Catena 208 (2022) 105771

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Understory shading exacerbated grassland soil erosion by changing community composition

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ARTICLE INFO

Keywords:
Forest-grassland complex ecosystem
Species richness
Soil erosion
Understory grassland
Vegetation restoration

ABSTRACT

The importance of understory herbs for soil erosion controlling in forests is well accepted, but its effectiveness was rarely reported. Understanding how understory shading affects herbs growth and soil erosion controlling benefits is essential for better policy management. Here, we investigated grassland characteristics and soil erosion process before and after grasslands placed beneath the forest canopies. Four typical grasslands (*Trifolium repens*, *Medicago sativa*, *Elymus dahuricus* and *Bromus inermis*) of the Loess Plateau were selected, and bare land was used as the control. Total fifteen plots (three replicates for each treatment) with a slope of 20° were constructed. All plots were placed outdoor (open areas) in the first year, and were moved to the undergrowth and remained in the *Sophora japonica* and *Populus cathayana* forests over the next five years. Time to runoff, runoff volume and sediment yield were examined by two simulated rainfall experiments before and after understory shading. Results showed that understory shading promoted the disappearance of the original grass species, increasing weeds with poor roots. Further, these changes led to more soil loss in all understory grassland treatments. After understory shading, the runoff volume (67.0–125.5 L) and biological soil crust coverage (1.0–15.7%) significantly decreased for all plots, whereas the sediment yield (5.0–1650.5 g), species richness (>5) and litter mass (75.8–241.0 g) significantly increased. Therefore, understory shading changed the community composition and structure of understory grasslands. Besides, we found that herb species difference, but not species richness difference, more determined understory soil erodibility. Our findings indicate that the shade-tolerant herb species application could effectively reduce soil erosion in forest-grassland complex ecosystem will help to achieve the sustainability of understory grassland during vegetation restoration.

1. Introduction

The importance of understory vegetation in forests for controlling soil erosion is now well recognized (Wang et al., 2016; López-Vicente et al., 2017). Although the canopy and the leaves of the forests intercept most of the rainfall, the remaining rain splash in artificial forests with the absence of understory vegetation may form the larger and higher kinetic energy drops, and result in more soil detachment (Geißler et al., 2012; Goebes et al., 2015). The understory grassland vegetation could effectively weaken the rain splash effects (Cerdà et al., 2018; Neyret et al., 2020). The presence of plant litter and understory vegetation increased the flow resistance and retarded the flow velocities, which were generally more effective in soil erosion controlling than forest canopy cover (Li et al., 2015). Moreover, the rainfall penetrating from forest canopy without undergrowth interception suggests increase retention of precipitation and promotes rainfall infiltration, but the canopy rainfall interception and stemflow were often used more rapidly than the throughfall during the rainy season. As a result, the forests actually decreased the surface runoff and shallow groundwater supplement.

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https://doi.org/10.1016/j.catena.2021.105771
Received 5 March 2021; Received in revised form 15 August 2021; Accepted 26 September 2021
Available online 6 October 2021
0341-8162/

However, the intensive afforestation activities in semi-arid regions caused soil water deficit even the dried soil layers and the death of some vegetation. All these may lead to the failure of large-scale afforestation from the ecologically sustainable perspective (Cao, 2008; Cao et al., 2011; Wu et al., 2020). Previous studies have reported that grassland is effective in sediment reduction and runoff maintenance to optimize the balance between soil erosion controlling and surface water resources in semi-arid regions (Liu et al., 2020; Wu et al., 2020). Therefore, developing forest-grassland complexed ecosystem might be a feasible strategy to control soil erosion and maintain the sustainability of existing vegetation in semi-arid regions under ongoing and future global climate change. But in fact, the understory vegetation is excessively sparse for many artificial forests in semi-arid regions, because the high density afforestation followed the excessive soil water consumption and the higher canopy density. The deeply rooted woody vegetation transpires large quantities of water, lowering the water table, even led to soil water deficit, which might be the key restricting the success of understory vegetation (Normile, 2007; Asner et al., 2008; Cao et al., 2009, 2010). In addition, light environment is a also key determinant of vegetation pattern and ecosystem processes, and is highly spatial-variable (Martens et al., 2000). Low light levels and thick litter layers may affect the growth of understory grassland community (Brantley and Young, 2007; Seitz et al., 2016).

Therefore, it is necessary to examine whether understory shading promotes (or inhibits) the growth of understory grasslands, thus to evaluate its effectiveness of understory grasslands on soil and water conservation. Previous reports involving forests are generally in field experiments, even if forest canopy were cutting off to examine the effects of understory grassland on soil erosion controlling, the effectiveness of understory grassland on soil and water conservation cannot be truly quantified due to the remaining influences by forest roots.

In this study, we investigated the grassland community characteristics and the hydrological response of four typical grasslands under simulated rainfall experiments before and after understory shading (Fig. 1). The main objective was to explore whether understory shading could change the community composition and structure of typical grasslands, and to quantify the effectiveness of understory grasslands on soil erosion controlling before and after understory shading. This study has realistic implications for understanding the effectiveness of understory grasslands on soil and water conservation and offer a theoretical guidance for selecting suitable understory herb species to develop the forest-grassland complex ecosystem during vegetation restoration.

2. Method

2.1. Site description and experiment setup

The experiments were conducted in the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau in Yangling, Shaanxi Province, China (107°59′-108°08′ E, 34°14′-34°20′ N). This site is located in the Loess Plateau and the climate ranges between semi-arid and semi-humid. Over the past years (1954–1980), the annual mean temperature, precipitation and evapotranspiration is 12.9 °C, 635.1 mm and 993.2 mm, respectively.

A total of 15 plots were established in the spring of 2013. Four typical grasses were planted, *Medicago sativa* (*M. sativa*), *Trifolium repens* (*T. repens*), *Elymus dahuricus* (*E. dahuricus*), and *Bromus inermis* (*B. inermis*). Bare land was set as the control treatment. Each treatment included three replicate plots. Each steel plot (length: 1.1 m × width: 0.8 m × depth: 0.25 m) moved freely with four wheels, and the ground surface was set at the critical slope of 20°, to simulate the erosion slope in the local field (Tang et al., 1998). A metal runoff collector was set at the bottom of the plot to direct runoff into a container. Apertures were formed at the bottom of each plot to allow soil water to freely infiltrate. Grasses were planted following a row spacing of 20 cm. The original soil corresponds to the typical loessial loam soil of the Loess Plateau region. Before filling the plots, soil was thoroughly mixed after passing through a 10-mm sieve, and then was packed in each plot in two 10-cm layers at a bulk density of 1.35 g cm^{-3}. In order to obtain representative and comparable results, all plots were placed in outdoor (open areas) to

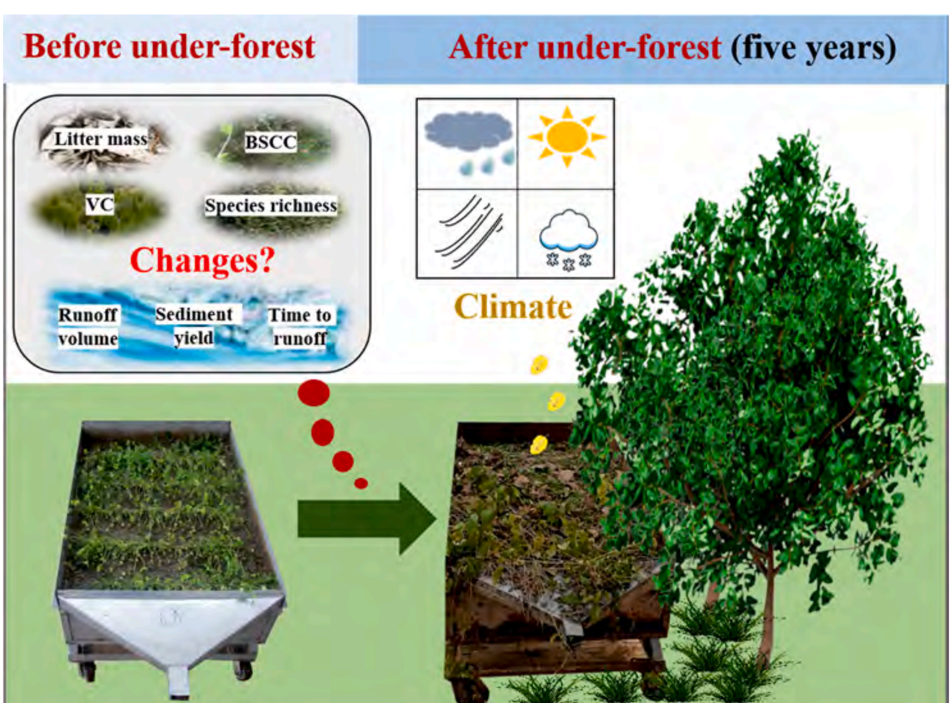

Fig. 1. The experiment design of this study. All plots were placed in outdoor (open areas) for one year to examine grassland community composition and erosion parameters before under-forest. After the rainfall experiment, all plots were placed in the undergrowth and remained in the forest for five years to examine grassland community composition and erosion parameters after under-forest.

ensure that plant growth was completely depended on rainfall without other outside interference.

2.2. Experiment methods

One year later, a simulated rainfall experiment with a side-sprinkle precipitation set-up system was carried out to examine grassland community composition and structure and erosion parameters before understory shading. The side-sprinkle precipitation set-up system could precisely control rainfall intensity by adjusting the nozzle size and water pressure (Pan and Shangguan, 2006). All rainfall simulations used deionized water in a water tank prepared by reverse osmosis (Bohl Bormann et al. 2010). The height of the rainfall simulator was up to 16 m, the simulated storm was of above 85% uniformity, the raindrop distribution and size could be controlled by varying the type of needles and their receptacles. The raindrop diameter, mean velocity and mean rainfall kinetic energy per unit time per unit area was 0.5–2 mm, 4.78 m s^{-1} and 0.2193 J m^{-2} s^{-1}, respectively. The rainfall intensities calibrations were conducted before the experiments and the differences from the target intensities never exceeded 10% (Liu et al., 2019).

After the rainfall experiment, all plots were moved to the undergrowth and remained in the forests without any human interference. Forests were mainly composed by *Sophora japonica* and *Populus cathayana*. The tree height and tree density are about 20–30 m and 40 ha^{-1}, respectively. Five years later, all plots were moved indoor to conduct the simulated rainfall experiment to examine grassland community composition and structure and erosion parameters after understory shading. The specific experiment design was shown in Fig. 1.

One day before each rainfall experiment, soil water content was measured with a specialized soil auger of 1-cm diameter and soil water content was adjusted to 15% gravimetrically with a commonly used household sprayer for all plots (Pan and Shangguan, 2006). Since the common storms intensity that causes serious soil erosion in the Loess Plateau generally ranges between 100 and 150 mm h^{-1} (Zhou and Wang, 1992; Tang, 2004), the simulated rainfall intensity was set at 120 mm h^{-1}, and each rainfall experiment was lasted 120 min. Before each rainfall experiment, we used a digital camera to take photos (perpendicular to the ground) that were used to calculate the understory grassland coverage and biological soil crust coverage. The computation procedure was done by using Photoshop CS 3.0™ and Image-J™ software package and the approach proposed by Huang et al. (2013a, b). During each rainfall event, the time to runoff was determined by staining technique. The runoff and sediments produced every five minutes were collected in plastic buckets. The volume of clear water after settling was regarded as the runoff amount. The soil in the bucket after drying at 105 °C was regarded as the sediment yield. The litter layer of all plots was collected and dried at 75 °C to determine litter mass.

2.3. Data analysis

We used independent Mann-Whitney *U* test to compare the differences in understory grassland coverage, biological soil crust coverage, litter mass, species richness, time to runoff, runoff volume and sediment yield among different treatments. The differences in understory grassland coverage, biological soil crust coverage, litter mass, species richness, time to runoff, runoff volume and sediment yield before and after understory shading were detected using a paired-samples *t*-test. Covariance analysis was performed to test the interaction between all variables and treatments on soil erosion after understory shading. To avoid the interference of different treatments, we proposed the use of partial correlation analysis to identify the relationships among understory grassland coverage, biological soil crust coverage, litter mass, species richness, time to runoff, runoff volume and sediment yield after understory shading. Moreover, we tested for correlations between soil erosion variables (runoff volume, sediment yield, and time to runoff), other characteristic variables (understory grassland coverage, biological soil crust coverage, litter mass, and species richness), and their interactions by the redundancy analysis (RDA), using the community ecology package vegan for C or R (Oksanen et al., 2007).

3. Results

The *t*-test results showed that the understory grassland vegetation coverage, biological soil crust coverage, litter mass, species richness, time to runoff, runoff volume and sediment yield of most treatments presented significant differences before and after under-forest (Table 1). Before under-forest, species richness of all understory grassland plots was very low (species richness = 1; Fig. 2). The grassland coverage of all plots was 0–87.5%. There was no surface litter in all plots, but the biological soil crust coverage were high (litter mass = 0; biological soil crust coverage = 15.0–87.5%). After under-forest, original grassland species of each plot decreased or even disappeared, weed species appeared –mainly included *Rubia cordifolia*, *Conyza sumatrensis*, *Lysimachia christinae*, *Youngia Japonica*, *Stellaria media*, *Cyperus rotundus*, *Ophiopogon bodinieri*, and *Senecio scandens*. The total species richness increased (species richness > 5). The *M. sativa* plots and bare land plots showed the lower coverage comparing with other plots. The biological soil crust coverage in all plots were decreased, but the surface litter were increased (litter mass = 75.8–241.0 g; biological soil crust coverage = 1.0–15.7%).

Regarding soil erosion processes (Fig. 3), the time to runoff get faster for all plots before under-forest (time to runoff = 16.5–85.5 s). And the runoff volume and sediment yield ranges were 133.0–174.4 L and 1.37–108.6 g, respectively. *M. sativa* plots and bare land plots showed the highest sediment yield. The time to runoff generation increased (time to runoff = 129.3–342.2 s), and runoff volume markedly decreased (67.0–125.5 L) after under-forest. However, the sediment yield (5.0–1650.5 g) and runoff turbidity increased. The covariance analysis showed that different treatments had interactions with time to runoff, vegetation coverage, biological soil crust coverage and species richness, which significantly affected soil erosion (Table 2). The results of partial correlation showed that there was a significant correlation between species richness and sediment yield after removing the effects of treatment (Table 3).

We conducted the RDA to determine the correlations between the soil erosion variables, other characteristic variables, and their interactions (Fig. 4). Time to runoff, on the negative side of axis 1, was significantly positively correlated with the interaction between vegetation coverage and plant litter, and significantly negatively correlated with biological soil crust coverage. Runoff volume, on the positive side of axis 1, was significantly positively correlated with biological soil crust coverage, and significantly negatively correlated with the interaction between vegetation coverage and litter. Sediment yield, on the positive side of axis 2, was significantly positively correlated with interaction between species richness and litter, and significantly negatively correlated with understory grassland vegetation coverage.

4. Discussion

Contrary to our expectations, understory shading also inhibited the growth of typical grasslands, just as native species in some areas were invaded by forests or shrubs (Normile, 2007; Asner et al., 2008; Cao et al., 2009, 2010). The microclimate change produced by forest canopy can greatly change the community composition and biomass yield of the understory grasslands (Morecroft et al., 1998; Benavides et al., 2009; Barnes et al., 2011; Alonso et al., 2020). The light environment is a key factor in determining the understory vegetation pattern, and its spatial variation perhaps leads to changes in understory grassland community composition (Martens et al., 2000). Modification of the light availability due to shading after under-forest, coupled with heavy litter, may exclude the potential competitors of the original herb species during the new forb species establishment, favoring the rapid change of the

Table 1
Paired-samples *t*-test results of the runoff volume, sediment yield, time to runoff, vegetation coverage, biological soil crust coverage, litter mass and species richness of all treatments before and after under-forest, respectively.

		Trifolium repens	*Medicago sativa*	*Elymus dahuricus*	*Bromus inermis*	Bare land
Runoff volume	Df	2	2	2	2	2
	P-value	0.054	**0.002****	0.086	**0.003****	0.173
Sediment yield	Df	2	2	2	2	2
	P-value	0.067	0.130	0.051	**0.015***	0.224
Time to runoff	Df	2	2	2	2	2
	P-value	0.321	0.065	0.176	**0.000*****	**0.027***
Vegetation coverage	Df	2	2	2	2	2
	P-value	**0.000*****	0.223	0.219	0.117	**0.013***
Biological soil crust coverage	Df	2	2	2	2	2
	P-value	**0.009****	0.394	0.134	**0.002****	0.056
Litter mass	Df	2	2	2	2	2
	P-value	**0.007****	**0.004****	**0.015***	0.098	**0.014***
Species richness	Df		2	2	2	2
	P-value		**0.007****	**0.020***	**0.034***	**0.026***

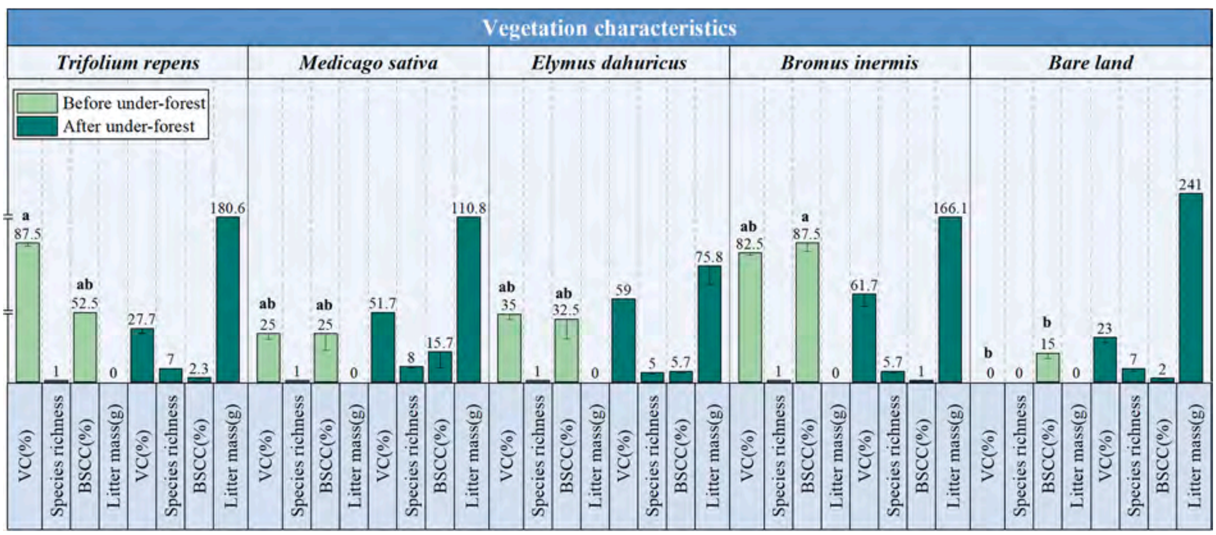

Fig. 2. Vegetation coverage (VC), species richness, litter mass and biological soil crust coverage (BSCC) for each treatment before and after under-forest, respectively. The number above each column represents the mean value. The different lowercase letters mean the significant differences among different treatments at the 0.05 level ($p < 0.05$).

community composition and ecosystem function (Brantley and Young, 2007). Our results showed that the original grassland species disappeared and the new weed species with poor roots settled successfully, the total species richness and surface litter increased, but the biological soil crust coverage decreased after understory shading, which suggest that forest canopy shading significantly changed the community composition and structure of understory grasslands.

Meanwhile, we found that understory shading increased runoff volume and sediment yield (Fig. 3). Before understory shading, the four grasslands had high biological soil crust coverage and understory grassland coverage (Fig. 2). At the beginning of a rainfall event, biological soil crusts imbibed water and swelled to form an impermeable seal in favor of soil water retention, thus leading to ponding rapidly (López-Vicente and Navas, 2012; Zhang et al., 2014). Biological soil crusts greatly improved soil resistance and reduce soil loss by binding and bonding soil particles in crusts (Wang et al., 2013; Liu et al., 2019). Grass species with high coverage have rich fine roots in the top soil (Wu et al., 2010, 2016). These roots tend to physically combined with soil particles, which increased soil cohesion and improves soil stability, and thus, promoting soil erosion controlling (De Baets et al., 2007; Liu et al., 2020). Compared with *M. sativa*, *E. dahuricus*, *B. inermis* and *T. repens* have more abundant fibrous roots (Vamerali et al., 2003; Fan et al., 2016), thus leading to the higher runoff volume and lower sediment yield (Fig. 3).

The impacts of understory grassland cover on runoff and erosion depend on the grassland type (Duan et al., 2016), its spatial distribution (Shi et al., 2013; Wei et al., 2014), the litter-stems, the biological crusts and roots (Jiang et al., 2020). In this study, runoff volume and sediment yield were significantly correlated with biological soil crust coverage, understory grassland coverage, litter, species richness and their interaction (Fig. 4). Understory shading changed grassland community composition. The original grass species were inhibited and new weed species appeared. Decaying grasses roots and increasing litter layer could improve soil fertility (Fischer et al., 2014), which in turn promoted the growth of new species. These new species were mostly overgrown weeds with poor roots. Coarse roots had lower decomposition rate than fine roots in in middle latitude areas (Zhang and Wang, 2015; Cui et al., 2019). Compared with other plots, *M. sativa* plots had lower coverage (Fig. 2). This may be due to the coarse root systems of original *M. sativa* (Vamerali et al., 2003; Fan et al., 2016).

After understory shading, the runoff volume of all plots significantly decreased due to the lower biological soil crusts. The significantly increased litter improved soil stability and porosity, which in turn increased the ability of water to infiltrate into the soil and finally reduced the runoff volume (Certini et al., 2015; Singh et al., 2016). Although litter layer could increase soil nutrient and soil anti-erodibility, and thus preventing soil loss (Novara et al., 2015), but understory shading still decreased the effectiveness of grasslands in

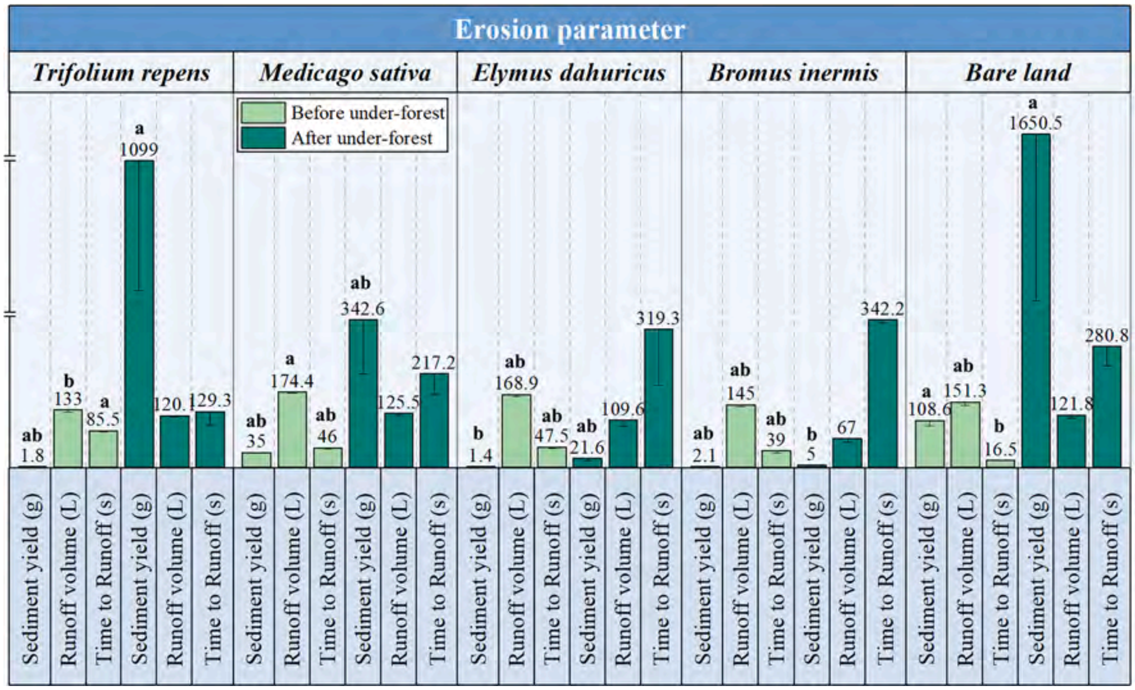

Fig. 3. Sediment yield, runoff volume and time to runoff for each treatment before and after under-forest, respectively. The number above each column represents the mean value. The different lowercase letters mean the significant differences among different treatments at the 0.05 level ($p < 0.05$).

Table 2
Statistical results of covariance analysis after under-forest.

		Df	Mean Square	F	P-value
Runoff volume	Treatment * Time to runoff	5	1724.309	36.174	**0.000****
	Treatment * Vegetation coverage	5	1329.204	4.975	0.018*
	Treatment * Biological soil crust coverage	5	1352.534	5.321	**0.015***
	Treatment * Litter mass	5	1093.058	2.744	0.089
	Treatment * Species richness	5	1532.264	9.927	**0.002****
Sediment yield	Treatment * Time to runoff	5	891760.720	1.132	0.409
	Treatment * Vegetation coverage	5	1110501.585	1.667	0.238
	Treatment * Biological soil crust coverage	5	1783685.113	6.106	**0.010****
	Treatment * Litter mass	5	1013336.628	1.407	0.309
	Treatment * Species richness	5	1882190.949	7.929	**0.004****

reducing soil loss (Fig. 3), even though the species richness increased and the understory grassland coverage remained high (Fig. 2, Table 1). This result was inconsistent with previous studies that high species richness and thick litter layer could promote soil development and reduce soil erosion (García-Fayos and Bochet, 2009; Pohl et al., 2009; Berendse et al., 2015; Goebes et al., 2015). This may be due to the differences between grass species in the properties of biological soil crusts and roots before and after understory shading. There are many factors affecting soil erosion (Fig. 4). Changes in one factor do not necessarily lead to an increase or decrease in soil erosion, which generally depends on its relative importance on reducing soil erosion. Jiang et al. (2020) have reported that the order of contribution to reduction of soil detachment in grasslands was roots > biological crust > litter-stems. In general, the aboveground parts mainly contribute to surface runoff process, whereas grass roots make a greater contribution to soil loss process (Zhou and Shangguan, 2007; Zhao et al., 2017). It is also the reason why we consider applying these original grass species with abundant fine roots to the forest-grass complex ecosystem in this study. Similarly, Seitz et al. (2016) have indicated that species-specific functional traits and site characteristics, but not species richness, affected the interrill erosion processes in young subtropical forests. Jiang et al. (2020) have indicated the significance of litter-stems, biological crusts and roots in controlling soil erosion, but greatly emphasized the importance of selecting appropriate grass species to control soil erosion. Therefore, even though the species richness and litter layer were high in all plots, soil loss was still high.

Table 3
Statistical results of partial correlation analysis of the effect of removal treatments after under-forest.

	Runoff volume	Sediment yield	Time to runoff	Vegetation coverage	Biological soil crust coverage	Litter mass	Species richness
Runoff volume	——	**0.561***	**−0.647***	−0.210	0.167	0.192	0.294
Sediment yield	**0.561***	——	−0.510	**−0.664****	−0.042	0.339	**0.596***
Time to runoff	**−0.647***	−0.510	——	−0.046	0.201	−0.233	−0.223
Vegetation coverage	−0.210	**−0.664****	−0.046	——	−0.202	−0.395	−0.334
Biological soil crust coverage	0.167	−0.042	0.201	−0.202	——	−0.316	0.048
Litter mass	0.192	0.339	−0.233	−0.395	−0.316	——	−0.014
Species richness	0.294	**0.596***	−0.223	−0.334	0.048	−0.014	——

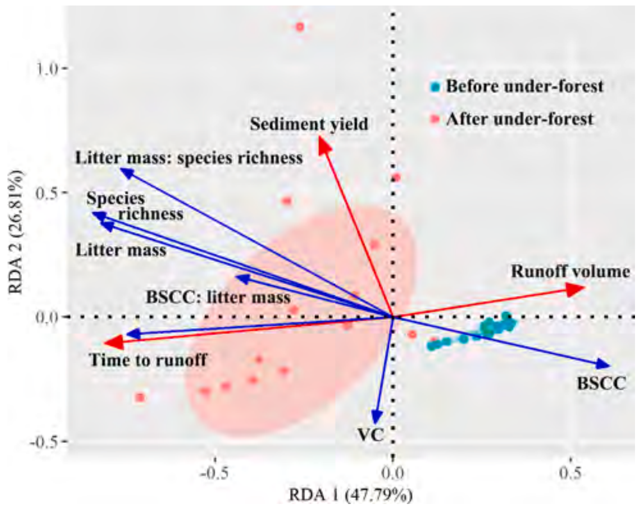

Fig. 4. Statistical results of the redundancy analysis (RDA) before and after under-forest. The red arrows indicate response variables and the blue arrows indicate explanatory variables. Note: Vegetation coverage-VC, biological soil crust coverage-BSCC, interaction between litter mass and species richness-Litter mass: species richness, interaction between biological soil crust coverage and litter mass-BSCC: Litter mass, interaction between vegetation coverage and litter mass-VC: Litter mass.

Overall, this multiyear study has found that understory shading inhibits herbs growth and changes grassland community composition, thus increase soil erosion. Meanwhile, grassland type but not species richness determined soil erosion for understory grasslands. Our findings suggest that selecting suitable shade-tolerant herb species application could improve the efficiencies of understory grasslands in soil erosion controlling, and achieve the sustainability of forest-grassland complex ecosystem during vegetation restoration. Additionally, considering woody or shrub plants often began to colonize in grasslands community with rich water and nutrient conditions as a result of climate warming, drought, nitrogen deposition and other global change factors in recent decades (Saintilan and Rogers, 2015; Zhang et al., 2021). How to make woody and herbs species coexist optimally so as to achieve the balance of soil and water resources conservation and biodiversity protection may be a potential issue in future research.

5. Conclusions

This study examined the dynamic response of grassland community composition and structure and soil erosion processes in four typical planted grasslands to understory shading. Understory shading significantly increased the total species richness and surface litter, but decreased the biological soil crust coverage. Understory shading inhibited the success of the original species in grassland community, and promoted the settlement success of new species with poor roots. Our findings showed that the runoff volume significantly decreased after understory shading, due to the low biological soil crust coverage. The sediment yield of all plots significantly increased after understory shading, despite the species richness and litter mass increased and the understory grassland coverage remained high. This change may be resulted from the decreased soil cohesion caused by the appeared weeds with poor roots after understory shading. Overall, our study revealed that understory herbs species determines soil erosion, but not species richness. The herbs roots changes generally made the greatest contribution to soil loss among various related factors. These findings have potential implications for understanding the effectiveness of understory grasslands on soil and water conservation and proposed that the shade-tolerant herb species application could effectively reduce soil erosion in forest-grassland complex ecosystem will help to achieve the sustainability of understory grassland during vegetation restoration.

Declaration of Competing Interest

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

Acknowledgments

We thank the editors and anonymous reviewers for their constructive comments and suggestions on this manuscript. This research was funded by the National Science Foundation of China (NSFC41930755, NSFC41977063, NSFC41722107), the Strategic Priority Research Program of the Chinese Academy of Sciences (XDB40000000), and the Youth Talent Plan Foundation of Northwest A&F University (2452018025).

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