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Discussions

Regulating effects of mixed-cultivated grasslands in surface water conservation and soil erosion reduction along with restoration of alpine degraded hillsides

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ABSTRACT

Vegetation restoration is among the most effective measures for controlling runoff and soil erosion resulting from human activity. Nevertheless, few studies have been undertaken to analyze the effects of plant restoration on maintaining the stability of the hydrological cycle, especially, in alpine degraded hillsides where mixed-cultivated grasslands predominate in the landscape. In this research, we conducted *in situ* monitoring using runoff plots to investigate the impact of three strategies, each combining two grass species per plot (three species in total), on a 20-degree slope, assessing the activation and volume of surface runoff and soil loss in alpine degraded hillsides over three years (2019, 2020 and 2022). A severely degraded meadow plot was used as control. The findings indicated that mixed-cultivated grasslands can effectively manage runoff and reduce soil loss as planting ages increase. Between 2019 and 2022, the values of the runoff reduction ratio decreased for *Deschampsia cespitosa* and *Elymus nutans* (*DE*), *Poa pratensis L.cv.* Qinghai and *Elymus nutans* (*PE*), and *Poa pratensis L.cv.* Qinghai and *Deschampsia cespitosa* and (*PD*) from -79.3% to -115.4%, from -130.4% to -156.1%, and from -48.5% to -87.6%, respectively. On the contrary, the mean sediment concentration reduction ratio increased from -120.9 to 55.8% (in *DE*), from 112.4 to 59.7% (in *PE*), and from -94.3 to 62.1% (in *PD*). This implies that protective measures should be prioritized during the initial planting stage of cultivated grasslands in alpine degraded hillsides. The key factors affecting soil loss and runoff were rainfall amount, duration and intensity (60-min intensity). We conclude that the results of this study can serve as scientific guides to design efficient policy decisions for planning the most effective vegetation restoration in the severely degraded hillside alpine meadows.

Keywords: Alpine meadow; Degraded hillside; Mixed-cultivated grassland; land management; runoff; soil erosion.

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1 Introduction

Grasslands are an essential component of terrestrial ecosystems and natural habitats for the development of animal livestock (O'Mara, 2012). They make significant contributions to biodiversity conservation, climate mitigation, carbon sequestration, and water supply and regulation (Bardgett et al., 2021). Despite the importance of grasslands, about half of them are degraded globally, with 5% undergoing severe degradation, which has become a major issue for humanity to overcome (Gang et al., 2014; Török et al., 2021). To date, numerous studies have been conducted to analyze the threatening drivers of degradation, its negative impacts, and management and restoration methods for grassland degradation (Gang et al., 2014; Grman et al., 2021; Han et al., 2020). Water and soil are critical for human survival and development, as well as irreplaceable basic natural resources that maintain the function of natural ecosystems and the development of socioeconomic systems. Precipitation is the main water source in semi-arid areas and the conversion of precipitation to runoff is influenced by vegetation restoration, which in turn nfluences river flow recharge. However, there have been limited studies focused on how effectively restored grasslands can regulate water supply and prevent soil erosion (Minea et al., 2022). This is particularly important for alpine grasslands, which play a vital role in the supply of fresh water and the development of livestock husbandry (Cui et al., 2022). Therefore, it is necessary to assess the impacts of grassland restoration on runoff and soil protection.

Vegetation restoration is widely considered as one of the most effective methods for controlling runoff and soil erosion worldwide (Anache et al., 2018). The effects of vegetation cover properties on runoff and soil loss reduction are strongly connected to plant species, leaf and branch coverage, above-ground biomass, litter biomass, and root systems (Liu et al., 2022; Freschet and Roumet, 2017; Gyssels et al., 2005; Zhu et al., 2021). Furthermore, the processes of runoff and soil loss are significantly influenced by the improvement of soil characteristics with vegetation restoration (Schwarz et al., 2015; Gyssels et al., 2005). The interaction between vegetation and soil could stabilize the topsoil and alter soil properties (Saxton and Rawls, 2006; Ma et al., 2023). Vegetation restoration promotes the formation of soil aggregates, decreases soil bulk density, enhances organic matter and nutrients and improves soil porosity, resulting in high soil hydraulic conductivity and field capacity (Qiu et al., 2022; Saxton and Rawls, 2006). The above-interlinked soil properties alter soil hydrological properties and ultimately influence hillslope and watershed hydrology, such as runoff and soil erosion (Lu et al., 2020; Qiu et al., 2022). While vegetation restoration holds the potential to be a key method of environmental restoration under human management, the inappropriate selection of species can negatively impact the sustainability of local economic and environmental development (Huang et al., 2017; 2019). For example, cultivated grasslands were already advocated as a sensible solution for the conservation of soil and water, as well as the regrowth of vegetation in semi-arid mountain areas (Liu et al., 2022; Wu et al., 2010). Grass communities with multiple stratified structures are better at maintaining surface runoff and decreasing soil loss than those with a single composition and structure (Mohammad and Adam, 2010).

Surface runoff – rainwater that moves over the ground surface – reaches the stream in the form of sheet, rill and gully flow (Rumynin, 2015). The conversion of rainfall to overland flow depends on the rainfall rate, the soil hydrological properties, such as saturated hydraulic conductivity and field capacity, and initial soil water content (Gyssels et al., 2005; De Baets et al., 2007). Because runoff is the primary driver of water erosion on hillslopes and a carrier of sediment transport, reducing the conversion of rainfall to runoff is regarded as an effective way to control water erosion, such as vegetation restoration (Zhou et al., 2016; Zhu et al., 2021). However, for the arid and semi-arid regions and headstreams (Qinghai-Tibetan Plateau), surface runoff is the major water supply source to the river streamflow, thereby it is vital for ensuring the sustainability of ecosystems (Liu et al., 2020; Robinson et al., 2003). Therefore, the fundamental objective of restoration efforts is to maintain runoff while reducing its level of sediment concentration.

Soil erosion can be reduced by various factors, including the above- and below-ground biomass of grasses, litter cover, and root systems (De Baets et al., 2007). Grasslands can control water erosion relying on the role of the the aboveground biomass in dissipating flow energy (Bochet and García-Fayos, 2004), living roots in decreasing soil detachment capacity (Zhang et al., 2013), grass plant cover in intercepting rainfall (Liu et al., 2019), and litter cover in enhancing rainwater infiltration (Liu et al., 2022). Moreover, the reciprocal cementation and interweaving of plant roots can remarkably alter the physical properties of the topsoil, enhancing its resistance to erosion (Schwarz et al., 2015; Wang et al., 2018). The impact of grassroots on the characteristics can be summarized as follows: i) increasing the stability of soil aggregates through aggregating fine soil particles into macroaggregates; ii) enhancing soil cohesion through interweaving with the soil; and iii) decreasing soil bulk density through increasing soil porosity (Wu et al., 2019; Gyssels et al., 2005). For example, numerous recent studies have confirmed that a grass with shallow yet dense fibrous root system appears to be more effective at controlling water erosion than grass with good ground cover but low root density (Liu et al., 2022; De Baets et al., 2007; Bochet et al., 2006).

Alpine meadows, especially in the Qinghai-Tibetan Plateau, constitute the predominant ecosystem, accounting for 44 and 6% of total grassland areas in China and the world, respectively (Wang et al., 2016). Alpine meadows are fragile ecosystems when rapid changes are involved and due to climate change and overgrazing have suffered substantial degradation in recent decades (Fig.

https://doi.org/10.5194/hess-2023-257
Preprint. Discussion started: 2 November 2023

1b and c). This situation is leading to a drop in vegetation cover and an increase in severely degraded meadows, especially for hillside grassland, ultimately posing a great hazard to the plateau from water and soil loss (Liu et al., 2022). The Qinghai-Tibetan Plateau serves as the headwaters for many of Asia's major rivers (Xu, 2018). The long-term and widespread degradation of hillside alpine meadow has disrupted the soil water balance, reducing runoff. This, in turn, diminishes river streamflow, ultimately constraining the sustainable development of both local and downstream regions. The importance of artificial grassland in restoring alpine degraded meadow is widely accepted (Wen et al., 2018; Wu et al., 2010). The establishment of artificial grassland on severely degraded areas provides a dual benefit by boosting productivity and improving the ecological environment of alpine grasslands (Shang et al., 2008; Liu et al., 2022).

While previous reports have often focused on carbon sequestration capacity, vegetation characteristics, soil quality and productivity of cultivated grassland (Wang et al., 2013; Wen et al., 2018), there have been a limited examination of the impacts of mixed-cultivated grasslands on the provision of runoff and prevention of soil erosion on the alpine hillsides. Here, we present novel research to examine the ability of alpine hillsides cultivated grasslands to regulate runoff and soil loss through three different mixed-cultivated grasslands (*DE*, *PE* and *PD*) compared to *SDM* in alpine degraded hillsides by a three-year field experiment. In particular, this study aimed to (1) assess the temporal variations in soil and water loss of *DE*, *PE* and *PD* grasslands during the growing season and under natural rainfall; and (2) determine the key factors influencing the mixed-cultivated grasslands in controlling runoff and soil erosion. In this vein, this study has realistic implications for understanding the contribution of mixed-cultivated grasslands restoration on soil erosion control in the degraded alpine hillside.

https://doi.org/10.5194/hess-2023-257
Preprint. Discussion started: 2 November 2023

2 Materials and methods

2.1 Study area

This study was carried out in the representative area of Zhique Village (33°40′01″ N and 99°43′06″ E, elevation over 4200 m a.s.l), Dari County, Qinghai province, which served as a field experimental site and model area for the restoration of severely degraded alpine meadow on the Qinghai-Tibetan Plateau (Fig. 1a). The climate conditions correspond to a typical highland one with low temperatures throughout the year, i.e., not showing distinct seasons, just cold and warm ones. In the study region, the average annual temperature is -0.1°C, with monthly variations from -18.3°C in January to 12.4°C in July (Li et al., 2018). The average annual precipitation is 416 mm, with the majority of it falling from July to September. Nevertheless, the majority of the precipitation and the warm season falls during the vegetation growth period (from May to September), favoring optimal conditions for the development of vegetation. The soil type in the study area is classified as alpine meadow soil (IUSS-WRB, 2015) (Liu et al., 2022). Currently, the remnant vegetation in this site is composed of an alpine shrub (*Salix cupularis* and *Potentilla fruticose*), alpine meadow (*Kobresia pygmaea, Kobresia humilis* and *Kobresia capillifoli*) and swamp meadow (*Carex atrofusca, Poa annua* and *Carex parva*).

Soil erosion in the degraded alpine meadows was severe, which was the primary source of sediment delivered to streams in the study area (Liu et al., 2022). The mattic epipedom of alpine meadow has experienced fragmentation (Fig. b) and even disappearance (Fig. c), eventually forming a severely degraded meadow. The average soil erosion rate and the total erosion in the study area were 13.63 t ha^{-1} y^{-1} and 323.58 × 106 t y^{-1}, respectively, before the implementation of the grassland restoration project, i.e., Subsidy and Incentive System for Grassland Conservation (Zhao et al., 2021). Severely degraded meadows were restored via mixed-cultivated grasslands and moderately degraded meadows were restored by broadcast sowing on the hillslopes during the implementation of the

https://doi.org/10.5194/hess-2023-257
Preprint. Discussion started: 2 November 2023

grassland restoration project. The grass species used for the projects have excellent characteristics like strong trampling tolerance, good palatability, abundant leaf quantity and developed rhizome, such as *Poa pratensis L. cv.* Qinghai, *Deschampsia cespitosa* and *Elymus nutans* (Shang et al., 2018).

2.2 Experimental design and measurement

The degraded hillslopes are the main component of runoff generation and confluence areas on the Qinghai-Tibetan Plateau. Hence, the grass species chosen for mixed-cultivated grasslands should not only be grazing-tolerant and good forage but also prevent soil and water loss. Potential grass species should also be fully acclimated to harsh alpine climate and have complementary morphological characteristics and habits (Liu et al., 2022). The community established by matching of grasses morphological characteristics and habits has a hierarchical vertical cover structure and little inter- or intraspecific competition. Following the above-mentioned guidelines for choosing grass species, we ultimately decided on three species (*Deschampsia cespitosa, Poa pratensis L. cv.* Qinghai and *Elymus nutans*) from the most widely utilized grass species. *Deschampsia cespitosa* is a cool-season bunching grass native to alpine environments. It typically forms a low, dense tussock (to 30–50 cm tall) of very thin (0.5 cm wide), arching, flat to inrolled, dark green grass blades (to 5 cm long). *Deschampsia cespitosa*, a common bottom grass, has 70% of its grass stems growing between 0 and 30 cm tall. *Elymus nutans* is a common and important plant species in the alpine meadows of the Qinghai-Tibetan plateau (Chen et al., 2009). It is a valuable fodder grass in alpine locations that has been extensively employed for animal production, disturbed grassland restoration, and artificial grassland construction due to its resilience to cold, drought and pests (Ren et al., 2010). *Elymus nutans* is a herbaceous perennial species with sparsely tufted culms that can grow to heights of 70 to 100 cm (Liu et al., 2022). *Poa pratensis L. cv. Qinghai* is the common and dominant species native to the Qinghai-

Tibetan Plateau. It is an excellent species that has been selected and cultivated to restore degraded alpine meadows. Also, *Poa pratensis L. cv.* Qinghai is a herbaceous perennial species with erect or geniculate base culms that grow 20–60 cm tall.

To reveal the effectiveness of mixed-cultivated grasslands in controlling runoff and soil loss on hillsides, field observation of mixed grass plots designed by us was conducted from the 2019 to 2022 growing seasons. Therefore, one plot with severely degraded meadow (*SDM*) as a control and three plots with two mixed grass seeds per plot of *Deschampsia cespitosa* and *Elymus nutans* (*DE*), *Poa pratensis L.cv.* Qinghai and *Elymus nutans* (*PE*), and *Poa pratensis L.cv.* Qinghai and *Deschampsia cespitosa* (*PD*) were selected as the testing site (Fig. 1d). All four runoff plots were spaced 1m apart and were located on the same hillside with the same elevation and soil texture. All plots were bounded by steel plates (30 cm high and 2 mm thick sheet) and built during May 2019, with an area of 10 m^2 (2 m wide and 5 m long parallel to the maximum slope gradient). To collect only runoff and soil loss from the runoff plot, the steel plate was put vertically into the soil to a depth of about 10 cm, with the remainder sticking out from the soil surface. At the outlet of each plot, a steel runoff collection and calibrated tank (75 L) were set up to gather sediment and runoff. To prevent the collected runoff from being lost to evaporation, the calibrated tank was set inside a sealed vat (Fig. 1d).

In addition, the grass seeding for each runoff plot was completed in May 2019. For the runoff plots, grass seeds were distributed to a depth of less than 1 cm in strips at 20 cm intervals following plowing. The seeding rate was set at 6.0 g m^{-2} for *Poa pratensis L.cv.* Qinghai and *Deschampsia cespitosa* and 4.5 g m^{-2} for *Elymus nutans* to ensure a constant number of plants based on germination and seedling emergence rates. None of the runoff plots experienced any human disturbance during the observation period (2019–2022), including grazing, harvesting, and excavation.

2.3 Rainfall, runoff and soil loss measurement

A Vantage pro 2^{TM} weather station (Davis Instruments Corp., USA) with a measurement accuracy of 4% is positioned next to the experimental plots to monitor precipitation intensity and duration (Fig. 1). A precipitation event was defined by the occurrence of a no-rain interval lasting more than 3 h between them. A total of 42 precipitation events were recorded from 2019 to 2022 throughout the growing season. Snow was not collected, and only rainfall was recorded. Precipitation characteristics of each event, including amount (P), duration (RD), maximum intensities of 60 minutes (RI_{60}), and average rainfall intensity (ARI) were recorded. After each rainfall-runoff event, both runoff and sediment were collected right away. The water level in the calibrated tank was first measured to calculate the runoff volume. Then, runoff was fully mixed inside the calibrated tank using a stirring bar to thoroughly whirl, and two 500 ml bottles were used to obtain mixture samples of sediment and runoff. When the calibrated tank had less than 1000 ml of runoff sample, all runoff was collected. Lastly, the calibrated tank was cleaned in order to collect sediment and runoff for the subsequent rainfall-runoff event. The mixture samples in the bottle were transported back to the lab to be filtered on quantitative analysis filter paper. The filter paper with sediment was oven-dried to a consistent weight at 105 °C. The ratio of soil loss amount to runoff volume in the mixed samples was applied to calculate the sediment concentration. Finally, runoff volume and sediment concentration were multiplied to calculate soil loss in each plot.

We collected runoff and soil erosion data during the growing season for the years 2019 to 2022. Data for 2021 could not be collected due to the prevention and control strategies for coronavirus (COVID-19). Soil erosion and runoff were portrayed in this work by soil erosion per unit area ($g\ m^{-2}$) and runoff depth (mm). The runoff depth (R) and soil erosion per unit area (S) could be calculated using the following formulas:

$$R = \frac{V_R}{A} \times 10^3 \tag{1}$$

$$S = \frac{S_T}{A} \tag{2}$$

where V_R is the volume of runoff from runoff plots (m^3), S_T is the total amount of soil erosion from runoff plots (g), and A is the area of runoff plot (m^2).

2.4 Vegetation and soil properties measurement

Vegetation cover (*VC*) was measured monthly from 2019 to 2022 growing seasons using a steel wire frame (50 cm × 50 cm) subdivided into 25 plots of 10 cm × 10 cm. Fig. 2 exhibited the change in vegetation coverage for all runoff plots from 2019 to 2022. After collecting runoff samples each year, the quadrats (50 cm × 50 cm) were positioned in the up-, mid-, and down-slope areas. Litter in each quadrant was collected and oven-dried to determine litter biomass (*LB*) (Zhu et al., 2021). The litter collection for 2019 was not completed due to the seeding of mixed-cultivated grasslands in May 2019, and the litter collection for 2020 and 2021 was collected at the end of the runoff collection for the current year. Undisturbed soil samples were taken in the 0–10 cm soil layers using steel rings in 2022. All soil samples were saturated and then weighed (W_{sat}). Then the saturated soil samples placed on the dry sand layer to drain water for about 2 h and 8 h, and weighed (W_{2h} and W_{8h}). Finally, soil samples were dried in an oven at 105 ◦C for 24 h and then weighed (W_{dr}). Based on the above measurement, soil bulk density (*BD*, g cm^{-3}), total porosity (*TP*, %), capillary porosity (*CP*, %), and field capacity (FC, %) were determined as follows:

$$FC = \frac{(W_{8h} - W_{dr})}{(W_{dr} - W_{sr})} \tag{3}$$

$$BD = \frac{(W_{dr} - W_{sr})}{V} \tag{4}$$

$$TP = (1 - \frac{BD}{ds}) \times 100 \tag{5}$$

$$CP = \frac{(W_{2h} - W_{dr})}{V} \tag{6}$$

$$NCP = TP - CP \tag{7}$$

where W_{sr} is the weight of the cu steel ring (g), *ds* is the soil particle density (generally being 2.65 g cm^{-3}), and *V* is the volume of the cutting ring (100 cm$^{3)}$.

In addition, root mass density (*RMD*) was obtained using a root drill, followed by washing with water and drying in the oven. Four undisturbed samples were collected in each quadrat using a steel ring (6.18 cm diameter and 2.0 cm height), and they were applied to a direct shear (ZJ type). The soil cohesion cohesion was obtained by the Mohr–Coulomb theory (Fattel et al., 2011).

2.5 Calculating the reduction effect of runoff and soil loss

Four metrics were employed to assess the efficiencies of the mixed-cultivated grasslands in regulating runoff and soil loss, which were: The runoff reduction ratio (*RRE*, %), sediment concentration reduction ratio (*CRE*, %), soil erosion reduction ratio (*SRE*, %), and the percentage of runoff reduction ratio to soil loss reduction ratio (*RRSR*) (Zhao et al., 2014). High values of *RRE*, *SRE* or *CRE* indicated that vegetation was able to reduce runoff, soil erosion or sediment concentration compared to the rates observed in the control plot (severely degraded meadow). In addition, a low *RRSR* implied that vegetation was more beneficial in minimizing soil erosion than in minimizing runoff (Liu et al., 2020). These indices were calculated as follows:

$$RRE = \frac{R_c - R_v}{R_c} \times 100 \tag{8}$$

$$SRE = \frac{S_c - S_v}{S_c} \times 100 \tag{9}$$

$$CRE = \frac{C_c - C_v}{C_c} \times 100 \tag{10}$$

$$RRSR = \frac{RRE}{SRE} \times 100 \tag{11}$$

where R_c and R_v are the runoff depths of the degraded meadow plot and plots covered by mixed-cultivated grasslands; S_c and S_v are the soil loss per unit area of the degraded meadow plot and plots covered by mixed-cultivated grasslands; C_c and C_v are the sediment concentrations of the degraded meadow plot and plots covered by mixed-cultivated grasslands, respectively.

2.6 Statistical analyses

Using SPSS statistics software (IBM, USA, version 26.0), all data were analyzed. The Kolmogorov–Smirnov test was used to test the normality of data. Duncan's multiple range tests of one-way analysis of variance (ANOVA) were applied to test for significant differences between soil and vegetation characteristics, runoff depth, soil erosion amount, and runoff and soil loss reduction ratio under various mixed-cultivated grasslands at 0.05 significance levels. Also, path analysis is a form of multiple regression statistical analysis that is used to evaluate causal models by examining the relationships between runoff, soil loss and soil and vegetation properties. By using this method, one can identify the major factors influencing runoff and soil loss and determine the direct and indirect effects of soil and vegetation properties on runoff and soil loss.

3 Results

3.1 Runoff and soil loss under various mixed-cultivated grasslands

Mixed-cultivated grasslands dramatically increased runoff and reduced soil erosion. One-way analysis of variance (ANOVA) revealed that runoff significantly ($P < 0.05$) increased after the severely alpine degraded hillside was restored by the mixed-cultivated grassland (Fig. 3). During the growing seasons of 2019, 2020, and 2022, the average runoff depths of *SDM* were 0.23, 0.34 and 0.25 mm, respectively, all less than the average runoff of mixed-cultivated grassland *DE* (0.44, 0.55 and 0.43 mm), *PE* (0.59, 0.51 and 0.54 mm), and *PD* (0.50 mm, 0.38 mm and 0.40 mm). However, the amount of soil loss in grasslands was significantly influenced by the age of the planting age. As depicted in Fig. 3b, in both 2019 and 2020 (the first and second years of planting) mixed artificial grasses produced higher soil loss than *SDM*, whereas mixed artificial grasses lost less soil in the fourth year of planting (2022) than *SDM*. The soil loss per unit area of *SDM* (0.23 g m^{-2}) was 1.4, 1.3 and 1.9 times that of *DE*, *PE* and *PD* (0.16, 0.18 and 0.12 g m^{-2}, respectively). The results showed that three mixed-cultivated grasslands (*DE*, *PE*, and *PD*) could be effective in controlling soil loss and maintaining runoff.

3.2 Runoff and soil loss reduction under various mixed-cultivated grasslands

Fig. 4 illustrates the runoff, soil loss and sediment concentration reduction ratio after planting various mixed-cultivated grasslands. Lower *RRE* values indicated a better ability to maintain runoff for mixed-cultivated grasslands, while higher *SRE* and *CRE* values indicated better effectiveness of grasslands in soil loss reduction. The mean *RRE* values of the grass community *DE*, *PE*, and *PD* were -79.3%, -130.4% and -48.5% in 2019, -36.9%, -53.5% and -21.5% in 2020, and -115.4%, -156.1% and -87.6% in 2022 (Fig. 4a). Regardless of the combination of the above-mentioned grass species, the increase ratio of runoff in 2022 (the fourth years of planting) was significantly higher than that in 2019 and 2020 (the first and second years of planting). The *SRE* of the three mixed-cultivated grasslands (*DE*, *PE*, and *PD*) increased with increasing planting age. It is worth noting that the average *SRE* values in the grassland communities of *DE*, *PE* and *PD* were 18.0%, 24.3%, and 31.9% in 2022, respectively (Fig. 4b). Additionally, *CRE* for all mixed-cultivated grasslands in 2022 was significantly higher than that in 2019 and 2020. The mean *CRE* values of the cultivated-grassland communities *DE*, *PE*, and *PD* increased from -120.9% to 55.8%, from -112.4% to 59.7%, and from -94.3% to 62.1% from 2019 to 2022, respectively (Fig. 4c). Regardless of the age of the grasslands, the value of *RRSR* was less than 1, suggesting that the soil erosion reduction effect of the grasslands was higher than its runoff reduction effect (Fig. 4d).

3.3 Key factors affecting runoff and soil loss

Precipitation characteristics and vegetation features played a significant role in influencing the hydrological response of the soil. In this study, path analysis was applied to identify the key factors affecting soil loss. The results of this analysis indicated that the sum of path coefficients of RI_{60}, *RD*, *P* and *VC* were 0.31, 0.36, 0.40 and 0.32, respectively (Table 1). This suggests that *P*, *RD*, *VC* and RI_{60} had positive effects on runoff yield, with *P* being the most influential factor. Direct influences on runoff were primarily attributed to *ARI* and *RD*, with direct path coefficients of 0.37 and 0.67, respectively. Meanwhile, the influences of *P* and *LB* on runoff were mainly indirect, with indirect path coefficients of 0.57 and 0.25, respectively. For instance, *P*, in combination with other factors, particularly RI_{60} and *RD*, contributed significantly to runoff.

Soil loss was significantly influenced by *R*, RI_{60}, *ARI* and *LB*, with *R* being the most relevant. The sum of path coefficients of *R*, RI_{60}, *ARI* and *LB* were 0.52, 0.20, 0.28 and -0.25, respectively (Table 2). These results show that *R*, RI_{60} and *ARI* had a promotional effect, whereas *LB* had an inhibitory effect on soil loss. Meanwhile, *R* and *P* had a direct positive influence on soil erosion, with direct path coefficients of 0.60 and 0.28, whereas RI_{60} and *RD* had a direct negative influence on soil erosion, with direct path coefficients of -0.29 and -0.41 (Table 2). In addition, the direct and indirect path coefficients both indicated that *LB* had an inhibitory influence on the soil loss per unit area, with values of -0.10 and -0.25, respectively.

4 Discussion

4.1 Contribution of mixed-cultivated grasslands on soil conservation and runoff maintenance

The mixed-cultivated grasslands (*DE*, *PE*, and *PD*) effectively maintained runoff and minimized soil loss (Fig. 4). This finding is similar to those of studies conducted checking different grassland communities (Liu et al., 2019; Liu et al., 2022). In this study, the mixed-cultivated grasslands significantly increased surface runoff compared to the *SDM*. The difference in runoff between mixed-cultivated grasslands and *SDM* may be attributed to the soil infiltration rate. Mixed-cultivated grasslands had more abundance of fibrous roots in the topsoil compared with *SDM* (Fig. 5), and those fine roots reduced infiltration by occupying the soil pore (Leung et al., 2015). In comparison to *SDM*, soil non-capillary porosity (*NCP*) and field capacity (*FC*) of *DE*, *PE* and *PD* significantly decreased by 46%, 32% and 48%, and increased by 55%, 59% and 48%, respectively (Fig. 5). This implied that *SDM* was restored to mixed-cultivated grasslands with lower permeability and better water retention. This was further evidence that infiltration was responsible for the difference in runoff between the mixed-cultivated grasslands and *SDM*.

Soil loss in all three mixed-cultivated grassland communities (*DE*, *PE* and *PD*) was higher than that in the *SDM* during the first- and second years following planting. However, by the fourth year, the *SDM* exhibited higher soil loss than the three mixed-cultivated grasslands (Fig. 3). These changes in soil erosion were dominantly attributed to the developing of the root system and improvement of soil structure (Zhu et al., 2021). The loosening of the soil structure caused by the seeding method of plowing resulted in a greater soil loss of the three mixed-cultivated grasslands than the *SDM* at the beginning of the planting. We confirmed that the age of plantation was a key factor in understanding the inter-annual changes of soil erosion. This idea was also demonstrated in other types of primary land uses such as woody crops or young forests (Rodrigo-Comino, et al., 2018). Nevertheless, we hypothesize that grassland topsoil demonstrated a stronger resilience to erosion as its root system grew, which had a reinforcement impact on the soil and led to lower soil loss in the fourth year of planting than that of the *SDM*. The topsoil (0-10 cm) of the grasslands had significantly different soil properties from the *SDM* in the fourth year after planting, as detailed in Table 3. In comparison to *SDM*, the root mass density and soil cohesion of grasslands *DE*, *PE* and *PD* increased by 672%, 890% and 589%, and by 379%, 282% and 315%, respectively.

4.2 Effect of rainfall and grassland community characteristics on runoff and soil loss

Surface runoff and erosion process is influenced and constrained by rainfall depth, intensity and duration, and by vegetation cover as well (Mohamadi and Kavian, 2015b; Bochet et al., 2006). In this study, the *VC* had a directly promoted effect on surface runoff. Moreover, this result was in line with the finding of Niu et al. (2021), who reported that the surface runoff increased with the grassland coverage. Our results also indicate that *P* could have an indirect effect on surface runoff through *RD* and RI_{60}. This implies that heavier and longer-lasting rainfall events were more likely to lead to surface runoff generation (Dos Santos et al., 2017). The findings demonstrated that *R* and *ARI* were the most and second most influential factors in promoting soil erosion (Table 2). The primary cause for this is that runoff velocity increases with higher precipitation intensity (Wang et al., 2013), which likely enhances the capacity of soil detachment and transport by surface runoff (Zhu et al., 2021). Furthermore, *LB* had a direct and negative impact on soil loss (Table 2), indicating that the effectiveness of grasslands in reducing soil loss increased as litter biomass increased. Liu et al. (2022) found that the soil loss rate decreased with increasing litter biomass in the grassland. Plant litter can intercept precipitation, reducing rainfall kinetic energy and splash erosion, while also increasing surface roughness (Liu et al., 2017; Xia et al., 2019) All these processes favor a reduction in runoff yield and soil loss rates.

4.3 Implications for mixed-cultivated grasslands restoration on the degraded alpine hillside

Our findings demonstrated that mixed-cultivated grasslands with complementing morphological features and habits can be more effective at maintaining runoff and reducing soil erosion. Three mixed-cultivated grasslands (*DE*, *PE*, and *PD*) exhibited an effective role in controlling soil loss on the degraded alpine hillside. The morphological characteristics of *Deschampsia cespitosa*, *Poa pratensis L.cv.* Qinghai and *Elymus nutans* are dense clump type, rhizomatic-sparse clump type, and sparse clump perennial grasses, respectively. In addition, *Deschampsia cespitosa* and *Poa pratensis L.cv.* Qinghai are bottom grasses, while *Elymus nutan*s belongs to the top grass. The mix of dense and sparse grasses (DE and PD), and mix of top and bottom grasses (*DE* and *PE*) can complement each other morphologically and structurally, thereby more effectively reducing the kinetic energy of raindrops (Liu et al., 2022). *Poa pratensis L.cv.* Qinghai, a rhizomatic grass, also has abundant root systems intertwined with the soil, increasing soil cohesion and consequently reducing soil detachment capacity (Wang et al., 2018). Overall, in this study, the morphological and root characteristics of mixed-cultivated grasslands reduced runoff velocity, influenced water infiltration process and decreased soil erodibility. However, at the start of planting, the mixed planted grassland had a greater soil erosion than severely degraded meadow, whereas the function of reducing soil loss was reached in the 4th year of planting (Figs. 2 and 3). This suggested that protection measures, such as mesh covering and anti-trampling, may be taken into account to reduce soil loss in the initial planting stage of cultivated grassland in alpine hillsides (Liu et al., 2022). Moreover, grass may also be planted with a no-till system to avoid the initial increase of soil erosion at the initial phases of cultivated grassland by destroying soil structure (Karayel and Sarauskis, 2019). In addition, spring meltwater is the main driver of soil erosion in degraded alpine meadows in alpine regions, which greatly turbidizes rivers (Zheng et al., 2022; Shi et al., 2020). The restoration of severely degraded hillslope meadows increased vegetation cover and soil ability, both of which could have an inhibitory impact against meltwater erosion (Liu et al., 2022). To better understand the effects of cultivated grassland on meltwater erosion, future experiments under natural freezing and thawing conditions need to be monitored.

Cultivated grasslands, considered a crucial component of vegetation restoration, have been extensively utilized in the rehabilitation of degraded alpine hillsides (Shang et al., 2008). Nevertheless, plant restoration is not necessarily beneficial to the long-term viability of on- and off-site ecosystems' functions, including natural succession and river ecosystems. Therefore, the selected vegetation types ought to be advantageous for the ecosystem's sustainability, both on- and off-site, such as maintaining river streamflow and unrestricted natural succession. The seed prices of cultivated grass communities of *Deschampsia cespitosa* and *Elymus nutans*, *Poa pratensis L.cv.* Qinghai and *Elymus nutans*, and *Poa pratensis L.cv.* Qinghai and *Deschampsia cespitosa* were about \$690, \$750 and \$480 per ha. Planting properly mixed-cultivated grassland on the alpine degraded hillsides can achieve both environmental and economic benefits. This study proved that mixed-cultivated grasslands could maintain runoff and decrease soil loss.

5 Conclusions

Based on the measured data during 2019, 2020 and 2022 growing seasons, the planting of mixed-cultivated grassland on severely degraded hillside alpine meadow could effectively maintain surface runoff and decrease soil loss, especially after the mixed-cultivated grassland played a positive role in consolidating the surface soil. The mean *CRE* values of the mixed-cultivated grasslands *DE*, *PE*, and *PD* increased from -120.9% to 55.8%, from -112.4% to 59.7%, and from -94.3% to 62.1% from 2019 to 2022, respectively. Planting the mixed-cultivated grasslands after ploughing loosened the soil structure and thus increased sediment concentration in runoff during the first stage after planting. Subsequently, sediment concentration decreased with the growth of the root system of the mixed-cultivated grasslands, strengthening the sloping soils due to the root architecture. To guarantee that they can perform the aforementioned functions, mixed-cultivated grasslands need protection measures in the initial planting stage. Our results also suggested that mixed-cultivated grasslands with complementary morphology and structure and abundant fine root systems were effective in maintaining surface runoff and reducing soil erosion. Precipitation amount, duration, vegetation coverage and maximum 60-minute intensity were the predominant factors affecting surface runoff and soil loss. The erosion resistance contribution of the above-ground community characteristics and below-ground roots along the cultivated time could maintain a relatively high surface runoff and decrease sediment concentration. These findings have potential implications for understanding the contribution of mixed-cultivated grasslands restoration on soil erosion control in the degraded hillsides of alpine areas.

Data availability. All data needed to evaluate the conclusions in the paper are present in the paper.

Author contributions. Yulei Ma: Investigation, Formal analysis, Methodology, Software, Writing - original draft. Yu Liu: Investigation, Methodology, Project administration. Jesús Rodrigo-Comino: Interpretation of data, Writing - review & editing. Manuel López-Vicente: Interpretation of data, Writing - review & editing. Gao-Lin Wu: Conceptualization, Funding acquisition, Supervision, Writing - original draft, review & editing.

Competing interests. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table 1. Results of path analysis of the factors affecting runoff depth.

Influence factor	Direct path coefficient	Indirect path coefficient							Sum of path coefficient
		RI_{60}	ARI	RD	P	VC	LB	Total	
RI_{60}	0.24^{*}		0.25	-0.09	-0.11	0.02	0.00	0.07	0.31
ARI	0.37^{**}	0.16		-0.34	-0.05	0.02	0.02	-0.19	0.18
RD	0.67^{**}	-0.03	-0.18		-0.08	0.03	-0.03	-0.31	0.36
P	-0.18^{**}	0.14	0.10	0.31		0.02	0.00	0.57	0.40
VC	0.29^{**}	0.01	0.03	0.06	-0.01		-0.06	0.03	0.32
LB	-0.12	0.01	-0.09	0.18	0.00	0.15		0.25	0.13

Note: RI_{60} is maximum 60-minute intensity (mm h^{-1}), ARI is average rainfall intensity (mm h^{-1}), RD is rainfall duration (h), P is rainfall amount (mm), VC is vegetation coverage (%), LB is litter biomass (g m^{-2}). * means the correlation is significant at 0.05 significance level, and ** means the correlation is significant at 0.01 significance level.

Table 2. Results of path analysis of the factors affecting soil loss per unit area.

Influence factor	Direct path coefficient	Indirect path coefficient								Sum of path coefficient
		R	RI_{60}	ARI	RD	P	VC	LB	Total	
R	0.60^{**}		-0.12	0.01	-0.10	0.11	0.01	0.01	-0.08	0.52
RI_{60}	-0.29^{**}	0.24		0.02	0.07	0.16	0.00	0.00	0.49	0.20
ARI	0.04	0.13	-0.19		0.21	0.07	0.01	0.02	0.25	0.28
RD	-0.41^{**}	0.15	0.05	-0.02		0.13	0.00	-0.04	0.27	-0.13
P	0.28^{**}	0.24	-0.17	0.01	-0.19		0.00	-0.01	-0.11	0.17
VC	0.03	-0.04	-0.04	0.01	-0.03	0.03		-0.06	-0.12	-0.10
LB	-0.10	-0.01	-0.01	-0.01	-0.16	0.03	0.02		-0.15	-0.25

Note: R is surface runoff (mm), RI_{60} is maximum 60-minute intensity (mm h^{-1}), ARI is average rainfall intensity (mm h^{-1}), RD is rainfall duration (h), P is rainfall amount (mm), VC is vegetation coverage (%), LB is litter biomass (g m^{-2}). ** means the correlation is significant at 0.01 significance level.

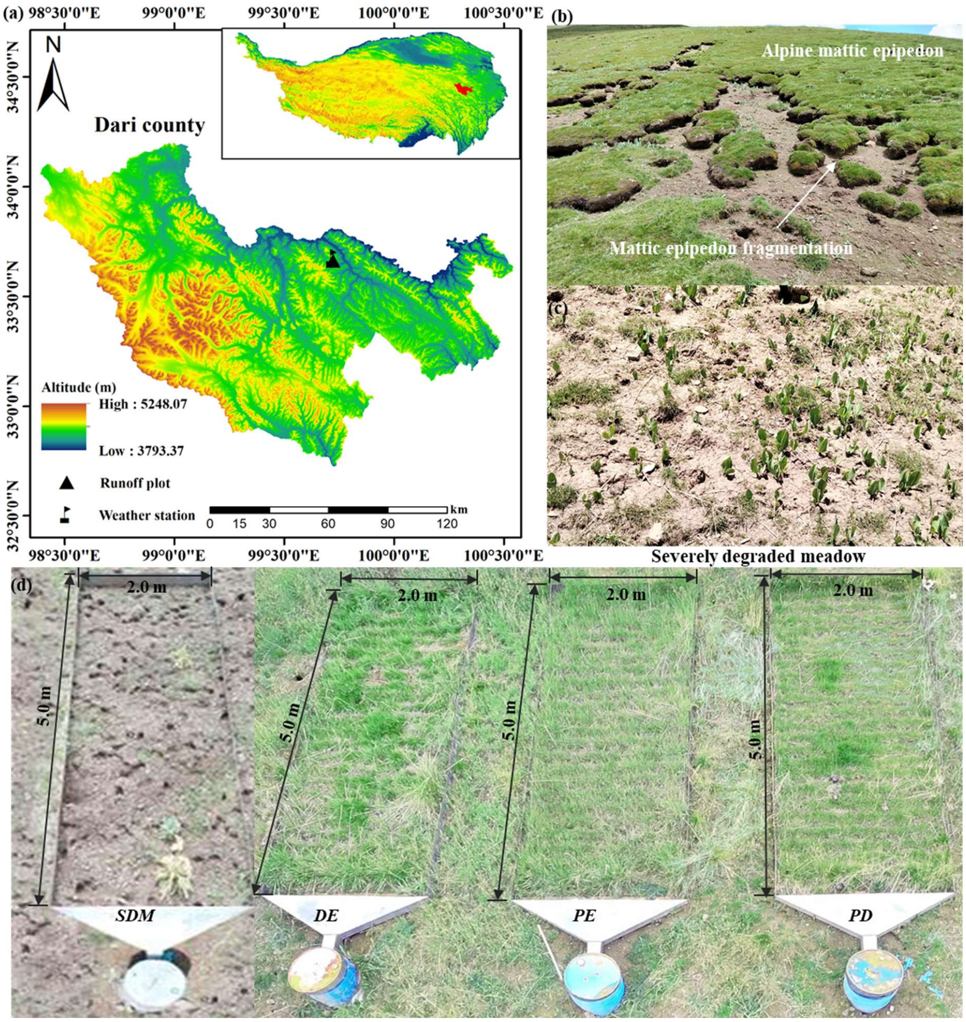

Figure 1. The location of the study area on the Qinghai-Tibetan Plateau, and the location of runoff plots in the study area. (a) The location of the study area, (b) the fragmenting mattic epipedom on the alpine hillslope and (c) severely degraded meadows formed by the disappearance of mattic eppipedom and (d) four runoff plots of severely degraded meadows (*SEM*) and mixed-cultivated grasslands. A typical severely degraded meadow with a slope of 20° was selected to plant mixed grasses. Runoff plots were photographed with a drone in the early stages of the 2022 growing season. *DE*, *Deschampsia cespitosa* and *Elymus nutans*; *PE*, *Poa pratensis L.cv.* Qinghai and *Elymus nutans*; and *PD*, *Poa pratensis L.cv.* Qinghai and *Deschampsia cespitosa*.

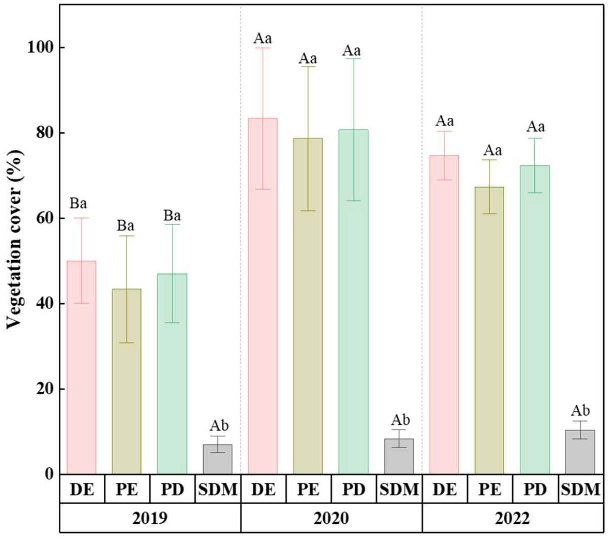

Figure 2. Changes in vegetation cover under various mixed-cultivated grasslands from 2019 to 2022. Different capital letters mean that differences were significant in different years for the same grassland community, and different lowercase letters mean that differences were significant between different communities in the same year.

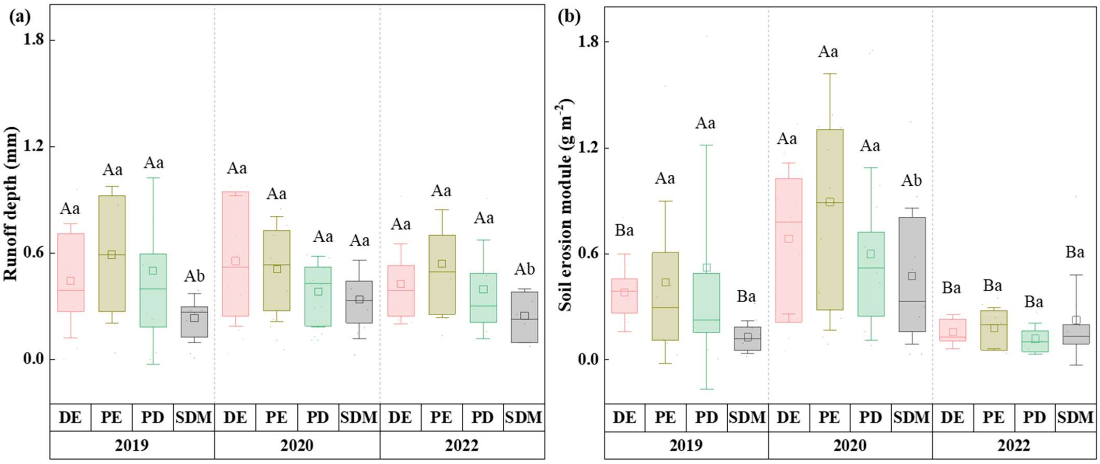

Figure 3. Changes in soil erosion and runoff under various mixed-cultivated grasslands from 2019 to 2022. (a) Runoff depth and (b) soil loss per unit area. Note: For the four treatment runoff plots, runoff and sediment were measured 14, 18, and 10 times, respectively, during the growing season of 2019, 2020, and 2022. Different capital letters mean that differences were significant in different years for the same grassland community, and different lowercase letters mean that differences were significant between different communities in the same year. *SDM*, severely degraded meadows, *DE*, *Deschampsia cespitosa* and *Elymus nutans*; *PE*, *Poa pratensis L.cv.* Qinghai and *Elymus nutans*; and *PD*, *Poa pratensis L.cv.* Qinghai and *Deschampsia cespitosa*. The lines in the middle of the box represent the median values. The squares in the box represent the average value.

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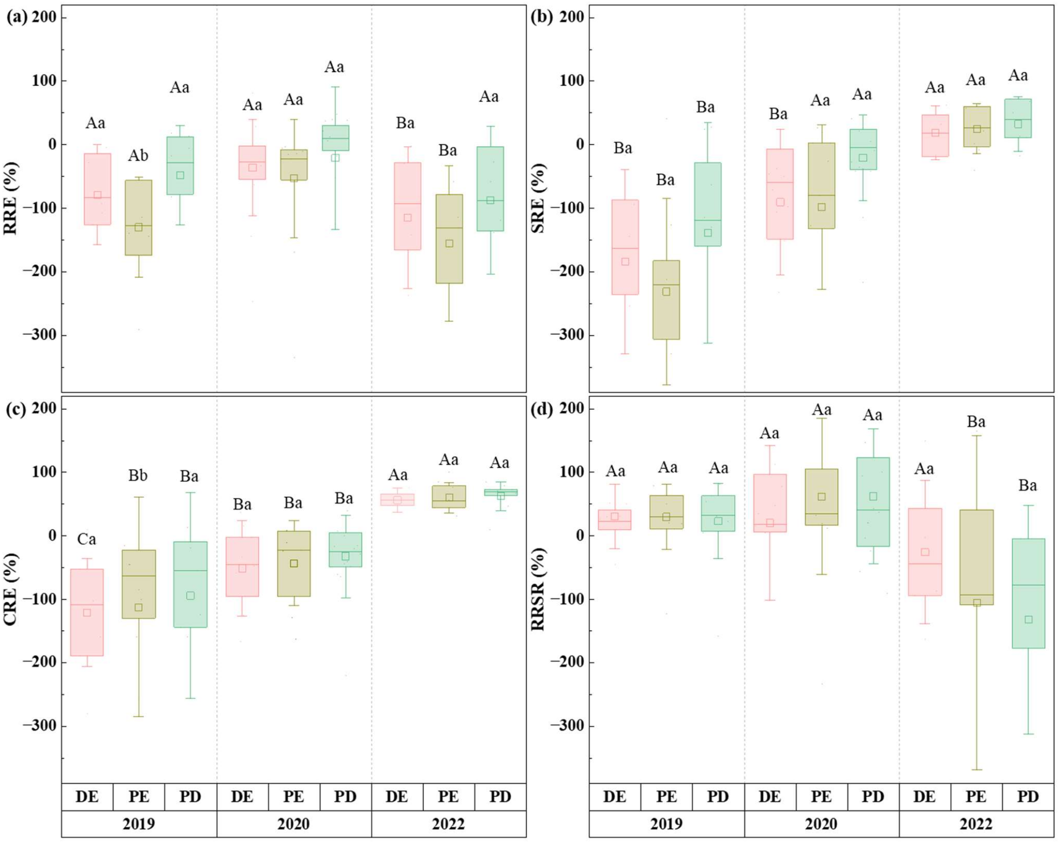

649 **Figure 4.** Runoff, soil loss and sediment concentration reduction ratio under different mixed-cultivated grasslands from 2019 to 2022. (a) Runoff reduction ratio (*RRE*), (b) soil loss reduction ratio (*SRE*), (c) sediment concentration reduction ratio (*CRE*) and (d) the percent of runoff reduction ratio to soil loss reduction ratio (*RRSR*). Note: Different capital letters mean that differences were significant in different years for the same grassland community, and different lowercase letters mean that differences were significant between different communities in the same year.

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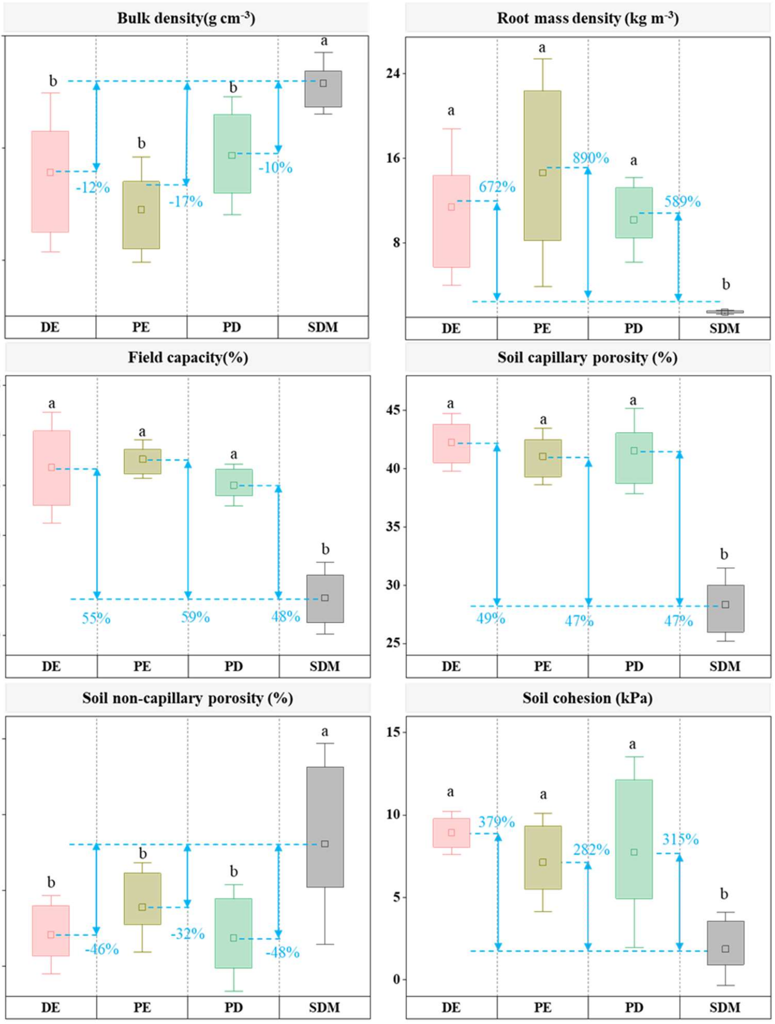

Figure 5. Changes in bulk density, root mass density, field capacity, capillary capacity, non-capillary porosity and soil cohesion in 0-10 cm soil layer when severely degraded meadow (*SDM*) were restored to mixed-cultivated grassland for 4 years. *DE*, *Deschampsia cespitosa* and *Elymus nutans*; *PE*, *Poa pratensis L.cv.* Qinghai and *Elymus nutans*; and *PD*, *Poa pratensis L.cv.* Qinghai and *Deschampsia cespitosa*. Percentages represent the increased rate of soil properties (increased rate = (V_{DE} or V_{PE} or V_{PD} – V_{SDM})/V_{SDM}), where V_{SDM}, V_{DE}, V_{PE} and V_{PD} are the mean values of soil characteristics of *SDM, DE*, *PE* and *PD*. The squares in the box represent the average value. Different lowercase letters mean that differences were significant between different communities.