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Mixed-cultivation 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 activities. Nevertheless, few studies have been undertaken to analyze the effects of grassland restoration on maintaining local runoff, especially on alpine degraded hillsides where mixed-cultivation grasslands predominate. In this research, runoff plots were established to investigate the impact of three mixed-cultivation grasslands, each sowing two grass species per plot on a 20° slope: *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*). The activation and volume of surface runoff and the magnitude of soil loss on alpine degraded hillsides over 3 years (2019, 2020, and 2022) were assessed. A severely degraded meadow (SDM) plot was used as a control. The findings indicated that mixed-cultivation 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 losses per unit area of SDM were 1.4, 1.3, and 1.9 times greater than those 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 formulate efficient policy decisions for planning the most effective vegetation restoration in 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.

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, with 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 $\mathrm{Tg\,C\,yr^{-1}}$. Grassland degradation causes a loss of up to 90 % of the soil structure, which facilitates water movement (infiltration) and retention (water-holding capacity) in soils (Wick et al.,

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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 $1.25\,\mathrm{t\,ha^{-1}}$ per month 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 $306.7\,\mathrm{t\,ha^{-1}}$ per month during the 2018–2020 grass growing season (Zhu et al., 2021).

Precipitation is the main water source of soil moisture supply in semiarid 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 studies, it was observed that vegetation restoration reduced surface runoff and decreased sediment production, which led to lower river levels and threatened the health of river ecosystems (Dijk and Keenan, 2007). A recent study conducted by Wu et al. (2020) proposed sustainable management strategies for semiarid areas, with a positive tradeoff between surface runoff maintenance and erosion control. However, to date very few studies have addressed 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 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 cover, aboveground biomass, litter biomass, and root systems (Liu et al., 2022a; 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 soil properties interlinked above 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 has the potential to be a key method of environmental restoration under human management, inappropriate selection of species can negatively impact the sustainability of local economic and environmental development (Huang et al., 2017, 2019). For example, cultivated grasslands have already been advocated as a sensible solution for the conservation of soil and water as well as the regrowth of vegetation in semiarid mountain areas (Liu et al., 2022a; 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 storm water runoff or overland flow – reaches the stream in the forms of sheet, rill, and gully flows (Rumynin, 2015). The conversion of rainfall to overland flow depends on the rainfall intensity, the soil hydrological properties (e.g., (non)saturated hydraulic conductivity, matrix flux potential, and field capacity), and the 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 of controlling water erosion through vegetation restoration (Zhou et al., 2016; Zhu et al., 2021). On the other hand, in arid and semiarid regions, surface runoff is the major water supply source to the river streamflow, so 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 aboveground and belowground biomasses 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 reliance on the roles of the aboveground biomass in dissipating flow energy (Bochet and García-Fayos, 2004), living roots in a 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., 2022b). 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 impacts of grass roots on the soil characteristics can be summarized as follows: (i) increasing the stability of soil aggregates by aggregating fine soil particles into macroaggregates; (ii) enhancing soil cohesion by interweaving with the soil; and (iii) decreasing soil bulk density by increasing soil porosity (Wu et al., 2019; Gyssels et al., 2005). For example, numerous recent studies have confirmed that a grass with a 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 on 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 alpine meadows have been subject to an increasing degree of degradation (Bardgett et al., 2021), with the extent of

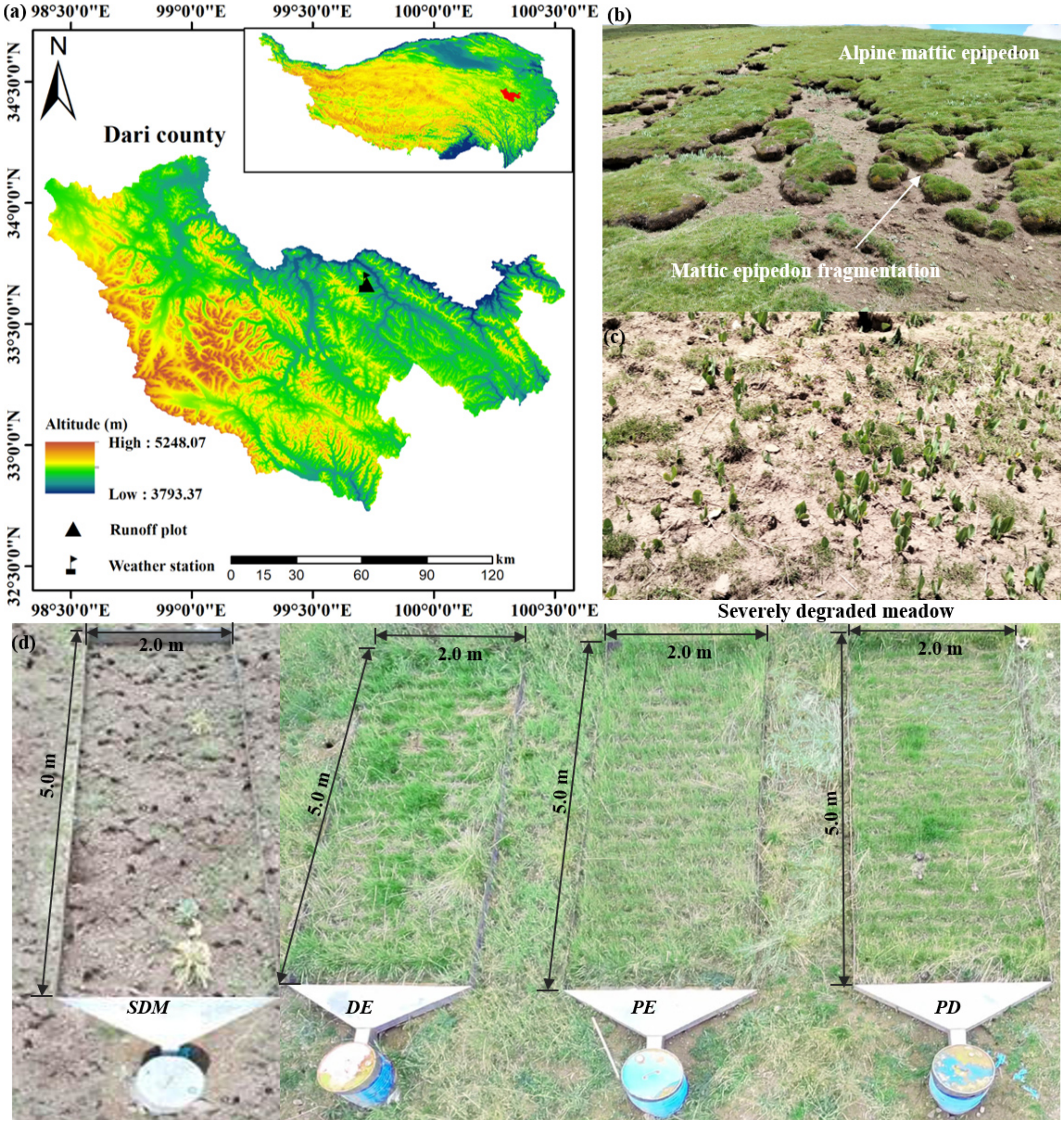

Figure 1. The location of the study area on the Qinghai–Tibetan Plateau and the locations of runoff plots in the study area. **(a)** The location of the study area, **(b)** the fragmenting mattic epipedon on the alpine hillslope, **(c)** severely degraded meadow (SDM) formed by the disappearance of the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

degradation depending on the meadow patch cover 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 activities exposing the subsoil (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) 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 headwater for many of Asia's major rivers (Xu, 2018). The eastern and southern parts of the Qinghai–Tibetan 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., 2021; 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 meadows 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 in 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., 2022a).

While previous studies have often focused on the carbon sequestration capacity, vegetation characteristics, soil quality, and productivity of cultivated grasslands (Wang et al., 2013a; Bai and Cotrufo, 2022), there has been limited examination of the impacts of mixed-cultivation grasslands on the provision of runoff and prevention of soil erosion on alpine hillsides. Recently, Liu et al. (2022a) evaluated the effects of plant morphological characteristics on runoff and soil erosion in different mixed-cultivation grasslands during natural rainfall events. Here, we presented novel research to examine the ability of cultivated grasslands to regulate runoff and soil loss and to evaluate the effect of three different mixed-cultivation 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*). These are compared to a severely degraded meadow (SDM) using a 3-year field experiment. In particular, this study aimed (1) to 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) to determine the key factors influencing the mixed-cultivation grasslands in controlling runoff and soil erosion. This study has realistic implications for understanding the contribution of mixed-cultivation grassland restoration to soil erosion control on 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 with low temperatures throughout the year, i.e., not showing the typical four-season pattern (spring, summer, fall, and 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 (CHIRPS) data. The majority of the precipitation in 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 at this site is composed of 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, having become the primary source of sediment delivered to streams in the study area (Liu et al., 2022a). The mattic epipedon of alpine meadow has experienced fragmentation and even disappearance (Fig. 1b), eventually forming a severely degraded meadow (Fig. 1c). Before the implementation of the grassland restoration project, i.e., the Subsidy and Incentive System for Grassland Conservation, the average soil erosion rate and the total erosion in the study area were 13.63 $t\,ha^{-1}\,yr^{-1}$ and $323.58 \times 10^6\,t\,yr^{-1}$, respectively (Zhao et al., 2021). Severely degraded meadows were restored via mixed-cultivation grasslands – fields were plowed 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 rhizomes, e.g., *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 components of runoff generation and confluence areas on the Qinghai–Tibetan Plateau. Hence, the grass species chosen for mixed-cultivation grasslands must not only be grazing-tolerant and have good forage, but they must also prevent soil loss and maintain surface runoff. Potential grass species should also be fully acclimated to harsh alpine climates and have complementary morphological characteristics and living habits (Liu et al., 2022a). The community established by matching of grass morphological characteristics and habits has a hierarchical vertical cover structure and little interspecific or intraspecific competition. Following the abovementioned 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 (up to 30–50 cm tall) of very thin (0.5 cm wide), arching, flat to inrolled, dark-green grass blades (up to 5 cm long). *Deschampsia cespitosa*, a common bottom grass, has 70 % of its stems growing between 0 and 30 cm. *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., 2022a). *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 effects of mixed-cultivation grasslands in controlling runoff and soil loss on hillsides, field observation of mixed grass plots designed by us was conducted for the 2019 to 2022 growing seasons. Therefore, one plot with SDM as a control and three plots with two mixed grass seeds per plot (*Deschampsia cespitosa* and *Elymus nutans – DE*; *Poa pratensis* L. cv. Qinghai and *Elymus nutans – PE*; *Poa pratensis* L. cv. Qinghai and *Deschampsia cespitosa – PD*) were selected as the testing sites (Fig. 1d). All four runoff plots were spaced 1 m apart and were located on the same hillside with the same elevation and soil texture. All the 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 placed 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 a 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 at 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). Precipitation events were 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 seasons. Snow was not collected, and only rainfall was recorded during the growing seasons (from 15 June to 25 August). Precipitation characteristics of each event, including amount (P), duration (RD), and maximum intensities of 60 min (RI$_{60}$), were recorded. The 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 measured first to calculate the runoff volume. Then, the runoff was fully mixed inside the calibrated tank using a stirring bar to thoroughly whirl it, 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 the soil loss amount to the runoff volume in the mixed samples was applied to calculate the sediment concentration. Finally, the runoff volume and sediment concentration were multiplied to calculate the 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) can 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 the runoff plots (m^2).

2.4 Vegetation and soil property measurement

Vegetation cover (VC), including dead (standing litter) and living vegetation, was measured monthly from the 2019 to 2022 growing seasons using a steel-wire frame

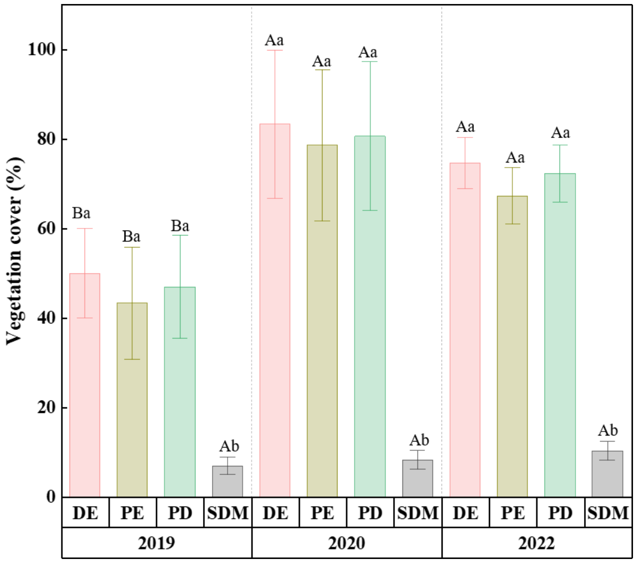

Figure 2. Changes in vegetation cover in various mixed-cultivation grasslands from 2019 to 2022. Different capital letters mean that differences were significant in different years for the same grassland community, and different lowercase letters mean that differences were significant between different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

(50 cm × 50 cm) subdivided into 25 plots of 10 cm × 10 cm. Figure 2 shows the changes in vegetation cover for all runoff plots from 2019 to 2022. After collecting runoff samples each year, the quadrants (50 cm × 50 cm) were positioned in the upslope, mid-slope, and downslope 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-cultivation grasslands in May 2019, and the litter collection for 2020 and 2021 was done 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}). The saturated soil samples were placed on the dry sand layer to drain water for about 2 and 8 h and then weighed ($W_{2\,h}$ and $W_{8\,h}$). Finally, the soil samples were dried in an oven at 105 °C for 24 h and then weighed (W_{dr}). Based on the above measurements, 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:

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

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

$$\mathrm{TP} = \left(1 - \frac{\mathrm{BD}}{d_s}\right) \times 100, \tag{5}$$

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

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

where W_{sr} is the weight of the steel ring (g), d_s is the soil particle density (generally 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 quadrant 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 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-cultivation grasslands in regulating runoff and soil loss, i.e., the runoff reduction benefit (RRB, %), sediment concentration reduction benefit (CRB, %), soil erosion reduction benefit (SRB, %), and percentage of runoff reduction 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:

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

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

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

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

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

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 the data. Duncan's multi-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

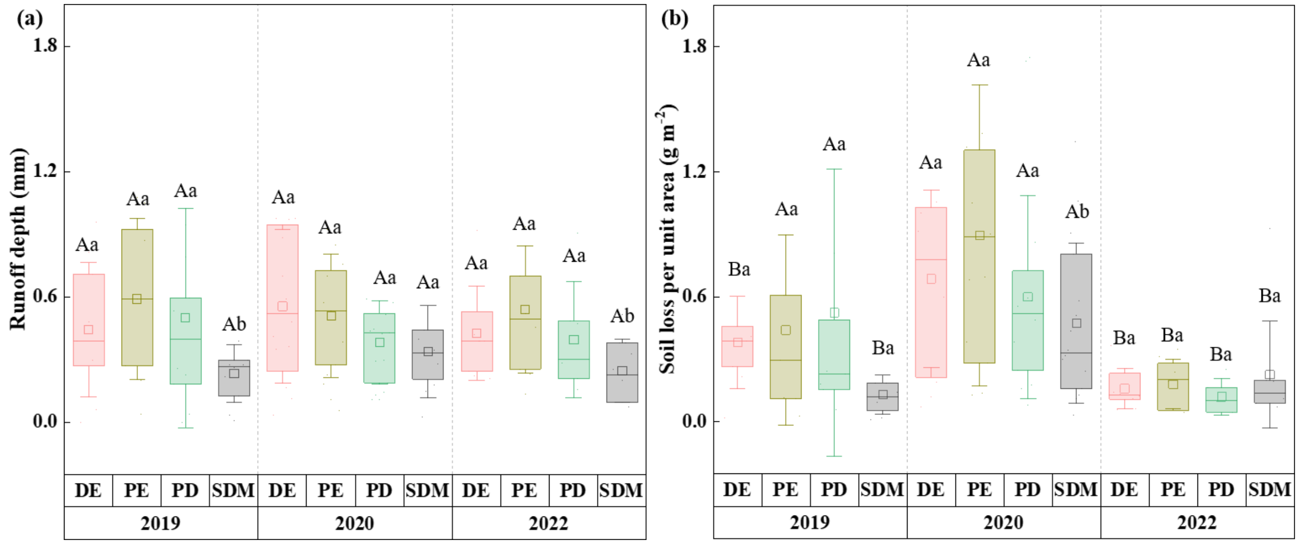

Figure 3. Changes in soil erosion and runoff in various mixed-cultivation grasslands from 2019 to 2022. **(a)** Runoff depth and **(b)** soil loss per unit area. Note: for the four treatment runoff plots, runoff and sediment were measured 14, 18, and 10 times, respectively, during the growing seasons 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 for SDM, *DE*, *PE*, and *PD*. The lines in the middle of the box represent the median values. The squares in the box represent the average values.

the runoff and soil loss reduction ratio in various mixed-cultivation grasslands at 0.05 significance levels. Also, path analysis is a form of multi-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-cultivation grasslands modified runoff amounts and soil losses

Mixed-cultivation grasslands increased runoff and reduced soil erosion. One-way ANOVA revealed that runoff significantly ($p < 0.05$) increased after the severely degraded alpine hillside was restored by the mixed-cultivation grassland (Fig. 3). During the three evaluated growing seasons (2019, 2020, and 2022), the average runoff depths for *DE*, *PE*, *PD*, and SDM were 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-cultivation 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; and 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 the planting age. As depicted in Fig. 3b, soil losses 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 losses produced by *DE*, *PE*, and *PD* were significantly higher ($p < 0.05$) than those of SDM. Satisfactorily, the three mixed-cultivation grasslands did exhibit a clear reduction in soil loss compared to SDM in 2022 (albeit not significantly), with soil losses 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-cultivation 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

Figure 4 illustrates the runoff, soil loss, and sediment concentration reduction ratio after planting various mixed-cultivation grasslands. Lower RRB values indicated a better ability to maintain runoff for mixed-cultivation grasslands, while higher SRB and CRB values indicated better effectiveness of grasslands in soil loss reduction. The mean RRB values of the grassland communities *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

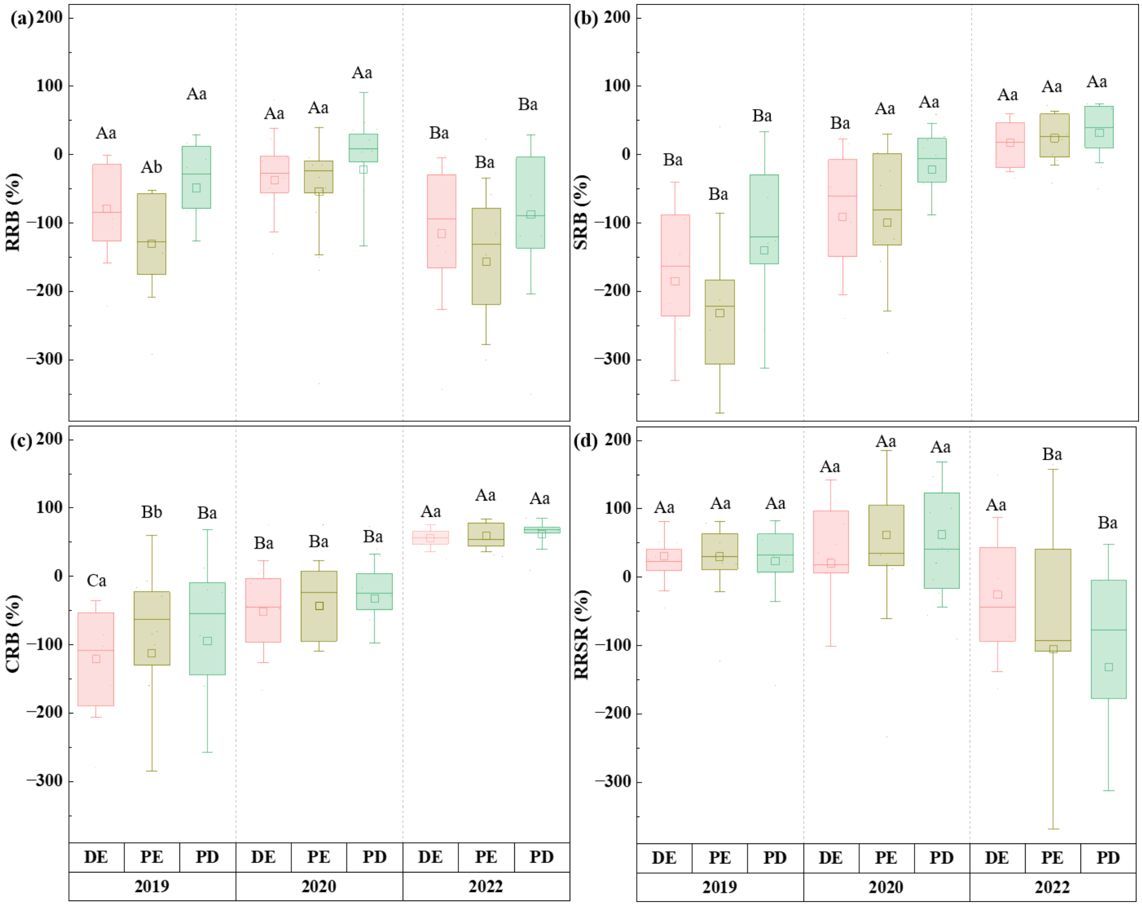

Figure 4. Runoff, soil loss, and sediment concentration reduction ratio in different mixed-cultivation grasslands from 2019 to 2022. **(a)** Runoff reduction ratio (RRB), **(b)** soil loss reduction ratio (SRB), **(c)** sediment concentration reduction ratio (CRB), and **(d)** percent of runoff reduction 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 values.

the combination of the abovementioned grass species, the average increase ratio of runoff in 2022 (the fourth year of planting) was significantly ($p < 0.05$) higher than those in 2019 and 2020 (the first and second years of planting). The SRB of the three mixed-cultivation 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 %, respectively, in 2022 (Fig. 4b). The *SRB* values of *DE*, *PE*, and *PD* in 2022 were significantly ($p < 0.05$) higher than those of 2019, whereas the *SRE* values between 2020 and 2022 were significant ($p < 0.05$) for *DE* but not ($p > 0.05$) for *PE* and *PD*. Additionally, the CRB for all mixed-cultivation grasslands in 2022 was significantly ($p < 0.05$) higher than those 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 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 the runoff amount, with *P* being the most influential factor. Direct influences on runoff were primarily attributed to the ARI and RD, with direct path coefficients of 0.37 and 0.67, respectively. Meanwhile, the influences of *P* and LB on runoff

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[a]		0.25	−0.09	−0.11	0.02	0.00	0.07	0.31
ARI	0.37[b]	0.16		−0.34	−0.05	0.02	0.02	−0.19	0.18
RD	0.67[b]	−0.03	−0.18		−0.08	0.03	−0.03	−0.31	0.36
P	−0.18[b]	0.14	0.10	0.31		0.02	0.00	0.57	0.40
VC	0.29[b]	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 the maximum 60 min intensity ($mm\,h^{-1}$), ARI is the average rainfall intensity ($mm\,h^{-1}$), RD is the rainfall duration (h), P is the rainfall amount (mm), VC is the vegetation cover (%), and LB is the litter biomass ($g\,m^{-2}$). [a] means the correlation is significant at the 0.05 significance level, and [b] means the correlation is significant at the 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 the surface runoff (mm), RI_{60} is the maximum 60 min intensity ($mm\,h^{-1}$), ARI is the average rainfall intensity ($mm\,h^{-1}$), RD is the rainfall duration (h), P is the rainfall amount (mm), VC is the vegetation cover (%), and LB is the litter biomass ($g\,m^{-2}$). * means the correlation is significant at the 0.01 significance level.

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 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 on soil loss, 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-cultivation grasslands for soil conservation and runoff maintenance

The mixed-cultivation 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, 2022a). In this study, the mixed-cultivation grasslands significantly increased surface runoff compared to the SDM. The difference in runoff between mixed-cultivation grasslands and SDM may be attributed to the soil infiltration rate. Mixed-cultivation 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 pores (Leung et al., 2015). In comparison to SDM, the soil NCP and 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-cultivation grasslands with lower permeability and better water retention.

Soil loss in all three mixed-cultivation grassland communities (*DE*, *PE*, and *PD*) was higher than that in the SDM during the first and second years following planting. How-

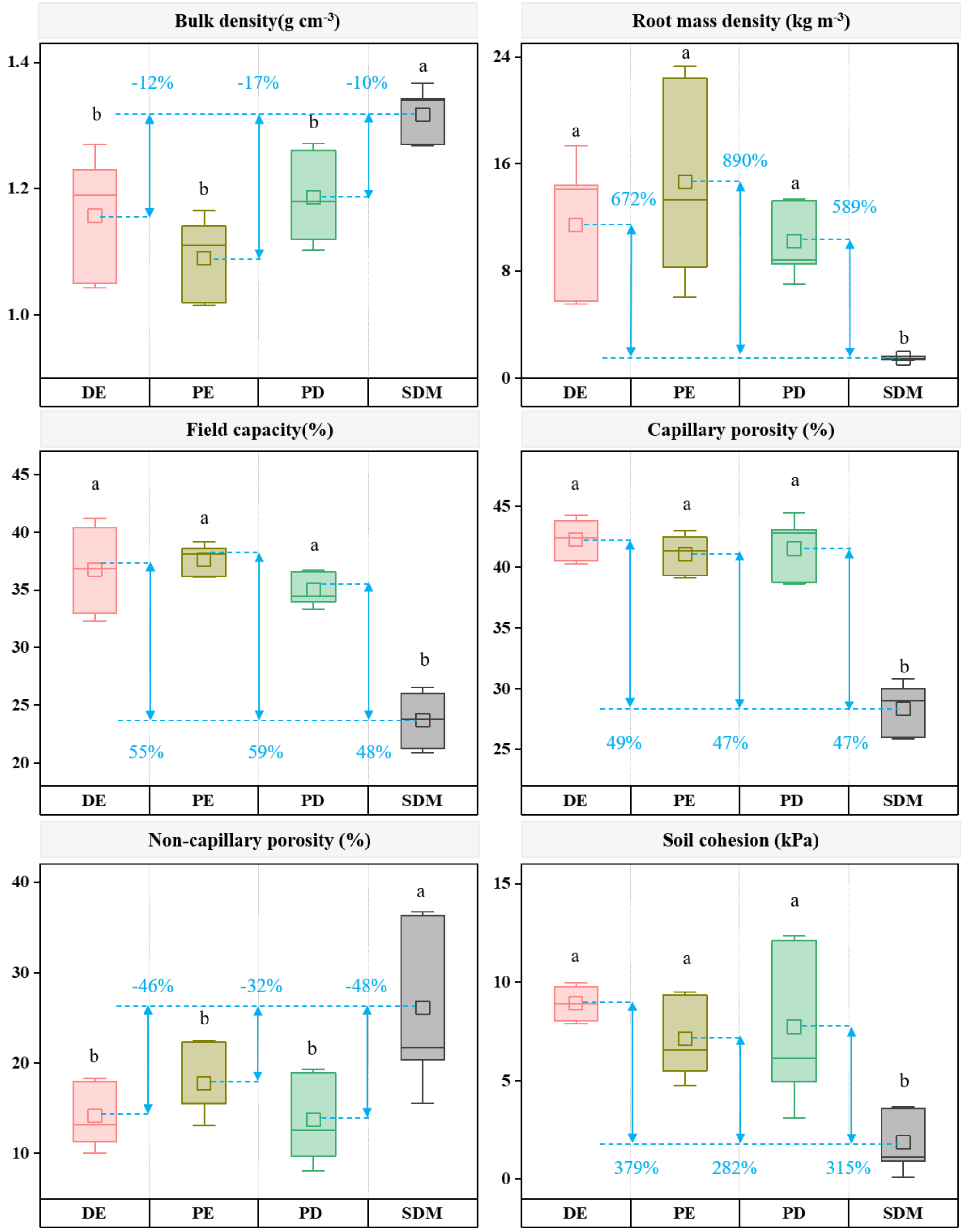

Figure 5. Changes in bulk density, root mass density, field capacity, capillary capacity, non-capillary porosity, and soil cohesion in the 0–10 cm soil layer when SDM was restored to mixed-cultivation grassland for 4 years for *DE*, *PE*, and *PD*. Percentages represent the increased rate of soil properties (increased rate = (V_{DE} or V_{PE} or $V_{\mathrm{PD}} - V_{\mathrm{SDM}}$)/$V_{\mathrm{SDM}}$), 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 values.

ever, by the fourth year, the SDM exhibited higher soil loss than the three mixed-cultivation grasslands (Fig. 3). These changes in soil erosion were predominantly attributed to the development of the root system and the improvement of the soil structure (Zhu et al., 2021). The seeding method of plowing led to a disruption of the soil structure, resulting in increased soil loss in the three mixed-cultivation grasslands during the initial stages of planting. We confirmed that the mixed-cultivation grassland age was a key factor in understanding the interannual changes in soil erosion. This idea was also demonstrated in other types of primary land uses, e.g., 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 Fig. 5. In comparison to the 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 Effects of rainfall and vegetation characteristics on runoff and soil loss

Surface runoff and erosion processes are influenced and constrained by rainfall depth, intensity, and duration as well as by VC (Mohamadi and Kavian, 2015; Bochet et al., 2006). In this study, VC had a directly posiitive 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 cover. Our results also indicated that rainfall amount (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 causes of this are runoff velocity increases with higher precipitation intensities (Wang et al., 2013b), 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 LB increased. Liu et al. (2022b) found that the soil loss rate decreased with increasing litter biomass in grasslands. 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., 2022a). In this study, the reduction in soil loss in the early stages of mixed-cultivation 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, rhizomatic sparse clump, and sparse clump perennial grasses, respectively. In addition, *Deschampsia cespitosa* and *Poa pratensis* L. cv. Qinghai are bottom grasses, while *Elymus nutans* is a top grass. The mix of dense and sparse grasses (*DE* and *PD*) and the 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., 2022a). *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-cultivation grasslands reduced the runoff velocity, influenced the water infiltration process, and decreased the soil erodibility.

4.3 Implications for grassland restoration on degraded alpine hillsides

Our findings demonstrated that mixed-cultivation grasslands with complementary morphological features and habits can be effective in maintaining runoff and reducing soil erosion. Three mixed-cultivation 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 greater soil erosion than the severely degraded meadow, whereas soil loss was reduced in the fourth 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 on alpine hillsides (Liu et al., 2022a). Moreover, grass may also be planted with a no-till system to avoid the initial increase in soil erosion in 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 the 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 on meltwater erosion (Liu et al., 2022a). 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 ecosystems' 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 USD 690, USD 750, and USD 480 ha^{-1}, respectively, in Xining, Qinghai Province, in 2019. Planting proper mixed-cultivation grassland on alpine degraded hillsides can achieve both environmental and economic benefits. This study proved that mixed-cultivation grasslands can 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-cultivation grasslands in severely degraded hillside alpine meadows effectively maintained surface runoff and decreased soil loss, especially after the mixed-cultivation 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-cultivation grasslands after plowing loosened the soil structure and thus increased the sediment concentration in runoff during the first stage after planting. Subsequently, sediment concentration decreased with the growth of the root system of the mixed-cultivation grasslands, improving root–soil cohesion due to the root architecture. To guarantee that mixed-cultivation 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-cultivation grasslands with different but complementary morphologies and structures and abundant fine-root systems were effective in maintaining surface runoff and reducing soil erosion. Precipitation amount, duration, maximum 60 min intensity, vegetation cover, and composition were the predominant factors affecting surface runoff and soil loss. The erosion resistance contribution of the aboveground community characteristics and belowground roots during the cultivation time could maintain a relatively high surface runoff and decrease the sediment concentration. These findings have potential implications for understanding the contribution of mixed-cultivation grassland restoration to soil erosion control on 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. YM: investigation; formal analysis; methodology; software; writing – original draft. YL: investigation; formal analysis; writing – review and editing. JRC: interpretation of data; writing – review and editing. MLV: interpretation of data; writing – review and editing. GLW: conceptualization; funding acquisition; supervision; writing – original draft, review, and editing.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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