while the loadings of 0.5–1 mm, 0.25–0.5 mm, and <0.25 mm water-stable aggregates were all around 0.85. Other significant indicators included soil bulk density, total soil porosity, and fractal dimension D. The second principal component, with a contribution rate of 14.19%, was primarily influenced by >5 mm water-stable aggregates and organic matter. The third principal component, with a contribution rate of 10.80%, was mainly determined by 2–5 mm water-stable aggregates.

Table 4. Principal component analysis of soil water infiltration capacity.

Principal Component		1	2	3
BD		−0.74	−0.53	0.33
Porosity		0.74	0.53	−0.33
SOM		0.23	0.75	−0.36
Water-stable	>5 mm	0.06	0.89	0.14
Aggregate	2–5 mm	0.08	−0.01	0.9
	1–2 mm	0.91	−0.08	0.03
	0.5–1 mm	0.84	0.4	−0.2
	0.25–0.5 mm	0.88	0.02	0.07
	<0.25 mm	−0.86	−0.44	−0.23
GMD		0.69	0.62	0.32
D		−0.9	−0.39	−0.14
Characteristic Value		6.98	1.56	1.19
Contribution Rate		63.47%	14.19%	10.80%
Cumulative Contribution Rate		63.47%	77.66%	88.46%

4. Discussion

As one of the most fundamental properties of soil, bulk density has a direct influence on soil structure and subsequently affects soil permeability, water retention capacity, and erosion resistance [23–25]. Chao et al. [26] found a gradual reduction in soil bulk density during the vegetation restoration process, suggesting a notable enhancement in soil structure. This study reveals that as the enclosed duration of grassland increases, the bulk density of topsoil in the region experiences a notable decrease. Specifically, the soil bulk density of grassland enclosed for 30 and 39 years was significantly lower than that of grassland enclosed for 2 and 14 years ($p < 0.05$), which is consistent with the findings of Du et al. [12]. However, no remarkable differences were detected in bulk density and total porosity between the soils of grasslands enclosed for 30 and 39 years.

Multiple factors contribute to the variation of soil bulk density, with soil organic matter content being the foremost physicochemical factor [27]. Our research findings also indicated that grasslands enclosed for 30 and 39 years exhibited significantly higher organic matter content ($p < 0.05$) compared to those enclosed for 2 and 14 years, underscoring the vital importance of soil organic matter [28]. In both G_{14a} and G_{30a} , the organic matter content of the topsoil is markedly elevated compared to that of the deep soil, a trend that can be ascribed to the accumulation and decomposition of plant litter [29]. Numerous research findings have indicated a positive correlation between organic matter content and the duration of vegetation restoration. During the process of vegetation restoration and growth, significant accumulation of humus occurs on the soil surface [30]. This accumulated humus, through the action of microorganisms and soil animals, facilitates the introduction of organic matter into the soil [6,29,31]. However, an intriguing exception to this trend is noted, where the soil organic matter content in grasslands enclosed for 2 years is notably

higher than that in grasslands enclosed for 14 years, a discrepancy attributed to grazing and human interference preceding enclosure.

According to research, grazing exerts an influence on the makeup of surface vegetation, as well as on the velocity of litter accumulation, utilization, and breakdown processes [10,18]. The study conducted by Schuman et al. [32] demonstrated that a 12-year grazing period augmented the organic matter content in the soil at depths ranging from 0 to 30 cm. Nevertheless, soil compaction resulting from livestock trampling during this grazing period persisted until the early stages of enclosure [6], creating conditions that were unfavorable for microbial activity and subsequent organic matter decomposition. As the enclosure period prolongs, vegetation experiences gradual regrowth, resulting in the consumption of previously accumulated organic matter. Throughout this process, the continuous production of fresh litter by plants and the decomposition of root systems within the soil contribute to the ongoing accumulation of organic matter [33]. Some studies have shown that after reaching a certain period of recovery, vegetation cover tends to stabilize or begin to decline [34]. In this study, as vegetation recovered and succeeded, grassland root biomass increased with the prolongation of enclosure duration. When the enclosure duration attained 30 years, the root biomass attains a significantly greater magnitude than that of other enclosed grasslands, only to subsequently embark on a decline, which may be related to changes in community structure [33]. It is recognized that the soil's capacity to sustain vegetation is finite, with soil moisture exerting a particularly restrictive influence on vegetation growth [7,35]. The growth of numerous vegetation consumes soil nutrients and moisture, ultimately resulting in a decrease in vegetation quantity and a subsequent decrease in root biomass.

The size distribution and stability characteristics of soil aggregates can indicate soil quality and also determine soil moisture conditions [36,37]. Stable aggregates are the main component of good soil structure, which can reduce soil erosion by surface runoff [12,38,39], while the sizes of the MWD and GMD can show the stability of soil aggregates [40]. Based on the diameter of aggregates, researchers categorize them into macro-aggregates (>0.25 mm) and micro-aggregates (<0.25 mm) [41]. This study indicated that as the enclosure years increased, the content of large aggregates, the MWD, and the GMD exhibited a corresponding increase, concurring with the outcomes of prior studies [33,42]. However, once the enclosure period surpassed 30 years, a decline in the stability indicators of aggregates and the content of large aggregates emerged, exhibiting no substantial difference between G_{30a} and G_{39a} . This tendency is intricately linked to the widespread underground root system development and the organic matter content within the process of vegetation recovery. Multiple research studies have highlighted a positive relationship between the content of macro-aggregates, aggregate stability, and organic matter [41,43,44]. Furthermore, it has been shown that fine roots and hyphae contribute to the binding of macro-aggregates [45]. The results of this study also indicate that root biomass is significantly positively correlated with the MWD and GMD ($p < 0.05$). Additionally, G_{39a} shows higher MWD and GMD, signifying better aggregate stability. As a result, even if the root biomass of G_{39a} is relatively low, it has still accumulated a significant amount of macro-aggregates through the long-term enclosure process. The micro-aggregate content of G_{2a} was notably higher than that of the other sample plots in this study, potentially attributed to the relatively short enclosure duration, which renders the soil more susceptible to erosion. Research findings have indicated a significant positive correlation between soil fractal dimension and soil erodibility, with the fractal dimension demonstrating the degree of soil disturbance [20,46]. In this study, an increase in the MWD and GMD led to a decrease in fractal dimension, aligning with the findings of Saiedi et al. [20]. Moreover, the fractal dimensions of G_{30a} and G_{39a} , which had longer enclosure periods, were notably lower than those of the other sample plots, and G_{14a} was also markedly lower than G_{2a} . These findings indicate that enclosure and afforestation have a significant effect on soil improvement in the Ningxia Yunwushan Nature Reserve, but this effect diminishes after more than 30 years.

Vegetation restoration has the potential to enhance soil infiltration capacity [9,15,47]. Numerous studies have utilized indicators, including initial infiltration rate, average infiltration rate, and stable infiltration rate, to assess soil infiltration capacity [17,48]. This study measured indicators including initial infiltration rate, average infiltration rate, and stable infiltration rate for four different grassland enclosures, each with varying years of enclosure. The results reveal that soil infiltration capacity exhibits an increasing trend with the prolongation of enclosure duration, yet a turning point is observed where soil infiltration capacity starts to decline when the enclosure duration surpasses 30 years (Figure 7). Wu G et al. [49] conducted an investigation on restored grasslands with varying years of abandonment and observed analogous phenomena. Notably, the soil infiltration rate attained its maximum on grasslands restored for 15 years, whereas no further augmentation in soil water conductivity was discernible on grasslands restored for 30 years. In this study, it was found that a closure period of up to 30 years was necessary for the infiltration rate to reach its maximum value. This is attributed to the maximum vegetation cover that can be supported under the climatic and precipitation conditions of different study areas.

Alterations in soil infiltration capacity are predominantly influenced by vegetation growth, mortality, and the subsequent modifications in soil structure [15,50]. Relevant research suggests that macro-aggregates exhibit stronger resistance to erosion compared to micro-aggregates. Additionally, the presence of larger pore structures between macro-aggregates enhances permeability [12,51]. Micro-aggregates, formed through the cementation of humus [43], have poor water stability and are easily dispersed. Soils with a greater content of micro-aggregates are more susceptible to erosion caused by rainfall [12]. This type of soil, possessing unfavorable pore connectivity and poor structure, generally exhibits a lower infiltration capacity [51]. Before enclosure, trampling and grazing activities of herbivores during pasturing resulted in decreased ground vegetation cover, soil hardening, and a reduction in soil porosity [52]. As the duration of enclosure increased, soil bulk density gradually decreased, whereas porosity showed a consistent increase (Table 2). Many studies have drawn similar conclusions, suggesting that with a decrease in bulk density and an increase in porosity, the soil becomes more porous and demonstrates improved permeability [12].

Moreover, the grassland that had been enclosed for 30 years exhibited the highest levels of organic matter content, root biomass, aggregate stability, and macro-aggregate count. Soil organic matter serves as a binder between soil particles, fostering the formation of macro-aggregates and enhancing aggregate stability, ultimately leading to improved soil porosity [47,53]. This is also the main reason for the strongest infiltration capacity of G_{30a} (Table 3). Although G_{39a} has a high porosity, the reduction in the number of its roots causes the soil pore structure to lose the support of the root system, resulting in poor stability [54]. Thus, the initial infiltration rate of G_{39a} is comparatively high, yet it undergoes a 62.65% decrease during the infiltration process before stabilizing. In contrast, G_{2a}, with a higher content of micro-aggregates, experiences these particles entering the soil concomitantly with water flow during infiltration. The subsequent dispersion of micro-aggregates results in pore blockage, causing a 51.21% decline in G_{2a}'s infiltration rate during the initial stage. Notably, the average infiltration rate of G_{2a} is lower than that of other grasslands, as evidenced in Figure 6.

5. Conclusions

This study investigated the soil properties and infiltration characteristics of four grasslands with different enclosure durations in Yunwu Mountain (2 years, 14 years, 30 years, and 39 years). Compared to the stable infiltration rate of G_{2a} at 1.51 mm/min, the infiltration rates of the enclosed grassland for 14 years, 30 years, and 39 years increased by 20.66%, 152.03%, and 61.19%, respectively. The enforcement of fenced enclosures has facilitated grassland vegetation recovery and augmented soil infiltration capacity, which is directly associated with the elevated total soil porosity, soil macro-aggregate content, and aggregate stability. The enhancement in root biomass and soil organic matter

exerts influence on the composition and stability of soil aggregates and total soil porosity, ultimately enhancing soil infiltration capacity. The research findings indicate that after 30 years of enclosure in the Yunwushan Nature Reserve, certain parameters (root biomass, soil organic matter, soil aggregate characteristics, and infiltration properties) have declined. Perhaps future studies will provide clearer answers. After reaching the optimal period of 30 years, no significant changes were observed in the soil's physicochemical properties and infiltration capacity. This study, which studies long-term fenced enclosure grasslands, contributes to a deeper understanding of the beneficial effects of enclosure on grassland soil. However, to comprehensively assess the ecological implications of enclosed measures, continued research is vital, integrating ecological surveys of aboveground vegetation to explore the impacts of enclosed measures on grassland rehabilitation and management.

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