Mixed-cultivated grasslands enhance runoff generation and reduce soil loss in the restoration of degraded alpine 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 grassland restoration on maintaining local runoff, especially, in alpine degraded hillsides where mixed-cultivated grasslands predominate. In this research, runoff plots were established to investigate the impact of three mixed-cultivated grasslands, each sowing two grass species per plot: *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*); on a 20-degree slope, assessing the activation and volume of surface runoff and the magnitude of soil loss in alpine degraded hillsides over three years: 2019, 2020 and 2022. A severely degraded meadow (*SDM*) plot was used as control. The findings indicated that mixed-cultivated grasslands can effectively maintain runoff and reduce soil loss as planting age increases. Between 2019 and 2022, the values of the average runoff depth for *DE*, *PE*, *PD* and *SDM* were 0.47, 0.55, 0.45 and 0.27 mm, respectively. Despite the increase in runoff, grassland restoration favored soil conservation: the net soil loss per unit area of *SDM* was 1.4, 1.3 and 1.9 times greater than that in *DE*, *PE* and *PD*, respectively. 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. To improve the effectiveness of grassland restoration, we suggest that protective measures should be prioritized during the initial planting stage of cultivated grasslands.

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

1 Introduction

Grasslands are an essential component of terrestrial ecosystems and 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 –5% of them undergoing severe degradation (based on net primary productivity)–, and this issue has become a major concern for landscape conservation (Gang et al., 2014; Török et al., 2021). Global grassland net primary productivity (NPP) has declined by 58.84 Tg C per year. Grassland degradation causes the loss of up to 90% of the soil structure that facilitates water movement (infiltration) and retention (water-holding capacity) in soils (Wick et al., 2016), reduces carbon storage potential (Liebig et al., 2013), and impedes soil functioning. Moreover, degraded grasslands are prone to severe soil erosion, especially in mountainous areas. For example, in the Swiss alpine uplands, water erosion ranges from 0.14 to 1.25 t ha^{-1} $month^{-1}$ according to the phenological stage of the grasses (Schmidt et al., 2019); and in the gully slope of the Loess Plateau, the average amount of soil erosion was 306.7 t ha^{-1} $month^{-1}$ during the 2018–2020 grass growing season (Zhu et al., 2021).

Precipitation is the main water source of soil moisture supply in semi-arid areas and the conversion of precipitation to runoff is one of the major contributors to river streamflow (Leung et al. 2015; Li et al., 2024). In some previous experiences, it was observed that vegetation restoration reduced surface runoff and decreased sediment production, which led to lower river levels, threatening the health of river ecosystems (Dijk et al., 2007). A recent study conducted by Wu et al. (2020) proposed sustainable management strategies for semi-arid areas with a positive trade-off between surface runoff maintenance and erosion control. However, very few studies have addressed to date the effects of restored grasslands in maintaining surface runoff and preventing soil erosion

(Minea et al., 2022). This topic 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 generation 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; Vanacker et al., 2022). 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 –also known as stormwater runoff or overland flow– 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 intensity, the soil hydrological properties, such as (non-)saturated hydraulic conductivity, matrix flux potential and field capacity, and initial soil water content (López-Vicente and Navas, 2012; Gyssels et al., 2005; De Baets et al., 2007). Because runoff is the primary driver of water erosion on hillslopes and serves as the main agent for sediment transport, reducing the conversion of rainfall to runoff is regarded as an effective way to control water erosion, through vegetation restoration (Zhou et al., 2016; Zhu et al., 2021). On the other hand, in arid and semi-arid regions, surface runoff is the major water supply source to the river streamflow, thereby it is vital for ensuring the sustainability of ecosystems and human activities (Liu et al., 2020; Robinson et al., 2003). Therefore, restoration efforts in areas with low rainfall should be oriented 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; Durán Zuazo and Rodríguez Pleguezuelo, 2008; Gyssels and Poesen, 2003; Wen et al., 2024). Grasslands can control water erosion relying on the role of 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 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 soil 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 (De Baets et al., 2007; Bochet et al., 2006).

Alpine meadows, especially in the Qinghai-Tibetan Plateau, constitute the predominant ecosystem in China and the world, accounting for 44% and 6% of total grassland areas, respectively (Wang et al., 2016). Over 50% of the alpine meadows have been subject to an increasing degree of degradation (Bardgett et al., 2021), with the extent of degradation depending on the meadow patch coverage resulting from the fragmentation of alpine meadows (Fig. 1b). Severely degraded meadows (also known as "black beach" and "black soil-type degraded meadow") formed after the mattic epipedon, typically 10 to 15 cm deep, was fully removed by overgrazing and rodent activity exposing the sub-soil (Fig. 1c; Ma et al., 2023; Shang et al., 2008). Severely degraded meadows amounted to about 30% of the total area of alpine meadows on the Qinghai-Tibetan Plateau (Shang et al., 2008). Recent studies by Niu et al. (2021) and Ma et al. (2024) have observed that fragmentation of alpine meadows and severely degraded meadows could reduce surface runoff and enhance soil erosion.

The Qinghai-Tibetan Plateau serves as the headwaters for many of Asia's major rivers (Xu, 2018). The eastern and southern parts of the Qinghai-Tibet Plateau are influenced by the monsoon, and rainfall is the primary source of streamflow (Cuo et al., 2014). The long-term and widespread degradation of hillside alpine meadows has disrupted the soil water balance, reducing surface runoff (Niu et al., 2019; Ma et al., 2024). 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 (Li et al., 2018; Wu et al., 2010). Artificial grassland –also known as tamed grassland, sowed grassland and cultivated grassland– refers to fields that have been broken up and replanted with exotic grasses and forbs and utilized for hay crop production or cattle grazing (Fisher et al., 2018). 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 studies have often focused on carbon sequestration capacity, vegetation characteristics, soil quality and productivity of cultivated grassland (Wang et al., 2013; Bai and Cotrufo et al., 2022), there has 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. Recently, Liu et al. (2022) evaluated the effects of plant morphological characteristics on runoff and soil erosion in different mixed-cultivated grassland under natural rainfall events. Here, we present novel research to examine the ability of cultivated grasslands to regulate runoff and soil loss and evaluate the effect of three different mixed-cultivated grasslands: *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*), compared to a severely degraded meadow (*SDM*) 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. This study has realistic implications for understanding the contribution of mixed-cultivated grasslands restoration on soil erosion control in degraded alpine hillsides.

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 the typical four-season pattern (spring, summer, autumn, winter), but rather just two main seasons: cold and warm. In the study region, the average annual temperature is -3.1 °C, with monthly variations from -14.7 °C in January to 7.5 °C in July (values corresponded to the period 1981-2018; data source: European Centre for Medium-Range Weather Forecasts). The average annual precipitation is 416 mm, with the majority of it falling from July to September, based on Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS). 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 plants. The soil type in the study area is classified as Mat Cryi-gelic Cambisols (IUSS-WRB, 2015). 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 is severe, becoming the primary source of sediment delivered to streams in the study area (Liu et al., 2022). The mattic epipedon of alpine meadow has experienced fragmentation and even disappearance (Fig. 1b), eventually forming a severely degraded meadow (Fig. 1c). Before implementing the grassland restoration project, i.e., Subsidy and Incentive System for Grassland Conservation, the average soil erosion rate and the total erosion in the study area were 13.63 t ha^{-1} y^{-1} and 323.58 × 10^{6} t y^{-1}, respectively (Zhao et al., 2021). Severely degraded meadows were restored via mixed-cultivated grasslands –fields were ploughed and replanted with two grass species– and moderately degraded meadows were restored by broadcast sowing on the hillslopes during the implementation of the 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., 2008).

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 not only must it be grazing-tolerant and good forage, but also prevent soil loss and maintain surface runoff. Potential grass species should also be fully acclimated to harsh alpine climate and have complementary morphological characteristics and living 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 an herbaceous perennial species with erect or geniculate base culms that grow 20–60 cm tall.

To reveal the effects 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™ weather station (Davis Instruments Corp., USA) with a measurement accuracy of 4% was 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 during the growing season (from June 15 to August 25). Precipitation characteristics of each event, including amount (*P*), duration (*RD*), and maximum intensities of 60 minutes (RI_{60}) were recorded. Average rainfall intensity (*ARI*) was calculated by dividing the total rainfall amount by the duration of the rainfall event. 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 filter paper with a pore size of 30–50 μm. 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:

$$R = \frac{V_R}{A} \times 10^3 \quad (1)$$

$$S = \frac{S_T}{A} \quad (2)$$

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*), including dead (standing litter) and living vegetation, 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 were 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*, %), non-capillary porosity (*NCP*, %), and soil water content at 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 steel ring (g), *ds* is the soil particle density (generally being 2.65 g cm^{-3}), and *V* is the volume of the 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 was obtained by the Mohr–Coulomb theory (Labuz and Zang, 2012).

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 benefit (*RRB*, %), sediment concentration reduction benefit (*CRB*, %), soil erosion reduction benefit (*SRB*, %), and the percentage of runoff reduction ratio to soil loss reduction ratio (*RRSR*) (Zhao et al., 2014). High values of *RRB*, *SRB* or *CRB* 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:

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

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

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

$$RRSR = \frac{RRB}{SRB} \times 100 \tag{11}$$

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

All data were analyzed using SPSS statistics software (IBM, USA, version 26.0). 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 Mixed-cultivated grasslands modified runoff amount and soil loss

Mixed-cultivated grasslands 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 three evaluated growing seasons (2019, 2020 and 2022), the average runoff depth for *DE*, *PE*, *PD* and *SDM* was 0.47, 0.55, 0.45 and 0.27 mm, respectively. The average runoff depths of *SDM* in 2019, 2020, and 2022 were 0.23, 0.34 and 0.25 mm, respectively, all significantly ($p < 0.05$) lower than (except for 2020) the average runoff of mixed-cultivated grassland *DE PE* and *PD*, which measured 0.44, 0.59 and 0.50 mm in 2019, 0.55, 0.51 and 0.38 mm in 2020, 0.43, 0.54 and 0.40 mm in 2022 (Fig. 3a). Regarding soil conservation, the amount of soil loss in grasslands was significantly influenced by planting age. As depicted in Fig. 3b, soil loss in *DE*, *PE* and *PD* (except for *DE* in 2019) were significantly ($p < 0.05$) higher in 2019 and 2020 (the first and second years of planting) than those in the fourth year of planting (2022). In 2020, soil loss produced by *DE*, *PE*, and *PD* was significantly higher ($p < 0.05$) than that of *SDM*. Satisfactorily, the three mixed-cultivated grasslands did exhibit a clear reduction in soil loss compared to *SDM* in 2022 (albeit not significantly), with soil loss per unit area for *SDM* being 1.4, 1.3 and 1.9 times higher than those for *DE*, *PE* and *PD*, respectively. No significant difference ($p > 0.05$) was observed in runoff depth and soil loss between *DE PE* and *PD* in 2019, 2020 and 2022. The results showed that any of the three mixed-cultivated grasslands (*DE*, *PE* and *PD*) could be effective in controlling soil loss and maintaining runoff.

3.2 Specific runoff and soil loss reduction ratios of the cultivated grasslands

Fig. 4 illustrates the runoff, soil loss and sediment concentration reduction ratio after planting various mixed-cultivated grasslands. Lower *RRB* values indicated a better ability to maintain runoff for mixed-cultivated grasslands, while higher *SRB* and *CRB* values indicated better effectiveness of grasslands in soil loss reduction. The mean *RRB* 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, respectively (Fig. 4a). Regardless of the combination of the above-mentioned grass species, the average increase ratio of runoff in 2022 (the fourth years of planting) was significantly ($p < 0.05$) higher than that in 2019 and 2020 (the first and second years of planting). The *SRB* of the three mixed-cultivated grasslands (*DE*, *PE* and *PD*) increased with increasing planting age. It is worth noting that the average *SRB* values in the grassland communities of *DE*, *PE* and *PD* were 18.0%, 24.3% and 31.9% in 2022, respectively (Fig. 4b). The *SRE* values of *DE*, *PE* and *PD* in 2022 were significantly ($p < 0.05$) higher than those of 2019, whereas *SRE* values between 2020 and 2022 was significant ($p < 0.05$) for *DE* but not ($p > 0.05$) for *PE* and *PD*. Additionally, *CRB* for all mixed-cultivated grasslands in 2022 was significantly ($p < 0.05$) higher than that in 2019 and 2020. The mean *CRB* 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). No significant differences ($p > 0.05$) appeared in *RRB*, *SRB*, *CRB* and *RRSR* between *DE PE* and *PD* in 2019, 2020 and 2022.

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 amount, 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*. 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 Benefits 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 some previous studies (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.

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 seeding method of plowing led to a disruption of soil structure, resulting in increased soil loss in the three mixed-cultivated grasslands during the initial stages of 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 vegetation 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 (*VC*) as well (Mohamadi and Kavian, 2015; 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 indicated that rainfall amount (*P*) could have an indirect effect on surface runoff through rainfall duration (*RD*) and maximum intensities of 60 minutes (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 runoff depth (*R*) and the average rainfall intensity (*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, litter biomass (*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 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.

Grass combinations with different morphological characteristics can effectively reduce soil loss (Liu et al., 2022). In this study, the reduction in soil loss in the early stages of mixed-cultivated grassland planting (2019 and 2020) was attributed to grassland cover and plant morphological characteristics. *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.

4.3 Implications for grasslands restoration on degraded alpine hillsides

Our findings demonstrated that mixed-cultivated grasslands with complementing morphological features and habits can be 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. However, at the start of planting, the mixed planted grassland had a greater soil erosion than the severely degraded meadow, whereas soil loss was reduced 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 increases turbidity of rivers (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 conducted and 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, respectively, in Xining, Qinghai Province, in 2019. 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 the 2019, 2020 and 2022 growing seasons, the planting of mixed-cultivated grassland on severely degraded hillside alpine meadow effectively maintained surface runoff and decreased soil loss, especially after the mixed-cultivated grassland played a positive role in consolidating the soil surface. The benefits were statistically significant compared with the control plot, but differences between the three types of cultivated grasslands were not significant. 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, improving root-soil cohesion due to the root architecture. To guarantee that mixed-cultivated grasslands can perform the aforementioned functions, protective measures should be implemented during the initial planting stage to support their healthy growth. Our results also suggested that mixed-cultivated grasslands with different but complementary morphology and structure and abundant fine root systems were effective in maintaining surface runoff and reducing soil erosion. Precipitation amount, duration, maximum 60-minute intensity, vegetation coverage and composition 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. The data that support the findings of this study are available on request from the corresponding author.

Author contributions. Yulei Ma: Investigation, Formal analysis, Methodology, Software, Writing - original draft. Yifan Liu: Investigation, Formal analysis, Writing - review & editing. 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.

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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.

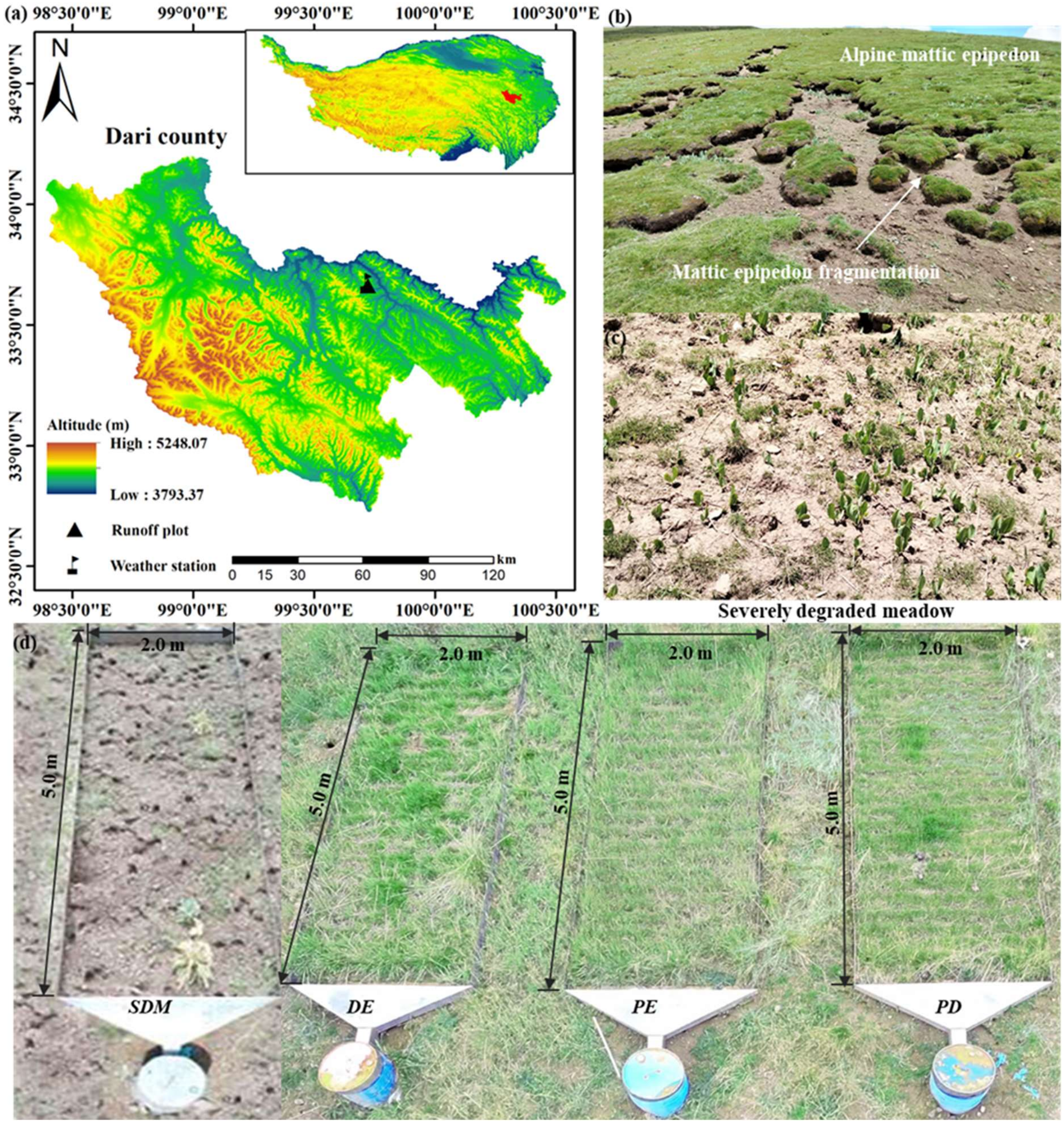

Figure 1. The location of the study area on the Qinghai-Tibetan Plateau, and the location of runoff plots in the study area. (a) The location of the study area, (b) the fragmenting mattic epipedon on the alpine hillslope and (c) severely degraded meadows formed by the disappearance of mattic eppipedon and (d) four runoff plots of severely degraded meadows (*SDM*) 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*.

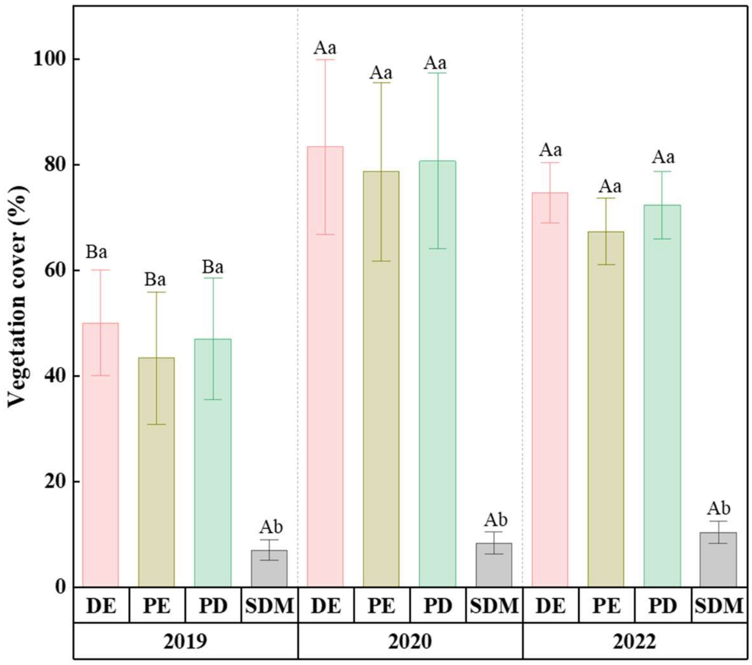

Figure 2. Changes in vegetation cover under various mixed-cultivated grasslands from 2019 to 2022. Different capital letters mean that differences were significant in different years for the same grassland community, and different lowercase letters mean that differences were significant between different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

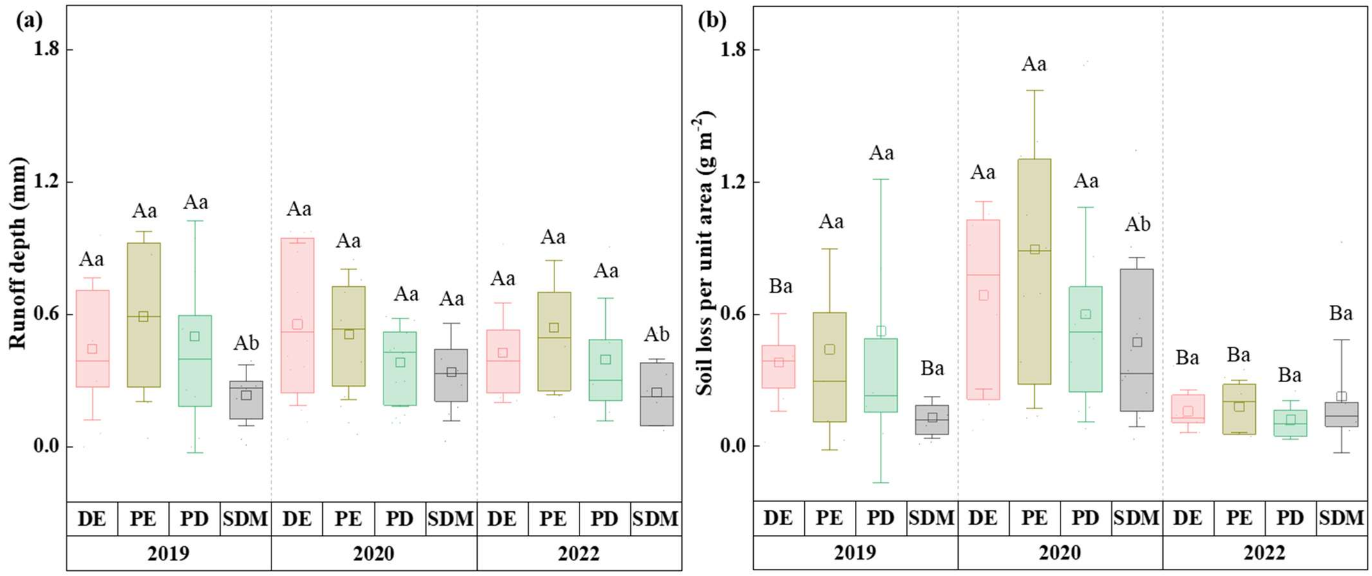

Figure 3. Changes in soil erosion and runoff under various mixed-cultivated grasslands from 2019 to 2022. (a) Runoff depth and (b) soil loss per unit area. Note: For the four treatment runoff plots, runoff and sediment were measured 14, 18, and 10 times, respectively, during the growing season of 2019, 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.

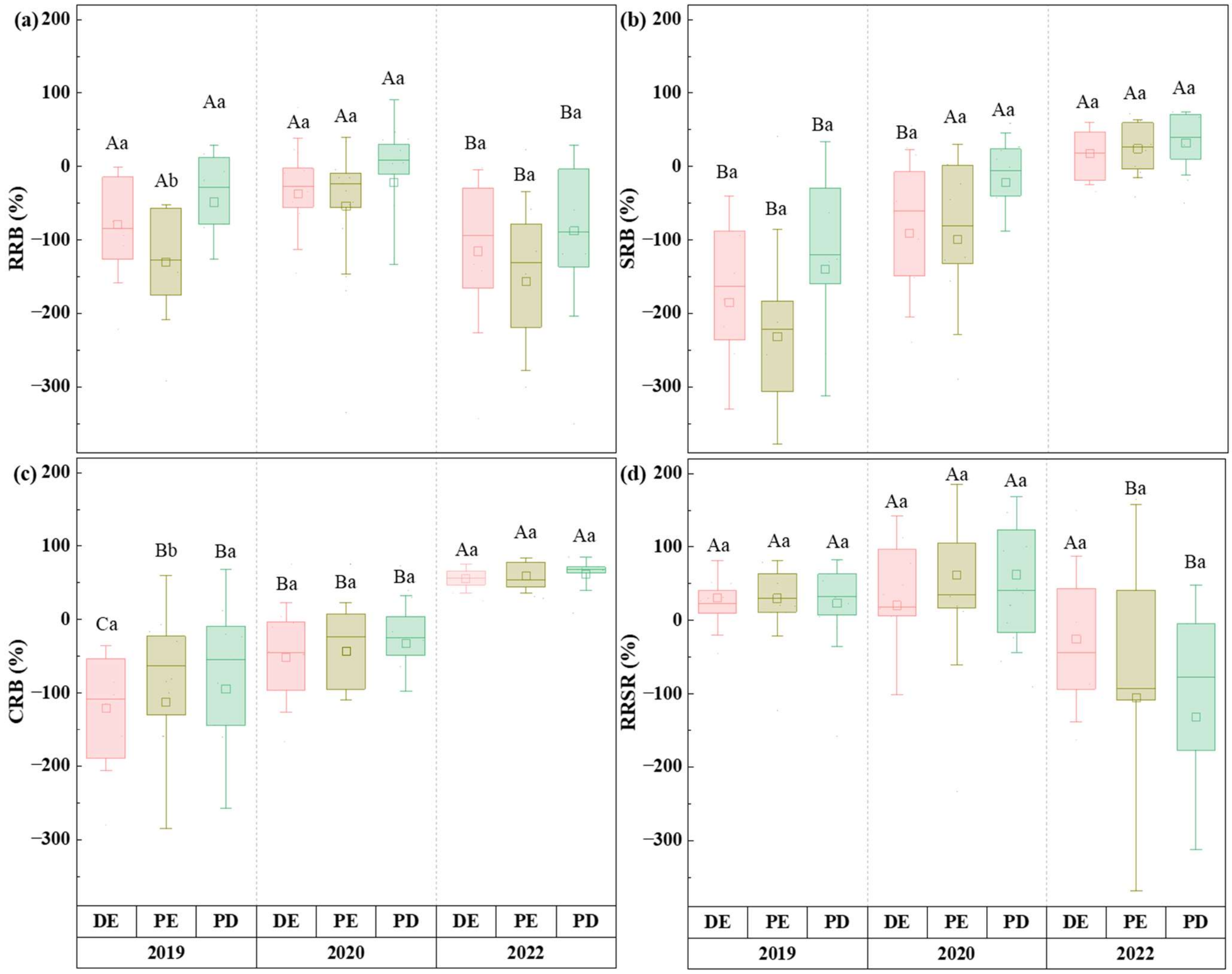

Figure 4. Runoff, soil loss and sediment concentration reduction ratio under different mixed-cultivated grasslands from 2019 to 2022. (a) Runoff reduction ratio (*RRB*), (b) soil loss reduction ratio (*SRB*), (c) sediment concentration reduction ratio (*CRB*) and (d) the percent of runoff reduction ratio 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. The lines in the middle of the box represent the median values. The squares in the box represent the average value.

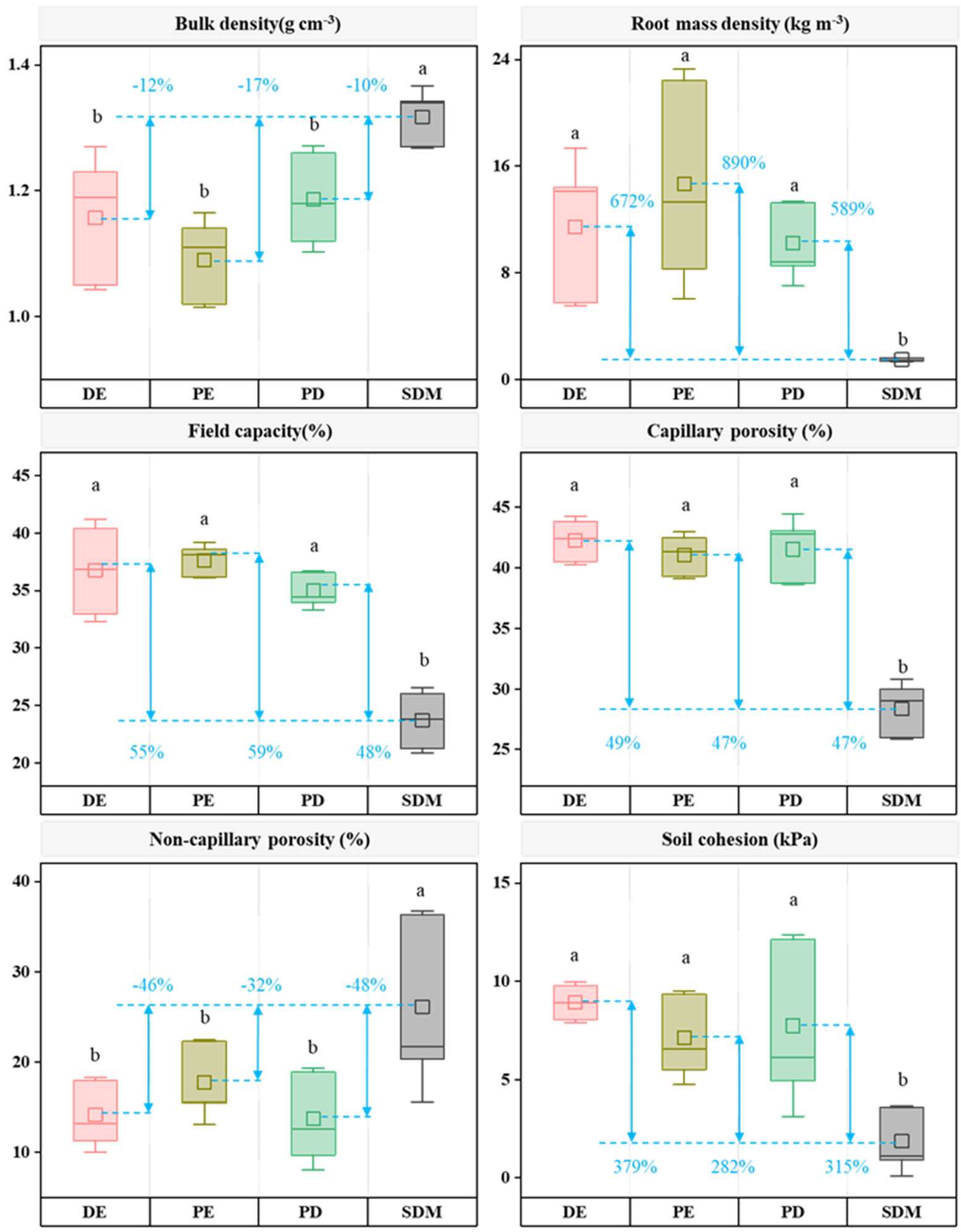

Figure 5. Changes in bulk density, root mass density, field capacity, capillary capacity, non-capillary porosity and soil cohesion in 0-10 cm soil layer when severely degraded meadow (*SDM*) were restored to mixed-cultivated grassland for 4 years. *DE*, *Deschampsia cespitosa* and *Elymus nutans*; *PE*, *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*. Different lowercase letters mean that differences were significant between different communities. The lines in the middle of the box represent the median values. The squares in the box represent the average value.