Integrated Tree–Shrub–Grass Vegetation Restoration in Sandy Riparian Zones of the Yarlung Tsangpo River: Techniques and Ecological Implications

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Article

Keywords: Vegetation assemblage, configuration model, soil physicochemical properties, Milin County, Yarlung Tsangpo River

Posted Date: June 5th, 2025

DOI: https://doi.org/10.21203/rs.3.rs-6612190/v1

Additional Declarations: No competing interests reported.

Abstract

To advance the theory and practice of vegetation restoration on desertified lands, we conducted a field-based investigation in the sand-control experimental zone of lirong Township, Milin County, situated in the middle reaches of the Yarlung Tsangpo River. Through a combination of long-term fixed-point observation and controlled field experiments, we examined the ecological impacts of integrating tree-shrub-grass species. We developed a composite planting model suited for sandy riparian zones and evaluated its performance. Results demonstrate that such vegetation assemblages effectively reduce wind speed, enhance relative humidity, and stabilize air, surface, and subsurface temperatures. Furthermore, the treatments improved soil water content and porosity while reducing bulk density and pH. Soil fertility metrics—including organic matter, total nitrogen, phosphorus, and potassium—also showed significant improvement, enhancing the land's productivity. Among the tested configurations, the assemblage of *Cupressus gigantea*, *Sophora moorcroftiana*, *Medicago sativa*, *Melilotus officinalis*, *Eragrostis nigra*, and *Astragalus adsurgens*, when paired with rainwater-collecting trays and geocell structures, proved optimal for ecological restoration in the riparian sandy soils of the central Yarlung Tsangpo basin.

Introduction

The Yarlung Tsangpo River, often referred to as the "Heavenly River," is the longest plateau river in China. In recent years, the region has experienced increasing ecological stress due to global climate change and intensified anthropogenic activities, resulting in wetland shrinkage, grassland degradation, and expanding desertification1[1,2]. The central reaches of the Yarlung Tsangpo River represent both the cultural and economic heart of Tibet and one of the regions most severely affected by wind-driven desertification[3,4], with sandy land currently covering nearly 3,000 hm^2.The primary driver of land desertification in this area is the seasonal exposure of river sediments caused by fluctuating precipitation. These exposed sediments, under the joint influence of strong solar radiation and frequent high winds, have led to widespread vegetation degradation across the middle and lower reaches[5,6]. The expansion of aeolian sand activity has exacerbated ecological problems such as grassland degradation and biodiversity loss, and has also disrupted transportation infrastructure, thereby impacting the livelihoods and environmental quality of local communities. Urgent action is needed to address these issues.

Considerable progress has been made in China's battle against desertification. For example, Wang et al.[7]demonstrated that integrated treatments such as "sheep manure + fiber grid sand barriers + protected species" and "sheep manure + peat soil + protected species" significantly enhanced sand fixation and vegetation recovery in the headwaters of the Yellow River. Similarly, Jiang et al.[8]found that planting *Caragana microphylla* Lam. within straw grids in the Horqin Sandy Land effectively stabilized mobile dunes and improved soil and biodiversity.In the central Yarlung Tsangpo basin, researchers have also explored restoration strategies. Shen et al.[9]reported promising germination and survival rates for species such as *Corethrodendron scoparium* Fisch., *Calligonum mongolicum*, *Hedysarum mongolicum* and *Sophora moorcroftiana* in mobile sandy soils. Song and Bianba Zhuoma[10]evaluated the ecological adaptability of forages and identified *Cichorium intybus*, *WL168HQ*, *Elymus nutans*, and *perennial ryegrass* as high-biomass candidates. However, comprehensive studies on the ecological effects of mixed tree–shrub–grass vegetation assemblages for sandy land restoration in this region remain lacking.

The tree–shrub–grass planting model is widely recognized for its structural complexity and multifunctionality in ecological restoration. It serves as a robust system for water and soil conservation, capable of withstanding extreme environmental conditions[11]. Both empirical knowledge and field trials confirm that biological measures—especially heterogeneous combinations of trees, shrubs, and grasses—are highly effective for stabilizing desertified land in the Yarlung Tsangpo River's central basin[10,12].Against this background, the present study focuses on the sandy land restoration trial zone in Lirong Township, Milin County. By investigating the establishment techniques and ecological outcomes of tree–shrub–grass assemblages, we aim to develop a practical and scientifically grounded restoration model. Our findings will support large-scale vegetation restoration and ecological reconstruction in the riparian sandy zones of the Yarlung Tsangpo River.

Materials and Methods

Study Area Overview

This study was conducted in the region between Lirong Township and Wolong Town, within Milin County, located in the central reaches of the Yarlung Tsangpo River (Fig. 1). The study area (29°8'16"N, 93°45'26"E; elevation: 2973 m) is characterized by a semi-arid plateau temperate climate. The rainy season spans from June to September, while the dry season extends from October to May of the following year. The region receives an average annual precipitation of 698 mm, with an annual evaporation of 1964.4 mm. The mean annual temperature is 8.7°C, with the highest monthly average in July (29.5°C) and the lowest in January (–15°C). The annual effective accumulated temperature is 2791.8°C, total sunshine duration is 1669.6 hours, the frost-free period lasts 153 days, and wind-blown sand events occur approximately 52 times per year[13,14].

Experimental Plots

Three experimental plots were established in the sand control demonstration area of Lirong Township: Treatment 1: A vegetation community composed of Cupressus gigantea, Sophora moorcroftiana, and a mix of herbaceous species, equipped with water-harvesting trays and geocell structures. Treatment 2: The same plant community configuration as Treatment 1 but without the use of water-harvesting trays and geocells. Control (CK): A bare sandy plot with no vegetation.

All plots were rectangular and covered approximately 528 m² of mixed grassland or sandy soil.

In Treatment 1, grass species including Medicago sativa, Melilotus officinalis, Eragrostis nigra, and Astragalus adsurgens were sown using surface broadcasting techniques with soil coverage of 1–2 cm, and overlaid with eco-friendly non-woven fabric (18 ± 2 g/m²) to preserve soil temperature and moisture. The geocells used (HQ-100-330, black, 100 mm depth, 165 mm diameter) served to support herbaceous plant rooting, while rainwater-collecting trays (Tal-Ya, Israel) were applied to support the growth of *Cupressus gigantea* and *Sophora moorcroftiana*. The density of *Cupressus gigantea* was 70 individuals per acre, with a survival rate of 94%. The plants were spaced at 1.2 × 2.0 m intervals, and their heights ranged from 1.37 to 2.0 m. The crown widths varied from 0.91 to 1.44 m, while the breast-height diameters were between 2.5 and 3.7 cm, and the ground diameters were 3.9–5.1 cm. For *Sophora moorcroftiana.*, the density was 90 individuals per acre, with a survival rate of 98%. These plants were spaced at 0.8 × 1.5 m intervals, with heights ranging from 0.81 to 1.20 m and crown widths from 0.72 to 0.80 m.

The grass plant community included Medicago sativa with an average height of 22.33 cm and a density of 52 plants per square meter, Melilotus officinalis with an average height of 63.20 cm and a density of 30 plants per square meter, Eragrostis nigra with an average height of 10.83 cm and a density of 106 plants per square meter, and Astragalus adsurgens with an average height of 16.00 cm and a density of 40 plants per square meter. The vegetation cover of the forage plants was 95%. All species were sown by broadcasting, followed by a soil cover of 1–2 cm and mulching with non-woven fabric to maintain soil temperature and moisture.In Treatment 2, the cultivation of forage plants (*Medicago sativa*, *Melilotus officinalis*, *Eragrostis nigra*, and *Astragalus adsurgens*), shrubs (*Sophora moorcroftiana*), and trees (*Cupressus gigantea*) was conducted without the use of environmentally friendly non-woven fabric (18 ± 2 g/m²), geocell structures (HQ-100-330/black, depth 100 mm, size 165 mm), or rainwater-collecting trays (Tal-Ya, Israel). The cultivation methods, densities, and spacings of the tree–shrub–grass planting model in the grassland were identical to those in Treatment 1. The survival rate of *Cupressus gigantea* was 61%, with plant heights ranging from 0.87 to 1.50 m, crown widths from 0.70 to 0.94 m, breast-height diameters from 1.9 to 2.7 cm, and ground diameters from 3.2 to 4.5 cm. For *Sophora moorcroftiana*, the survival rate was 73%, with plant heights ranging from 0.65 to 0.82 m and crown widths from 0.63 to 0.77 m. The grass community included *Medicago sativa* (average height 15.46 cm, density 44 plants/m²), *Melilotus officinalis* (average height 50.40 cm, density 21 plants/m²), *Eragrostis nigra* (average height 7.65 cm, density 79 plants/m²), and *Astragalus adsurgens* (average height 10.30 cm, density 19 plants/m²), with a vegetation cover of 56%.The control group was an open area with no vegetation cover.

Observation Period

All vegetation was planted in April 2020. Five monitoring points were established within each plot. Microclimatic measurements were taken from July 25 to 30, 2022, with observations made every two hours daily. Soil sampling was conducted on July 30, 2022.

Measurement Methods

Microclimate Monitoring

Air temperature, relative humidity, light intensity, wind speed, and subsurface temperature (at 5 cm depth) were recorded using a parallel observation method. Measurements were taken 80–100 cm above the ground using a digital thermometer-hygrometer (C20A, China), a light meter (RE-Y2061A, Zhejiang), and an anemometer (AR856, Guangdong).

Soil Physical and Chemical Properties

Soil water content was determined via the drying method, using soil cores extracted from 0–50 cm depths (layered into 0–10, 10–20, 20–30, 30–40, and 40–50 cm intervals).Determination of soil bulk weight and porosity: The bulk weight and porosity of the soil layers at depths of 0–10, 10–20, 20–30, 30–40 and 40–50 cm were determined by the ring knife-soaking method (ring knife volume of 100 cm^3) with three replications at each level.

$$soil\ bulk\ density\ (\ pd\ ) = \frac{M}{V}\ \#\ (1)$$

$$Soil\ porosity\ =\ \left(1\ -\ \frac{columetric\ weight}{relative\ density}\right)\ \times\ \ 100\%\ \#\ (2)$$

Where, pd is the bulk density of a layer of soil (g/cm^3); M is the mass (g); V is the unit volume (cm^3) [15,16,17].

Measurement of soil chemical properties

pH was measured using a soil-to-water ratio of 1:2.5 with a pH meter[18].Total nitrogen, phosphorus, and potassium were measured following standard protocols. Organic matter content was determined using the potassium dichromate oxidation method.

Data Analysis

Data were processed using Excel 2022. One-way analysis of variance (ANOVA) was performed using SPSS 22.0 to assess significance ($P < 0.05$), and visualizations were created in Origin 9.0.

Results

Effects of Vegetation Assemblages on Microclimate: Air Temperature, Humidity, Light Intensity, and Wind Speed

Significant differences were observed in microclimatic conditions—namely air temperature, relative humidity, light intensity, and wind speed—across the three treatments (Table 1). At 14:00, the highest recorded air temperatures were 31.15°C, 31.80°C, and 37.55°C for Treatments 1, 2, and the control, respectively. Compared to the control, Treatment 1 showed significantly higher air humidity at 08:00, 10:00, 14:00, 16:00, and 18:00 ($P < 0.05$). At all measured time points (08:00, 10:00, 12:00, 14:00, 16:00, 18:00, and 20:00), light intensity in Treatment 2 was significantly lower than in the control ($P < 0.05$), while at 10:00, 12:00, 14:00, and 16:00, light intensity in Treatment 1 was significantly lower than in Treatment 2 ($P < 0.05$), indicating enhanced shading from denser vegetation cover. Air wind speeds in Treatments 1 and 2 were significantly lower than the control at 08:00, 16:00, and 18:00 ($P < 0.05$). At 10:00 and 14:00, wind speed in Treatment 1 was significantly lower than the control ($P < 0.05$); at 12:00, wind speed in Treatment 2 was significantly reduced, with Treatment 1 showing significantly lower wind speed than Treatment 2 ($P < 0.05$).

Surface microclimatic patterns mirrored those of the air (Table 2). At 14:00, the surface temperature peaked at 27.65°C, 28.90°C, and 44.50°C in Treatments 1, 2, and the control, respectively. Compared to the control, Treatment 1 showed a significant decrease in surface temperature at 12:00 ($P < 0.05$), and both Treatment 1 and 2 showed reductions at 14:00 ($P < 0.05$). Treatment 1 also had significantly higher surface humidity at multiple time points (08:00, 12:00, 16:00, and 18:00). Surface light intensity in Treatment 2 was significantly lower than in the control at most time points, while Treatment 1 showed significantly lower values than Treatment 2 ($P < 0.05$). Wind speed measurements followed a similar trend, with both vegetated treatments reducing wind speed significantly compared to the control.

Subsurface temperature measurements at 5 cm depth revealed a similar temporal pattern to surface and air temperatures (Table 3), showing a general increase followed by a rise and fall during the day. Peak subsurface temperatures at 14:00 were 25.70°C, 27.15°C, and 34.10°C in Treatments 1, 2, and the control, respectively, with Treatment 1 significantly lower than the control ($P < 0.05$).

Table 1
Plant community air temperature, humidity, light level and wind speed test results

time	Treatment 1				Treatment 2				control(CK)			
	Temp-erature/ °C	Humi-dity /%	light level /lx	wind speed m/s	Temp-erature/ °C	Humi-dity /%	light level /lx	wind speed m/s	Temp-erature/ °C	Humi-dity /%	light level /lx	wind speed m/s
06:00	14.90a	61a	9.50a	1.50a	15.55a	55a	9.50a	2.20a	16.65a	43a	14.50a	2.25a
08:00	16.20a	58a	2660b	0.95b	16.20a	50ab	3695b	0.95b	16.65a	37b	7565a	1.60a
10:00	20.95a	53a	9270c	0.85b	21.30a	41ab	19700b	1.10ab	21.90a	29b	98900a	1.40a
12:00	26.15a	39a	10000c	0.80c	26.65a	34a	28300b	1.50b	30.30a	28a	167950a	2.35a
14:00	30.90a	32a	14700c	2.00b	31.80a	28ab	73250b	2.95ab	37.55a	21b	211000a	3.65a
16:00	29.10a	34a	30200c	2.60b	29.85a	29ab	72600b	3.00b	31.85a	21b	132150a	4.70a
18:00	25.20a	40a	25100b	1.80b	26.15a	34ab	37400b	2.10b	27.90a	24b	118200a	4.05a
20:00	22.20a	48a	10800b	2.45a	21.60a	44a	15575b	2.80a	21.00a	35a	47580a	3.30a

Note: Different lowercase letters in the same row indicate that the difference of the same index between different treatments is significant ($P < 0.05$), the same as Table 2, Table 3 and Table 5 below.

Table 2
Plant community surface temperature, humidity, illumination and wind speed test results

time	Treatment 1				Treatment 2				control(CK)			
	Temperature/ °C	Humidity /%	light level /lx	wind speed m/s	Temperature/ °C	Humidity /%	light level /lx	wind speed m/s	Temperature/ °C	Humidity /%	light level /lx	wind speed m/s
06:00	15.60a	69a	2c	0.40c	15.60a	60a	5.5b	0.85b	15.50a	48a	9a	1.30a
08:00	16.60a	64a	895c	0.40b	16.95a	55ab	1430b	0.50b	15.75a	42b	6360a	1.05a
10:00	19.55a	59a	5155c	0.40b	21.00a	46ab	10615b	0.55b	24.85a	30c	82300a	0.90a
12:00	24.60b	44a	6000c	0.40b	27.15ab	40ab	15050b	0.50b	37.20a	27b	145450a	1.40a
14:00	27.65b	38a	8650c	0.40c	28.90b	33ab	30900b	0.95b	44.50a	25b	176650a	2.85a
16:00	27.40a	40a	11200c	0.60c	28.00a	33ab	25200b	1.00b	39.25a	25b	111700a	3.15a
18:00	24.10a	46a	10300c	0.25c	25.55a	39ab	16650b	0.80b	30.95a	29b	65850a	2.95a
20:00	23.55a	54a	6002b	0.20b	22.80a	50a	7175b	0.30b	21.70a	39a	17395a	2.10a

Table 3
Test results of below-ground (-5 cm) temperature (°C) of plant communities

time	Treatment 1	Treatment 2	control(CK)
06:00	16.00 ± 1.54a	16.00 ± 1.91a	15.50 ± 2.04a
08:00	17.00 ± 0.96a	17.00 ± 1.07a	16.00 ± 0.85a
10:00	19.00 ± 1.15a	20.00 ± 1.62a	21.00 ± 1.73a
12:00	23.00 ± 2.33a	23.65 ± 1.95a	26.15 ± 1.42a
14:00	25.70 ± 2.19b	27.15 ± 2.36ab	38.10 ± 1.90a
16:00	25.05 ± 1.84a	26.95 ± 1.58a	28.55 ± 2.03a
18:00	23.35 ± 1.25a	24.00 ± 1.77a	26.35 ± 1.00a
20:00	20.00 ± 0.92a	20.00 ± 0.81a	20.35 ± 0.64a

Diurnal Variation of Air, Surface, and Subsurface Temperatures

Both Treatments 1 and 2 exhibited lower air, surface, and subsurface temperatures compared to the control group (Table 4; Fig. 2). Temperature variations throughout the day followed an “S-shaped” curve. Maximum surface temperatures in Treatments 1 and 2 were significantly lower than in the control ($P < 0.05$), as were maximum subsurface temperatures in Treatment 1. Additionally, the diurnal temperature range in air, surface, and subsurface layers was significantly narrower in Treatment 1 than in the control ($P < 0.05$), indicating that vegetation cover effectively moderated temperature extremes. Daily minimum temperatures for all plots occurred at 04:00, while maximum temperatures were recorded at 14:00. At 04:00, the lowest air, surface, and subsurface temperatures for Treatment 1 were 14.40°C, 14.75°C, and 16.00°C, respectively; for Treatment 2, these were 14.20°C, 14.55°C, and 16.00°C; and for the control, 13.70°C, 13.30°C, and 15.00°C.

Table 4
Test results of air, surface and subsurface temperatures of plant communities-Daily averages

Treatm-ent	Temperature indicators								
	Maxim-um temperat-ure (°C)	Minimum temperatu-re (°C)	Diurnal temperature range (°C)	Surface maximum temperatu-re (°C)	Surface minimum temperatu-re (°C)	Surface diurnal temperature range (°C)	Undergr-ound maximum temperature (°C)	Undergr-ound minimum temperatu-re (°C)	Below-ground diurnal temperatu-re range (°C)
Treatme-nt1	30.90a	14.40a	16.75b	27.65b	14.75a	12.90b	25.70b	16.00a	9.70b
Treatme-nt2	31.80a	14.20a	17.50ab	28.90b	14.45a	14.35b	27.15ab	16.00a	11.50b
control(CK)	37.55a	13.70a	23.25a	44.50a	13.30a	31.20a	38.10a	15.00a	19.10a
Note: Different lowercase letters in the same column indicate significant differences between treatments ($P < 0.05$). Table 6 below is the same.									

Effects of Vegetation Assemblages on Soil Physical Properties

As soil depth increased, soil water content and total porosity in Treatments 1 and 2 initially rose and then declined, while bulk density showed the opposite trend—decreasing and then increasing. In contrast, the control group exhibited a gradual increase in soil water content and porosity with depth and a corresponding decrease in bulk density (Table 5). In the 0–40 cm soil profile, Treatment 1 had significantly higher water content than the control ($P < 0.05$). The 20–30 cm layer recorded the highest water content (5.56% for Treatment 1, 4.14% for Treatment 2), the greatest total porosity (43.35% and 41.3%, respectively), and the lowest bulk density (1.11 g/cm³ and 1.25 g/cm³). From 20–50 cm, total porosity in Treatment 1 was significantly higher than in the control ($P < 0.05$), indicating enhanced soil structural development under vegetative cover.

Table 5
Soil physical property test results

sampling depth(cm)	Treatment 1			Treatment 2			control(CK)		
	Moistu-re content (%)	capacity (g/cm^3)	total porosity (%)	Moistu-re content (%)	capacity (g/cm^3)	total porosity (%)	Moistu-re content (%)	capacity (g/cm^3)	total porosity (%)
0～10	4.04a	1.23a	32.16a	2.92ab	1.42a	38.81a	2.34b	1.52a	36.50a
10～20	4.61a	1.22a	41.45a	3.22ab	1.38a	40.82a	2.68b	1.40a	34.99a
20～30	5.56a	1.11a	43.35a	4.14ab	1.25a	41.30ab	3.16b	1.35a	27.51b
30～40	5.31a	1.14a	35.20a	3.90ab	1.28a	33.14ab	3.33b	1.31a	23.32b
40～50	4.97a	1.18a	31.82a	3.74a	1.28a	28.12ab	3.58a	1.29a	20.89b

Effects of Vegetation Assemblages on Soil Chemical Properties

Marked differences in soil chemical characteristics were observed across treatments (Table 6). Both Treatments 1 and 2 exhibited significantly higher total nitrogen and organic matter contents compared to the control ($P < 0.05$), with Treatment 1 outperforming Treatment 2 ($P < 0.05$), suggesting enhanced soil fertility under improved vegetation structure. Treatment 1 also showed significantly greater total phosphorus content than the control ($P < 0.05$), although no significant differences were observed in total potassium levels among treatments. Soil pH was highest in the control group (7.9), followed by Treatment 2 (7.3), and lowest in Treatment 1 (6.8). Compared to the control, soil pH in Treatments 1 and 2 decreased by 13.92% and 7.6%, respectively, indicating a substantial acidifying effect associated with vegetation recovery.

Table 6
Results of soil chemical properties testing of plant communities

Treatment	Chemical indicators				
	Total N(g/kg)	Total P(g/kg)	Total K(g/kg)	Organic matter(g/kg)	pH value
Treatment 1	0.34a	0.62a	20.64a	5.86a	6.8a
Treatment 2	0.23b	0.49ab	20.16a	3.63b	7.3a
Control (CK)	0.12c	0.46b	20.05a	2.25c	7.9a

Discussion

Microclimatic Modulation by Vegetation Assemblages

Riparian zones are recognized as ecologically sensitive interfaces where vegetation restoration presents significant challenges [19]. The selection and spatial arrangement of plant species must align with local ecological adaptability and biogeographic principles to ensure restoration success. Our previous research identified a suite of tree, shrub, and herbaceous species with high ecological suitability for the central Yarlung Tsangpo region. Building on this, the present study demonstrates that, at 14:00, surface temperatures in both Treatments 1 and 2 were significantly lower than in the control group ($P < 0.05$). This supports the hypothesis that vegetation, via transpiration and canopy shading, can buffer against extreme surface temperatures—findings consistent with previous studies [20]. Subsurface temperatures were similarly moderated, indicating that increased vegetation coverage can influence deeper soil thermal regimes.

Significant reductions in light intensity were recorded across vegetated plots at all observation times (08:00，10:00，12:00，14:00，16:00，18:00 and 20:00), attributed to increased canopy density and shading effects. Notably, Treatment 1 consistently exhibited lower light intensities than Treatment 2 ($P < 0.05$), confirming denser plant coverage and a more developed vertical structure. These findings parallel earlier work on vegetation-induced light attenuation [21].Wind is a critical driver of aeolian processes and strongly influences vegetation dynamics [22,23]. Our study found that vegetated treatments significantly reduced both surface and air wind speeds compared to the control, particularly in Treatment 1. This indicates the potential of woody–shrubby–herbaceous systems to mitigate wind erosion and stabilize sandy substrates—echoing prior research conducted in similar desert environments [24].Microclimate stabilization was further reflected in increased humidity across vegetated plots. At multiple time points (08:00，10:00，14:00，16:00 and 18:00), both air and surface humidity levels were significantly higher in Treatment 1 ($P < 0.05$). This may result from reduced wind-driven evaporation and the ability of dense vegetation to retain transpired and soil-emitted moisture [25,26].

The diurnal temperature range (DTR) of air, surface, and subsurface temperatures, defined as the difference between the maximum and minimum temperatures within a day, is an important indicator of climate change [27,28]. Vegetation cover not only affects surface and subsurface temperatures but also significantly influences the DTR of air, surface, and subsurface temperatures. In this study, the DTR of air in Treatment 1 was significantly lower than that in the control group ($P < 0.05$). The maximum surface temperature in both Treatment 1 and Treatment 2 was significantly lower than that in the control group ($P < 0.05$), and the DTR of surface and subsurface temperatures in these treatments was also significantly lower than that in the control group ($P < 0.05$). These findings indicate that tree–shrub–grass plant communities have the capacity to stabilize regional temperatures and prevent the occurrence of extreme temperatures. This effect may be attributed to the ground cover provided by the vegetation, which shields the soil from direct sunlight during the day and reduces temperature drops caused by wind at night. Additionally, the reduction in wind speed is also an important factor influencing the DTR of air, surface, and subsurface temperatures.

Improvement of Soil Physical and Chemical Properties

Soil total porosity, bulk density, and moisture content are key indicators of soil physical properties [29,30,31]. In this study, in the 20–50 cm soil layer, the total porosity of soil in Treatment 1 was significantly higher than that in the control group ($P < 0.05$). This indicates that the root systems of tree–shrub–grass plants can improve soil aggregate structure, which is of great physical significance for accelerating the soil formation process of sandy soils in desertified areas. The reason may be that the dead branches and leaves of tree–shrub–grass plants mix with the sandy soil, providing necessary nutrients for microbial activity. Meanwhile, with the increase of dead branches and leaves, microbes become more active, thereby increasing soil porosity. This is similar to the findings of Yang et al.[32] on the impact of straw returning duration on the physical properties of the plow layer soil. In this study, in the 20–30 cm soil layer, the total porosity of soil in Treatment 1 and Treatment 2 reached the maximum, while the soil bulk density reached the minimum. The reason may be that the root systems of the tree–shrub–grass plant community are concentrated in this soil layer. In the 0–40 cm soil layer, the soil moisture content in Treatment 1 was significantly higher than that in the control group ($P < 0.05$). This indicates that the root systems of the tree–shrub–grass plant community under Treatment 1 have a strong water retention capacity. The reason may be the increase in soil total porosity and the decrease in bulk density.

The improvement of soil physicochemical properties and the promotion of microbial activity accelerated the decomposition of returned materials, thereby increasing soil nutrient content and enzyme activity [33,34,35]. In this study, the total nitrogen and organic matter content of the soil in Treatment 1 and Treatment 2 were significantly higher than those in the control group ($P < 0.05$). This indicates that tree–shrub–grass plants have the ability to enrich soil fertility, which is of great ecological significance for reducing the amount of fertilizer applied to sandy lands and improving their productivity. This is consistent with the findings of Wei et al. [36]on the effects of mixed sowing of *Medicago ruthenica* and *Agropyron cristatum* on soil nutrient content and enzyme activity in grasslands. Moreover, compared with Treatment 2, the total nitrogen and organic matter content of the soil in Treatment 1 were significantly higher ($P < 0.05$), indicating that Treatment 1 has a greater capacity to enrich soil fertility than Treatment 2.

The soil pH value, which serves as an indicator of soil acidity or alkalinity, can alter the distribution and transformation of soil nutrients through its effects on the physical, chemical, and biological properties of soil [37,38]. In this study, the control group had the highest soil pH value (7.9), while the soil pH values in Treatment 1 and Treatment 2 were reduced by 13.92% and 7.6% respectively compared with the control group. This suggests that the pH value of sandy soil is alkaline, and the tree–shrub–grass plants have reduced the pH value of sandy soil. The reason may be that the absorption by tree–shrub–grass plants and the leaching effect of precipitation have led to the consumption of base cations by plants [39].

Conclusions

The vegetative assemblage comprising *Cupressus gigantea*, *Sophora moorcroftiana*, *Medicago sativa*, *Melilotus officinalis*, *Eragrostis nigra*, and *Astragalus adsurgens*, structured in a stratified the tree–shrub–grass configuration and supported by cultivation facilities (geocell structures and rainwater-collecting trays), formed a synergistic system in which species coexisted harmoniously, promoting ecological stability and functional integration.The tree–shrub–grass planting model composite ecosystem significantly improved microclimatic conditions—reducing wind speed, increasing relative humidity, and stabilizing air, surface, and subsurface temperatures. Concurrently, it enhanced soil physical and chemical properties by lowering bulk density and pH while increasing porosity, water content, and concentrations of organic matter, total nitrogen, total phosphorus, and total potassium.The integrated configuration mode of the tree–shrub–grass combination of Cupressus gigantea, Sophora moorcroftiana, Medicago sativa, Melilotus officinalis, Eragrostis nigra, and Astragalus adsurgens, combined with rainwater-collecting trays and geocell structures, can achieve comprehensive restoration of the environment, soil, and ecology. This approach is conducive to rebuilding a favorable ecological environment in the riparian sandy lands of the middle reaches of the Yarlung Tsangpo River and to realizing the sustainable use of water and soil resources.

Declarations

The authors declare no competing interests.

Author Contribution

Jiajia Zhang designed the experiment;Yanhui Ye , Xianlei Gao and Chuanqi Wang,conducted experiments, Chuanqi Wang wrote papers, Yanjun Miao revised the papers.

Acknowledgements

This study was funded by a project chaired by Prof. Yanjun Miao of Xizang Agricultural and Animal Husbandry University Key R&D and Transformation Projects of the Department of Science and Technology of the Tibet Autonomous Region (CGZH2024000084).

Data Availability

Data will be made available on request. If anyone needs data from this study, they can contact the first author, Jiajia Wang.

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Figures

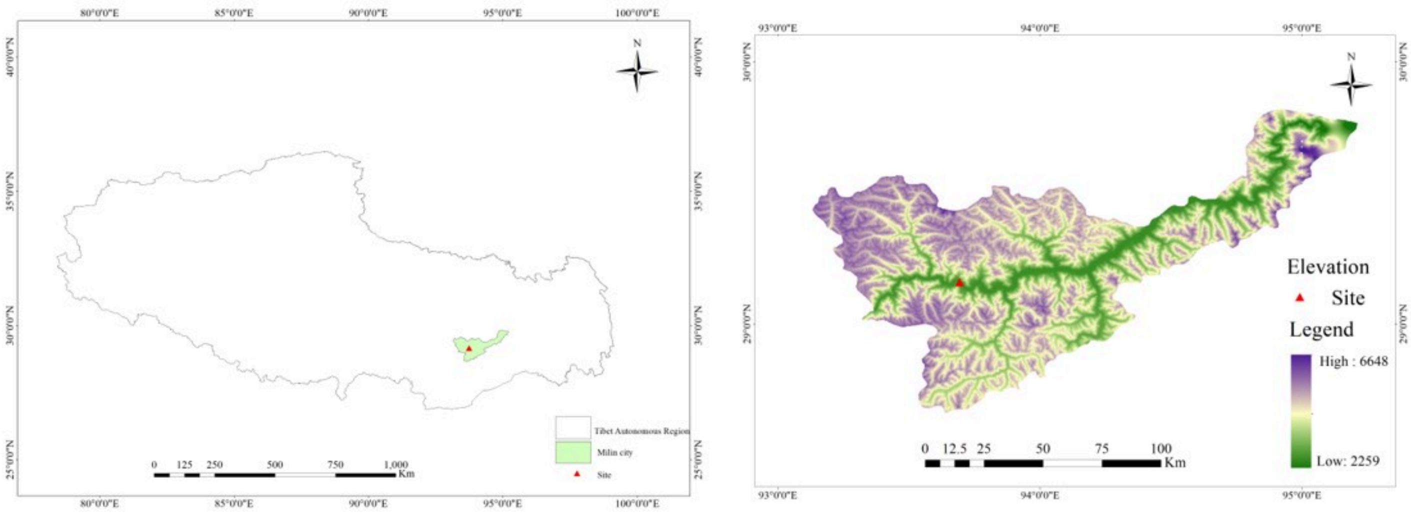

Figure 1

Overview map of the Study area

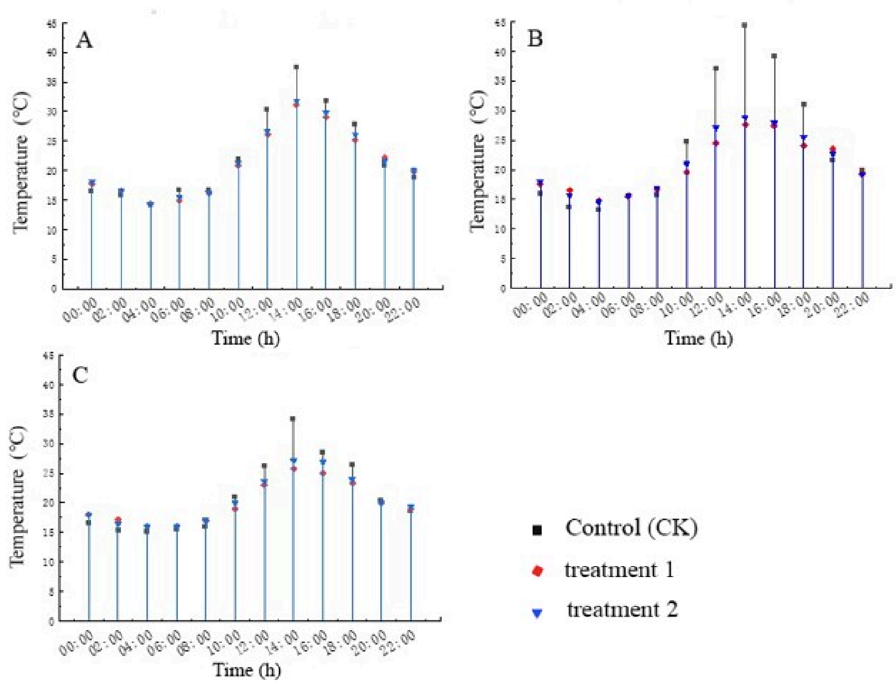

Figure 2

Daily variation of air, surface and subsurface temperatures in plant communities

A air temperature; B surface temperature; C subsurface temperature