Heliyon 10 (2024) e24035

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Long-term ecological restoration increased plant diversity and soil total phosphorus content of the alpine flowing sand land in northwest Sichuan, China

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ARTICLE INFO

Keywords:
Flowing sandy land
Alpine region
Ecological restoration durations
Vegetation functional group composition
Soil characteristics

ABSTRACT

The ecological restoration techniques that combine grazing, sand barriers with willows, fertilization, artificial planting, and continuous management are increasingly adopted in the management of flowing sandy land in high-altitude and cold regions. However, few studies have focused on the long-term ecological restoration effects of such technologies. This study systematically compared the vegetation and soil characteristics under different ecological restoration durations (0 (CK), 3 (F1), 14 (F2), 26 (F3), and 46 (F4) years) in the alpine sandy land of northwest Sichuan. The results showed that, with the increase of ecological restoration durations, (1) the aboveground and underground biomass of plants, and species number significantly increased, while the shannon-wiener index, margalef index, and simpson index dramatically decreased; (2) in the early stage of ecological restoration (0–3 yr), Cyperaceae accounted for the main groups, while in the late stage of ecological restoration (14–46 yr), Leguminosae and Forb groups predominated; (3) ecological restoration durations significantly influenced the total phosphorus (TP) content at a soil depth of 0–60 cm, but soil organic carbon and C/P ratio were only significantly impacted at 40–60 cm; (4) the plant and soil characteristics of F1, F2, and F3 treatments were more similar, and CK and F4 treatments were clearly distinguished on PC1 of principal component analysis; (5) there was no significant correlation between Leguminosae groups and environmental factors. Instead, a correlation between total nitrogen (TN) and Forb groups, Gramineae groups, and Cyperaceae groups was revealed. TN was very significantly positively correlated with species diversity and TP. Long-term ecological restoration improved plants biomass, plant species diversity, functional plant groups, and increased soil TP content in the alpine sandy land of northwest Sichuan.

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https://doi.org/10.1016/j.heliyon.2024.e24035
Received 1 June 2023; Received in revised form 19 December 2023; Accepted 2 January 2024
Available online 3 January 2024
2405-8440/

1. Introduction

About 41.7 % of China's land area, i.e. 4×10^8 hm^2, is covered by grasslands. Grasslands have extremely important ecological service functions, which can not only be used for grazing, but also have the functions of regulating climate, conserving water resources, controlling soil and water loss, etc. [1,2]. However, grassland desertification in China is serious due to climate change, plague of rodents, disorderly development, and over-grazing [3–5]. According to incomplete statistics, the area of grassland desertification has reached about 1.43×10^8 hm^2 in the western region, and the total area of grassland desertification is about 3.6×10^8 hm^2 in China [4,6]. Therefore, how to rationally use and protect grassland resources become a considerable issue in China.

The total area of Zoige alpine meadows grasslands, located in the alpine region of northwest Sichuan, is about 5.3×10^6 hm^2. The Zoige grassland is an important part of the "three zones and four belts" ecological barrier area of the Qinghai-Tibet Plateau (QTP), which is not only one of the main pastoral areas in China, but also the largest and best-preserved plateau peat swamp wetland in the world, known as "the kidney of the plateau" and "the reservoir of the Yellow River" [5,7]. However, due to the influence of natural factors (topography, climate change), biological factors (serious rodent damage), human interference (overgrazing), and other factors, the Zoige grasslands are undergoing serious degradation, resulting in a large amount of land desertification, and the function of important ecological barriers in some areas continues to decline [5,8,9]. The area of grassland desertification is about 8×10^4 hm^2 in the Zoige alpine meadows grasslands, with an annual economic loss of 8.7 million yuan. By the end of 2019, the government of Zoige County had invested 370 million yuan in total to control sandy land of 2.7×10^4 hm^2, accounting for 33.6 % of desertification land. Grassland desertification has become one of the main environmental problems threatening the production and ecological functions of alpine grasslands in northwest Sichuan [10,11]. Therefore, restoring the ecological barrier function of Zoige alpine meadows grasslands is the key to ecological protection in the alpine region of northwest Sichuan.

To a certain extent, ecological restoration measures can offset the negative impact of grassland desertification on biodiversity and ecosystem functions in alpine areas [5,12–15]. Most studies showed that ecological remediation measures can increase plant diversity and productivity, ameliorate soil nutrient accumulation, and improve soil microbial activities [5,13–15]. Nevertheless, the unique geographical environment and harsh climatic conditions make the sandy land difficult to rely on the recovery after the desertification of grassland in alpine and cold regions [5,14]. The alpine flowing sandy land has the characteristics of a thin soil layer, flowing easily, and low vegetation, so the restoration degree of natural force is limited; however, vegetation can be restored by setting various sand barriers, grazing exclusion, artificial planting, applying organic fertilizer, and other measures [11,15–17]. Among them, the sand barrier is mainly used to alleviate the flow of sand through physical action, which plays an important role in the process of vegetation restoration [18,19]. Fertilization is one of the main means to control the fertility decline of sandy land, and the appropriate amount of fertilizer is conducive to the sustainability of sandy soil [20–22]. Most studies believed that artificial planting of native plant species could increase plant diversity, plant productivity, and soil fertility in the plateau sandy land [15,17]. Most of these native plants have a strong ability to withstand drought, cold, and low nutrient conditions, such as *Elymus sibiricus*, *Poa annua*, etc. [15,17]. Grazing exclusion is one of the most effective strategies to prevent grassland degradation and support sustainable grazing [11,16]. Most recent studies only considered the single ecological restoration measure, and few studies combined several ecological restoration measures [11,15–17,20].

The ecological restoration technology, combining grazing exclusion, sand barrier with *Salix takasagoalpina*, fertilization, artificial planting, and continuous management, has been widely used in the treatment of flowing sands in the northwest Sichuan alpine region, for the purpose of solving the technical bottleneck problems of "flowing sand fixation, plant survival, and stable community construction" in the treatment of mobile sand therein. At present, the ecological restoration technology has won the second prize in the Sichuan Science and Technology Progress Award, which fully affirms the ecological restoration effects of this technology. However, some studies showed that short-term grazing exclusion could effectively promote the growth of alpine meadows and grassland aboveground biomass, but long-term grazing exclusion had not brought any ecological and economic benefits [11,16]. Therefore, it is necessary to evaluate the impact of long-term ecological restoration on the plant and soil characteristics of the frigid flowing sandy land in northwest Sichuan. This study compared the plant and soil characteristics, and plant-soil interaction relationships under different ecological restoration durations (0, 3, 14, 26, and 46 years) in the flowing sandy land in northwest Sichuan to understand whether long-term ecological restoration is beneficial to improve the plant and soil characteristics of the flowing sandy land in northwest Sichuan. The main objectives of this study are: (1) exploring the sustainable effect of ecological restoration of flowing sandy lands in northwest Sichuan; (2) understanding the relationships between functional plant groups and soil properties; (3) identifying factors affecting functional plant groups. We strive to provide a new idea for the long-term sustainable management of the flowing sandy land ecosystem in northwest Sichuan.

2. Materials and methods

2.1. Study area

The study site is located in Xiaman Township, Zoige County, which is in the eastern edge of QTP and in the north of Aba Tibetan and Qiang Autonomous Prefecture (Fig. 1A). The area of natural grassland in Zoige County is 5×10^4 hm^2, accounting for 91.7 % of the grassland area and 48.0 % of the total land area. The terrain is complex in the territory. The central and western parts and the south are typical hilly plateaus, accounting for 69 % of the total area of the county, with an average elevation of 3500 m. The north and southeast are high mountains and deep valleys with steep terrain, with an elevation of 2400 m–4200 m. The Zoige County belongs to continental plateau cold monsoon climate [5]. The average annual temperature is 1.1 °C and the annual precipitation is 648.5 mm, with no absolute frost-free period. Rainfall is mostly concentrated from late May to July, and the average annual relative humidity is 69 %. The land begins to freeze in September and completely thaws in next May, with the deepest frozen soil reaching 72 cm. The soil type of our sample plot is alpine meadow soil (Chinese Soil Taxonomy Research Group, 1995).

2.2. Sample plot

This study relies on the special project of desertification control of Sichuan Province Academy of Forestry Sciences. The Academy implemented ecological restoration technology in the year of 1976, 1996, 2008, and 2019 in the desertification land of Xiaman Township, Zoige, respectively (Fig. 1B). This ecological restoration technology is a collection of a series of measures such as fencing, alpine willow sand barriers, shrub-grass composite planting, organic fertilizer supplement, continuous management, and protection, which had been listed as a key scientific and technological achievement popularization technology by the State Forestry Administration. A 2 m high fence with 2.2 × 10 wire ties was used to prevent the entry of large herbivores, but the fence had no effect on small herbivores [11]. In order to limit the rapid expansion of flowing sand dunes, we twisted several thin branches of alpine together to weave a rectangular frame (2 m × 4 m), and then used the thicker branches as fixing piles to firmly penetrate the frame into the sand and form alpine sand barriers to fix the sand. In the "shrub-grass" management mode, *Salix cupularis* was selected as the shrub, and *Elymus dahuricus*, *Elymus sibiricus*, *Avena sativa*, and *Lolium perenne* were used as the ecological restoration plants. The seeds proportion of these plants was 1:1:1:1. On this basis, the bio-organic fertilizer with microbial bacteria ≥20 million/g and organic matter ≥40 % was used for continuous management of five years. In this study, five study sites were selected for the treatments (Fig. 1 and Table 1), i.e., F1 (Fig. 1D), F2 (Fig. 1E), F3 (Fig. 1F), and F4 (Fig. 1G) (desertification control in 2019, 2008, 1996, and 1976 with ecological restoration technology, respectively), and CK (Fig. 1C) was the control without ecological restoration.

2.3. Vegetation survey and sampling

Samples were taken during the season of vigorous plant growth. Vegetation survey and sampling were conducted in July 2022. Each treatment was divided into a transect with a length of 20 m × 20 m, and three sampling points with similar site conditions were set in the transect. Five small herbaceous quadrats with a length of 0.5 m × 0.5 m were randomly selected from each sampling point, and 75 small herbaceous quadrats were set in total [11]. Statistics were made on the species name, quantity, height, crown width and other indicators of all herbaceous plants in the quadrat, with records of the latitude and longitude of the quadrat and site factors (elevation, slope, slope length, height, etc.). The five whole plants were randomly collected from each treatment, and the soil attached to the plant roots was removed; the plants were put into plastic sample bags and brought back to the laboratory, where the plants were divided into aboveground and underground parts and put into envelopes, then the envelopes were put into an baking oven at 65.0 °C and dried to constant weight. An electronic balance with accuracy of 0.0001 g was used to measure their dry weight to calculate the

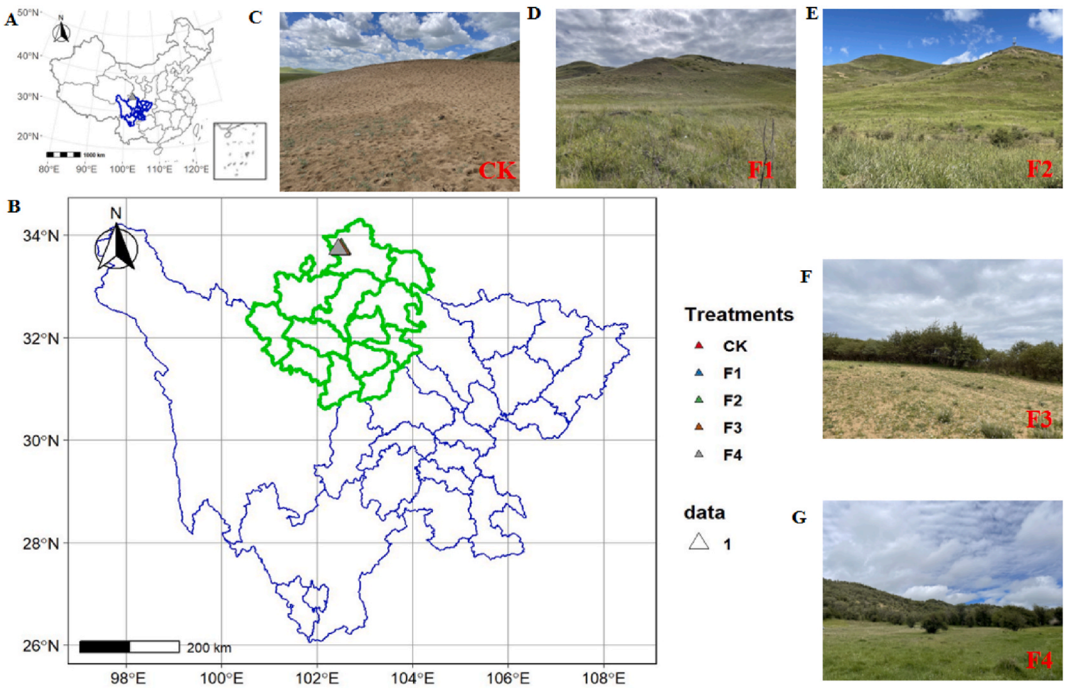

Fig. 1. Study area and sampling location.

Table 1
Basic information of the study sites.

Treatments	Ecological restoration durations	Location	Elevation/ m	Implementation year of ecological restoration technology	Original sand type	Current sand type
CK	0	N 33.71067447 E 102.49422061	3455	–	Shifting sandy land	Flowing sandy land
F1	3	N 33.71612670 E 102.49374997	3449	2019	Shifting sandy land	Fixed sand
F2	14	N 33.74117472 E 102.50720268	3467	2008	Shifting sandy land	Fixed sand
F3	26	N 33.72102650 E 102.48622266	3446	1996	Shifting sandy land	Fixed sand
F4	46	N 33.72480741 E 102.44095652	3461	1976	Shifting sandy land	Fixed sand

aboveground biomass (ABS) and underground biomass (UBS) of the plant respectively.

2.4. Soil physical and chemical properties

Soil samples were also collected in July 2022. The soil was collected in layers (0–20 cm, 20–40 cm, and 40–60 cm) within each quadrat using the "S" sampling method. Each treatment consisted of three replicates. A soil sample composition of 20 points (approximately 2 kg) was randomly collected for each independent replicate. In addition, soil bulk density was determined using a ring knife (V = 100.00 cm^3 and h = 5.0 cm) [23], which was randomly stratified from each plot. To prevent evaporation of soil water, soil samples were immediately packed in polyethylene valve bags and then taken back to the laboratory. The soil samples were dried naturally, and then sieved after manual removal of gravel, animal and plant debris. Soil organic carbon (SOC) content was determined by the rapid potassium dichromate oxidation method [24]; soil total nitrogen (TN) content was determined by the semi-micro Kjeldahl method [25]; soil total phosphorus (TP) content was determined by the $HClO_4$ -H_2SO_4 digestion-molybdenum antimony anti colorimetric method [26].

2.5. Data analysis

The α diversity indices (margalef index (M, see formula (1)), simpson index (D, see formula (2)), shannon-wiener index (H′, see formula (3)), and pielou index (J, see formula (4))) were calculated as follows [27]:

$$M = \frac{S-1}{\ln Q} \tag{1}$$

$$D = 1 - \sum_{i=1}^{S} P_i^2 \tag{2}$$

$$H' = -\sum_{i-1}^{S} P_i \ln P_i \tag{3}$$

$$J = -\frac{\sum_{i=1}^{S} P_i \ln P_i}{\ln S} \tag{4}$$

where S is the total number of species; Q is the sum of the individual numbers of all species; Qi is the number of individuals of the ith species; Pi is the proportion of species i, that is, the relative importance value of the ith species, Pi = Qi/Q.

The effect values of biomass, species diversity and soil nutrients were quantified to show the differences between the control and restoration of 3, 14, 26, and 46 years. The effect was calculated as follows (see formula (5-6)):

$$y_i = lnR = LN\frac{Y_e}{Y_c} \tag{5}$$

where Ye and Yc were the mean value of the treatment and control, respectively.

$$V_i = \frac{S_e^2}{N_e Y_e^2} + \frac{S_c^2}{N_c Y_c^2} \tag{6}$$

in which Ne and Nc indicated the sample size, and Se and Sc were the standard deviation of the target variable in the restoration treatment and control groups, respectively.

All data were subjected to statistical analysis after the assumption of normality (Shapiro-Wilk test) and the assumption of homoskedasticity (Bartlett test). Differences among mean values for the treatments were determined using a one-way analysis of variance (ANOVA), with the least significant difference (LSD) test for pairwise comparison. Significant levels were set at $P < 0.05$. Moreover, the effects of different restoration years and soil depth on soil nutrients were evaluated by two-factor analysis of variance with generalized linear model (GLM). The differences of biomass, species diversity and soil nutrients in different restoration years were studied by principal component analysis (PCA). Mantel-Test correlation analysis was used to calculate the correlation between the composition of plant functional groups and environment indicators.

Microsoft Excel 2010, R software (version: 4.2.2) (R Core Team 2015), and AI 22.0 software were used for tabulation and graphing. Graph visualization, data processing, diversity indicator, and correlation analysis were performed using the ggplot2 package, reshape2 package, vegan package, and corrplot package, respectively.

3. Results

3.1. Effects of different ecological restoration durations on plants ABS and UBS of alpine sandy land in northwest Sichuan

The ABS and UBS of plants in alpine sandy land were significantly affected by different restoration times in northwest Sichuan ($P < 0.05$, Fig. 2A–B). The ABS reached the maximum after 46 years of ecological restoration ($P < 0.05$), but the difference between different restoration durations was not significant ($P > 0.05$). Compared with CK, the UBS increased by 142.41 % ($P > 0.05$), 319.49 %

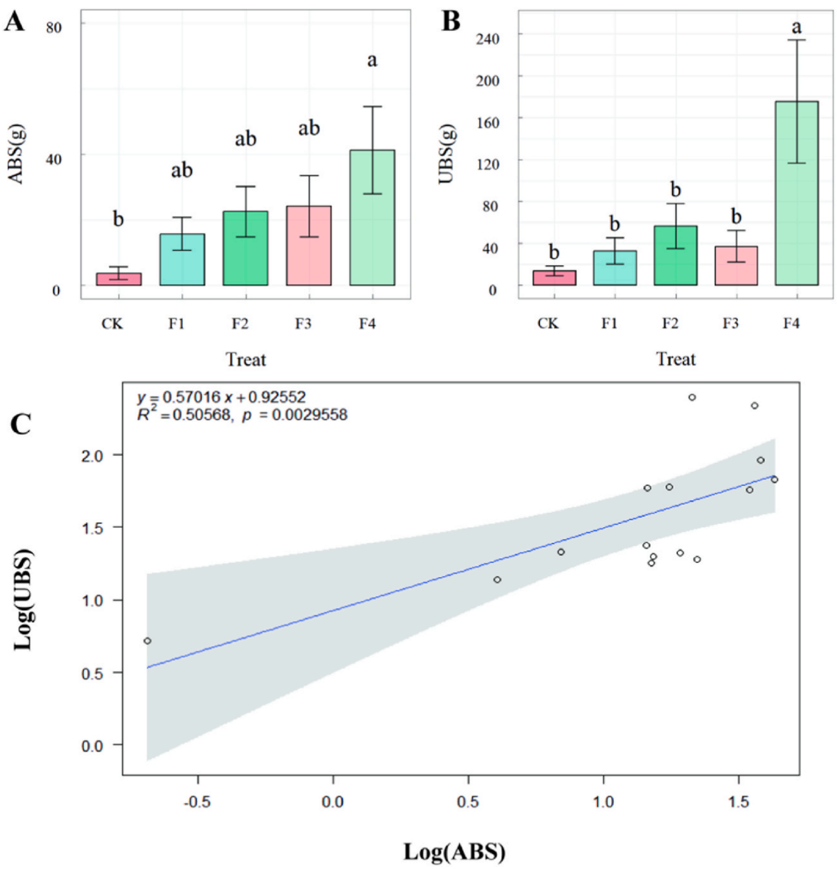

Fig. 2. ABS (A) and UBS (B) of plants and their relationship (C) in alpine sandy land of northwest Sichuan under different ecological restoration durations. CK, F1, F2, F3, and F4 represent ecological restoration of 0, 3 years, 14 years, 26 years, and 46 years respectively. ABS: aboveground biomass, UBS: underground biomass. Different letters indicate significant differences ($P < 0.05$). The shaded area represents the 95 % confidence interval (CI).

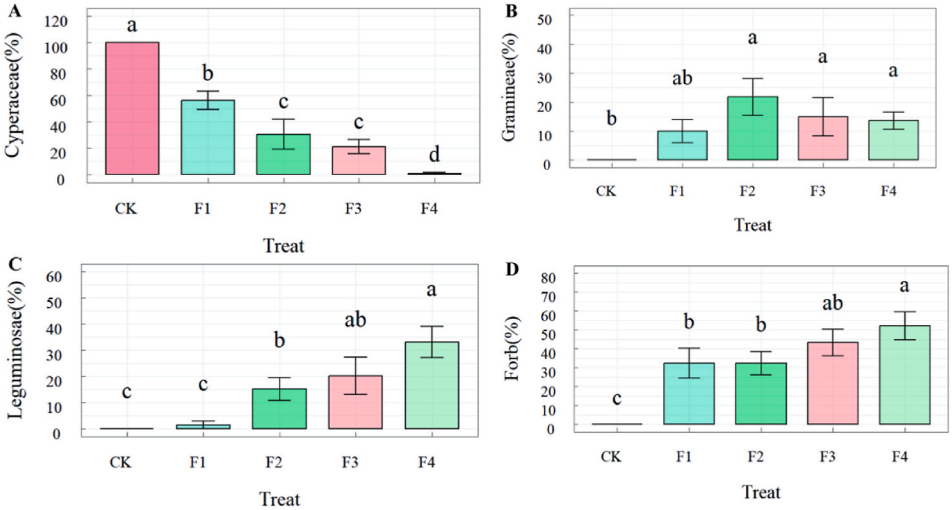

Fig. 3. Cyperaceae (A), Gramineae (B), Leguminosae (C), and Forb (D) groups in alpine sandy land of northwest Sichuan under different ecological restoration durations. CK, F1, F2, F3, and F4 represent ecological restoration of 0 years, 3 years, 14 years, 26 years, and 46 years, respectively. Different letters indicate significant differences ($P < 0.05$).

($P > 0.05$), 174.90 % ($P > 0.05$), and 1204.79 % ($P < 0.05$) in the F1, F2, F3, and F4, respectively. In addition, the regression slope of log (ABS) versus log (UBS) was 0.57 (Fig. 2C).

3.2. Effect of ecological restoration durations on the composition of plant functional groups of alpine sandy land in northwest Sichuan

As shown in Fig. 3, ecological restoration durations had significant effect on Cyperaceae groups, Gramineae groups, Leguminosae groups, and Forb groups in alpine meadow steppe ecosystem ($P < 0.05$). With the increase of ecological restoration durations, the percentage of Cyperaceae groups in the alpine meadow grassland ecosystem decreased, while Leguminosae increased (Fig. 3A–C). Compared with CK, the Gramineae groups significantly increased in the F2, F3, and F4, respectively (Fig. 3B, $P < 0.05$), and the Forb groups significantly increased in all treatment groups (Fig. 3D, $P < 0.05$). The Cyperaceae groups were the main taxonomic groups in the early stage of ecological restoration, while Leguminosae and Forb groups predominated in the late stage of ecological restoration.

3.3. Effect of ecological restoration durations on plant species diversity of alpine sandy land in northwest Sichuan

As shown in Fig. 4, ecological restoration durations had significant effect on plant species diversity of alpine sandy land in northwest Sichuan ($P < 0.05$). Compared with CK, the Shannon-wiener index of each treatment decreased by 44.51 %, 39.72 %, 18.78 %, 26.21 %, respectively ($P < 0.05$, Fig. 4A), Margalef index decreased by 53.80 %, 46.74 %, 25.54 %, 38.22 %, respectively ($P < 0.05$, Fig. 4B), Simpson index decreased by 29.27 %, 10.98 %, 10.98 %, 17.07 %, respectively ($P < 0.05$, Fig. 4C). Accordingly, compared with CK, the number of species increased significantly by 300.0 %, 367.0 %, 556.0 %, 525.0 %, respectively ($P < 0.05$, Fig. 4D).

3.4. Effects of ecological restoration durations on soil physical and chemical properties of alpine sandy land in northwest Sichuan

Table 2 showed that the ecological restoration durations, soil depth, and their interaction had significant influence on TP of the alpine sandy soil in northwest Sichuan ($P < 0.001$). Ecological restoration durations had significant effects on SOC ($P < 0.01$) and C:P ratio ($P < 0.05$). The effects of ecological restoration durations, soil depth, and their interaction on soil bulk density, TN, and C:N ratio were not significant ($P > 0.05$). Soil depth had no significant effect on SOC, TN, C:N ratio, and C:P ratio ($P > 0.05$). The interaction between restoration durations and soil depth had no significant effect on SOC, TN, C:N ratio, and C:P ratio ($P > 0.05$).

Table 3 showed that the soil bulk density (BD), TN, and C:N ratio at the depth of 0–20 cm, 20–40 cm, 40–60 cm were not significantly different ($P > 0.05$). The SOC and C:P ratio at the depth of 0–20 cm, 20–40 cm were not significantly different ($P > 0.05$), but significantly different at the depth of 40–60 cm ($P < 0.05$). Specifically, the SOC content and C:P ratio at 40–60 cm depth increased first and then decreased with the increase of ecological restoration durations ($P < 0.05$). Significantly, ecological restoration durations had significant effects on TP content at the depth of 0–20 cm, 20–40 cm, 40–60 cm ($P < 0.05$). Compared with CK, the TP content of soil at 20–40 cm and 40–60 cm depth increased first and then decreased ($P < 0.05$), which was, however, always significantly higher than that of CK ($P < 0.05$). Moreover, compared with CK, TP content was significantly higher ($P < 0.05$) at 0–20 cm depth, while the difference among other treatments were not significant ($P > 0.05$).

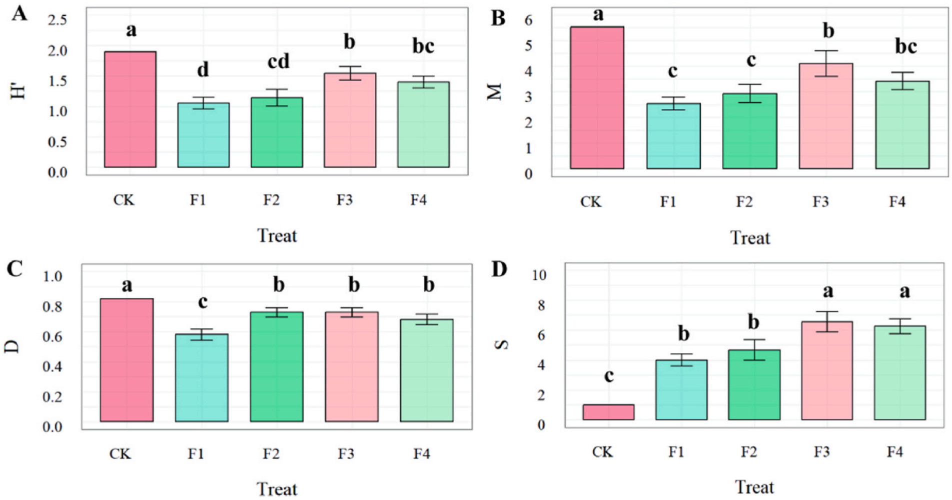

Fig. 4. Plant species diversity of alpine sandy land in northwest Sichuan under different ecological restoration durations. CK, F1, F2, F3, and F4 represent ecological restoration of 0, 3 years, 14 years, 26 years, and 46 years, respectively. H': Shannon-wiener index, M: Margalef index, D: Simpson index, S: species. Different letters indicate significant differences ($P < 0.05$).

Table 2
Effects of ecological restoration durations, soil depth and their interaction on soil physical and chemical properties of alpine sandy land in northwest Sichuan.

Indexes	Factor	Df	Sum Sq	Mean Sq	F	P
BD	Ecological restoration durations	4	0.040	0.010	2.359	0.076
	Soil depth	2	0.000	0.000	0.029	0.972
	Ecological restoration duration × soil depth	8	0.042	0.005	1.263	0.299
SOC	Ecological restoration durations	4	30.030	7.508	4.635	0.005**
	Soil depth	2	7.480	3.742	2.310	0.117
	Ecological restoration duration × soil depth	8	16.960	2.120	1.309	0.277
TN	Ecological restoration durations	4	0.449	0.112	2.701	0.203
	Soil depth	2	0.040	0.020	0.476	0.626
	Ecological restoration duration × soil depth	8	0.245	0.031	0.737	0.658
TP	Ecological restoration durations	4	0.430	0.108	168.570	0.000***
	Soil depth	2	0.055	0.028	43.150	0.000***
	Ecological restoration duration × soil depth	8	0.071	0.009	13.870	0.000***
C:N	Ecological restoration durations	4	715.100	178.780	3.910	0.189
	Soil depth	2	76.100	38.070	0.833	0.445
	Ecological restoration duration × soil depth	8	382.400	47.810	1.046	0.425
C:P	Ecological restoration durations	4	115.660	28.914	5.096	0.003*
	Soil depth	2	15.330	7.665	1.351	0.274
	Ecological restoration duration × soil depth	8	45.600	5.700	1.005	0.453

Note: ***$P < 0.001$, **$P < 0.01$, *$P < 0.05$. BD: bulk density, SOC: soil organic carbon, TN: total nitrogen, TP: total phosphorus, C:N: carbon/nitrogen, C:P: carbon/phosphorus.

3.5. PCA

In Fig. 5, the PCA results showed that the first and second axes respectively explained 30.41 % and 20.98 % of the standardized variance. C:P, ABS, Shannon-wiener index, Margalef index, and Simpson index (load value > 0.80) had significant influence. TP and Margalef index (Simpson index, Shannon-wiener index) showed a negative correlation. Meanwhile, species number (ABS, UBS, TN) and BD (SOC, C:N ratio, C:P ratio) showed a negative correlation. Moreover, the plant and soil characteristics of F1, F2, and F3 treatments were more similar, and CK and F4 treatments can be clearly distinguished on PC1.

3.6. Mantel test correlation analysis

With plant functional groups as a matrix, Mantel test was conducted to examine the correlation between plant functional group composition and environmental factors (Fig. 6). The results showed that there was no significant correlation between Leguminosae groups and environmental factors (soil physical and chemical properties, plant biomass, plant species diversity) ($P > 0.05$). There was a correlation between TN and Forb groups, Gramineae groups, and Cyperaceae groups ($0.01 < P < 0.05$). There was a correlation between species number and Forb groups ($P < 0.01$), Cyperaceae groups ($0.01 < P < 0.05$). Meanwhile, the correlation between Forb

Table 3
Bulk density, soil organic carbon, total nitrogen, total phosphorus, carbon/nitrogen, and carbon/phosphorus of alpine sandy land in northwest Sichuan under different ecological restoration durations.

Indexes	Ecological restoration durations	Soil depth		
		0–20 cm	20–40 cm	40–60 cm
SOC	CK	4.29 ± 1.87 a	3.37 ± 1.33 a	1.28 ± 0.56 b
	F1	3.09 ± 0.16 a	2.68 ± 0.96 a	3.15 ± 0.21 ab
	F2	4.92 ± 0.70 a	4.48 ± 1.72 a	4.60 ± 0.88 a
	F3	3.51 ± 1.58 a	3.33 ± 2.47 a	4.00 ± 1.59 a
	F4	3.17 ± 1.08 a	2.45 ± 0.96 a	0.96 ± 0.54 b
BD	CK	1.47 ± 0.08 a	1.47 ± 0.02 a	1.36 ± 0.06 a
	F1	1.44 ± 0.01 a	1.41 ± 0.11 a	1.46 ± 0.06 a
	F2	1.41 ± 0.02 a	1.43 ± 0.09 a	1.45 ± 0.04 a
	F3	1.41 ± 0.05 a	1.44 ± 0.08 a	1.43 ± 0.06 a
	F4	1.35 ± 0.06 a	1.33 ± 0.05 a	1.40 ± 0.09 a
TP	CK	0.43 ± 0.02 b	0.40 ± 0.01 c	0.24 ± 0.03 c
	F1	0.64 ± 0.02 a	0.53 ± 0.02 b	0.63 ± 0.01 a
	F2	0.66 ± 0.05 a	0.57 ± 0.01 ab	0.62 ± 0.02 a
	F3	0.63 ± 0.03 a	0.61 ± 0.04 a	0.59 ± 0.03 a
	F4	0.61 ± 0.02 a	0.54 ± 0.02 b	0.48 ± 0.01 b
TN	CK	0.26 ± 0.16 a	0.20 ± 0.11 a	0.19 ± 0.10 a
	F1	0.32 ± 0.04 a	0.24 ± 0.09 a	0.32 ± 0.11 a
	F2	0.34 ± 0.07 a	0.37 ± 0.11 a	0.30 ± 0.09 a
	F3	0.36 ± 0.17 a	0.60 ± 0.36 a	0.44 ± 0.18 a
	F4	0.66 ± 0.37 a	0.42 ± 0.42 a	0.34 ± 0.15 a
C:P	CK	9.98 ± 4.60 a	9.33 ± 3.15 a	5.24 ± 1.98 ab
	F1	4.83 ± 0.35 a	5.08 ± 1.80 a	4.97 ± 0.26 ab
	F2	7.60 ± 1.54 a	7.82 ± 3.10 a	7.45 ± 1.56 a
	F3	5.50 ± 2.32 a	5.30 ± 3.10 a	6.79 ± 2.78 ab
	F4	5.20 ± 1.67 a	4.50 ± 1.56 a	2.00 ± 1.08 b
C:N	CK	20.66 ± 13.39 a	21.68 ± 12.01 a	9.29 ± 6.92 a
	F1	9.82 ± 0.73 a	13.31 ± 8.14 a	10.77 ± 4.79 a
	F2	15.02 ± 5.12 a	12.59 ± 6.69 a	16.06 ± 3.84 a
	F3	12.25 ± 8.49 a	5.24 ± 0.87 a	9.88 ± 5.00 a
	F4	5.29 ± 1.76 a	9.43 ± 6.02 a	3.00 ± 1.27 a

Note: CK, F1, F2, F3, and F4 represent ecological restoration of 0, 3 years, 14 years, 26 years, and 46 years respectively. Different lowercase letters indicate significant differences in different ecological restoration years under the same soil depth ($P < 0.05$). BD: bulk density, SOC: soil organic carbon, TN: total nitrogen, TP: total phosphorus, C:N: carbon/nitrogen, C:P: carbon/phosphorus.

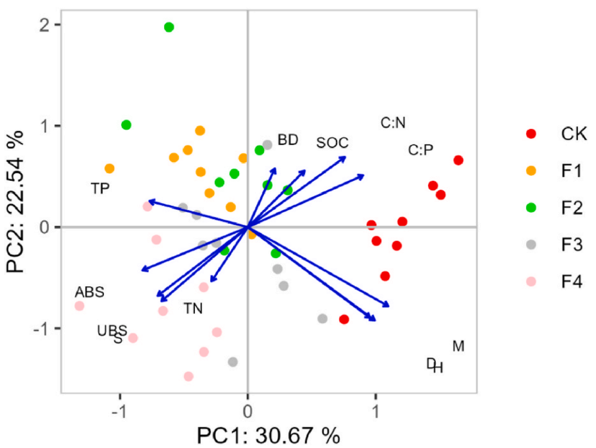

Fig. 5. PCA of plant diversity and soil physical and chemical properties of alpine sandy land in northwest Sichuan under different ecological restoration durations. ABS: aboveground biomass, UBS: underground biomass, M: Margalef index, D: Simpson index, H': Shannon-wiener index, J: Pielou index, S: species, BD: bulk density, SOC: soil organic carbon, TN: total nitrogen, TP: total phosphorus, C:N: carbon/nitrogen, C:P: carbon/phosphorus.

groups and species diversity index (Margalef index, Simpson index, and Shannon-wiener index) was significant ($P < 0.01$). Furthermore, the correlations between Cyperaceae groups and plants UBS ($P < 0.01$), SOC ($0.01 < P < 0.05$), and C:P ratio ($0.01 < P < 0.05$) were significant.

The size of the squares in Fig. 6 showed the correlation between the two indicators. TN was very significantly positively correlated

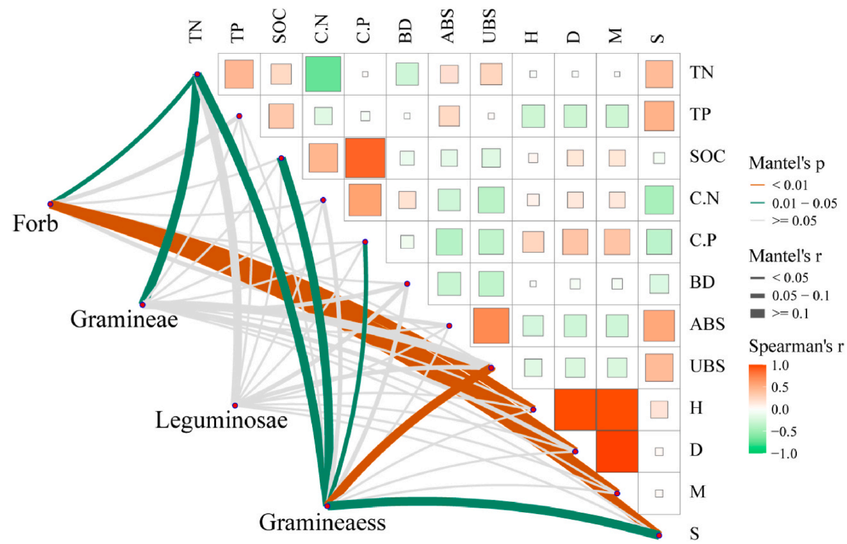

Fig. 6. Mantel Test showing the correlations between the composition of plant functional groups, plant diversity, and soil physical and chemical properties of alpine sandy land in northwest Sichuan under different ecological restoration durations.

with species diversity, TP, ABS, and UBS, but significantly negatively correlated with C:N ratio and BD. Species diversity was very significantly positively correlated with TN, TP, ABS, and UBS, but significantly negatively correlated with C:N ratio and C:P ratio. Margalef index was very significantly positively correlated with Simpson index, Shannon-wiener index, but significantly negatively correlated with TP and ABS. SOC was very significantly positively correlated with C:P ratio and C:N ratio. Moreover, plant UBS was very significantly positively correlated with TN and ABS, but significantly negatively correlated with C:N ratio, C:P ratio, BD and SOC. Plant ABS was very significantly positively correlated with TN and TP, but significantly negatively correlated with C:N ratio, C:P ratio, and BD.

3.7. *Effect value analysis*

It can be seen from Fig. 7 that the total effect values were intersected with 0, indicating that none of the effect values were significant at each ecological restoration duration. In the pair QE test, values ($P < 0.0001$) indicated strong heterogeneity and explanatory variables could be introduced to explain the heterogeneity. Therefore, we introduced the ecological restoration durations as an explanatory variable, and carried out Qm test. Values ($P > 0.05$) indicated that the introduced explanatory variable had no significant effect on the effect values. There were no significant differences in plant diversity, plant biomass, and soil properties under different ecological restoration durations of alpine sandy land in northwest Sichuan.

4. Discussion

The long-term ecological restoration showed improved or reduced restoration effect in the degraded alpine grassland [5,23,28]. We studied the effects of long-term ecological restoration on the characteristics of plants and soil nutrients in the alpine flowing sandy land, which were consistent with the results of Du et al. [28]. We here showed that with the increase of ecological restoration durations, the plants ABS, UBS, species number, Gramineae groups, Leguminosae groups, and Forb groups increased, but Shannon-wiener index, Simpson index, and Margalef index showed a trend of initial decrease and then increase. Moreover, SOC, TP, and C:P ratio of the deep soil (40–60 cm) showed a trend of first increase and then decline. After the adoption of our ecological restoration technology, the flowing sandy land had been transformed into fixed sandy land, the vegetation coverage had increased, the soil nutrient status became better, indicating the desertification control worked positively. Overall, long-term ecological restoration had positive restoration effects in degraded alpine grassland.

4.1. *Effects of long-term ecological restoration on plants functional groups*

Long-term ecological restoration is conducive to vegetation restoration in the alpine sandy land in northwest Sichuan. Generally speaking, grazing exclusion has a broad impact on plant species composition, plant species diversity, vegetation productivity, and soil nutrient in the alpine grassland [11,29]. The fence of grazing exclusion in the ecological restoration technology directly prevents livestock (*Bos mutus*, *Ovis aries*, etc.) from entering the sample land, reduces the animals' feeding on herbs and trampling on plants, and increases the plant biomass [5,10,11,18,29], which were consistent with the results of our study. The proportion of Cyperaceae species decreased significantly with the increase of ecological restoration durations, while the proportion of Gramineae species increased

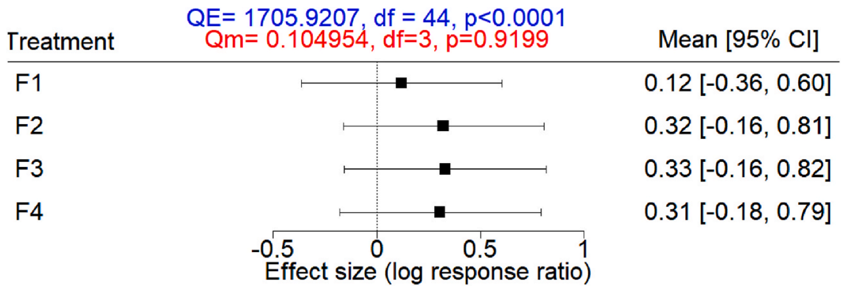

Fig. 7. Total effect value of ecological restoration durations on plant characteristics and soil properties of alpine sandy land in northwest Sichuan. F1, F2, F3, and F4 represent ecological restoration of 3 years, 14 years, 26 years, and 46 years respectively.

significantly. Grazing exclusion cannot prevent small rodents, who preferably feed on Cyperaceae plants, from entering the sample land, which led to a significant reduction of Cyperaceae plant groups [5]. At the same time, Gramineae plant groups were often used in various ecological restorations. We also used Gramineae plants for ecological restoration, so their abundance increased rapidly. With the increase of ecological restoration durations, the biomass and species number of herbaceous plants increased significantly, while the plant diversity decreased dramatically, which were not consistent with the study of Cardinale et al. [30], but consistent with the study of Li et al. [23]. Although the plant diversity significantly reduced in this study, the composition of herbaceous plants improved, thus increasing the biomass. In contrast, Cyperaceae accounted for 100 %. With the increase of ecological restoration years, the increase of Gramineous, Leguminosae, and Forb populations in the sample plots suggested that the herbaceous vegetation became more stable. Interestingly, the species diversity index, the proportion of Gramineae, Leguminosae, and Forb populations, and ABS/UBS were higher in F4 than in other treatments, indicating that long-term ecological restoration could bring sustainable benefits to the diversity of herbaceous plants in the alpine sandy land of western Sichuan, which was not consistent with Li et al. [23], Wu et al. [31], and Jiang et al. [11]. This may be related to the ecological restoration technology. Previous research, such as Hu et al. [32], mainly focused on a single ecological restoration technology, while the ecological restoration technology used in this study included a variety of ecological restoration technologies combined with many techniques, which makes the underlying restoration mechanisms more complex and requires further exploration.

4.2. Effects of long-term ecological restoration on soil nutrients

Soil nutrient is a key index in measuring functional restoration and maintenance of degraded ecosystems, and plays an important role in the succession of plant communities [33]. Long-term ecological restoration did not change the nutrient status of surface soil (0–20 cm), but had a significant impact on the deep soil (40–60 cm). This may be due to the short growing season of plants in alpine grassland, which is not enough for roots to extend into the deeper layer, resulting in shallow root distribution, root death, decomposition, and conversion into organic matter and other nutrients; therefore the nutrients in the surface soil layer were supplemented [34,35]. Wang et al. [36] believed that the soil nutrient content of seriously degraded sandy land decreased significantly. The results of this study showed that after the long-term ecological restoration of seriously degraded sandy land, the content of SOC in sandy land (40–60 cm) increased at first and then decreased. On the one hand, SOC is mainly from plants; the increase in vegetation coverage could enhance the protection of soil nutrients, and the increases in grassland productivity also increase the input of plant litter or root exudates to soil nutrients, thus improving the SOC content [37,38]. On the other hand, applying organic fertilizer can rapidly supplement the content of organic matter in the soil [39].

The availability of soil nitrogen and phosphorus nutrients is an important factor in regulating the composition of different functional groups of plants [40]. The results of this study showed that long-term ecological restoration had no significant effect on soil TN content, but significantly affected soil TP content. At the same time, there was a significant correlation between soil TN content and plant functional groups. These imply that phosphorus might be the main limiting factor for plant growth and species composition in alpine sandy land. Some studies have shown that soil phosphorus mainly comes from parent material weathering and atmospheric phosphorus deposition, but the parent material mineralization process is slow in the terrestrial ecosystem, and the atmospheric phosphorus deposition is relatively low compared with the nitrogen deposition [40,41]. Therefore, soil with phosphorus deficiency might be more sensitive to phosphorus addition. In this study, we adopted the method of fertilization to restore the sandy land, which greatly improved the soil phosphorus content. The effects of nutrient input and N/P ratio on various functional groups of plants differed [42,43]. When nutrients are abundant, grasses have a stronger ability to absorb nutrients and are more dominant in the community. However, when the nutrient supply was unbalanced, the survival and performance of non-gramineous plants were worse than that of gramineous plants [44,45]. At the same time, the prohibition of grazing could promote the growth of upright plants such as Gramineae, so that the overall external pattern of the community was greatly changed [46].

5. Conclusions

This study compared the vegetation, soil characteristics and plant-soil interaction under different ecological restoration durations (0, 3, 14, 26, and 46 years) in the alpine sandy land of northwest Sichuan, China. Under long-term ecological restoration, sandy plants can adapt to the living environment in alpine areas by increasing root biomass well. Ecological restoration durations significantly affected the composition of plant functional groups and plant species diversity. Long-term ecological restoration increased the proportion of the Gramineae groups, Leguminosae groups, and Forb groups, decreased the proportion of Cyperaceae population. Meanwhile, Long-term ecological restoration increased species number, but decreased the other diversity indexes. In addition, the other soil indexes at the depth of 0–20 cm were not significantly different between treatment groups and control, except for a significant increase in TP content at 0–20 cm. Long-term ecological restoration improved SOC, TP, and C/P ratio at the depth of 40–60 cm. There was a significant correlation between TN and Forb groups, Gramineae groups, and Cyperaceae groups. TN was significantly positively correlated with species diversity, TP, ABS, and UBS. Therefore, long-term ecological restoration improved plants biomass, plant species diversity, functional plant groups, and increased soil TP content in the alpine sandy land of northwest Sichuan. These results provide a theoretical reference for the further development of ecological restoration strategies in the alpine sandy land in northwest Sichuan.

Funding

This research was funded by Sichuan Provincial Science and Technology Department Project (No. 2023NSFSC0750), Ecological and Security Key laboratory of Sichuan Province, China (ESP2204), Sichuan Academy of Forestry Sciences (HX2022075), Scientific Research Project of Mianyang Normal University (No. QD2022A02), and Hainan Natural Science Foundation (No. 2019RC316).

Data availability statement

Available as Supplementary (Excel) File (see Supplementary Materials) upon request to the authors) upon request to the authors.

CRediT authorship contribution statement

Xue Jiang: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yanping Qu:** Writing – review & editing, Writing – original draft, Investigation. **Houyuan Zeng:** Writing – review & editing, Writing – original draft, Software, Data curation. **Jingtian Yang:** Visualization, Methodology, Formal analysis. **Lei Liu:** Supervision, Software, Project administration. **Dongzhou Deng:** Methodology, Investigation, Data curation. **Yunlong Ma:** Validation. **Dechao Chen:** Project administration, Conceptualization. **Banghong Jian:** Investigation, Data curation. **Lingliang Guan:** Funding acquisition. **Li He:** Writing – review & editing, Writing – original draft.

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 Dr. Huang Bocong for his beautification of the picture.

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