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Plant investigation and the impact on earthen site soil properties in the east city wall of the Sanxingdui site

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Abstract

In southern China, vegetation on exposed earthen sites serves not only to mitigate erosion but also alters their visual appearance, leading to biodeterioration. However, how plants influence the properties of earthen sites is virtually unknown. This study undertook an ecological investigation of the original habitat in the east city wall of the Sanxingdui site, analyzing its soil properties and investigating plant-soil interactions. Research findings indicate that existing plant communities are not conducive to biodiversity nor site presentation. Plants exert a direct influence within a vertical range extending 0–40 cm beneath the site; root content correlates negatively with soil pH value but positively with organic matter content. The herbaceous community (E-2 and E-3) exhibits higher clay content than the arbor community (E-1) within this range. The above conclusions exhibit statistical significance. This study offers a scientific elucidation of the ecological parameters governing plant communities concerning the conservation of earthen sites, and provides an initial influence range of plant communities and biodegradation on the east city wall of the Sanxingdui sites, thereby revealing the technical potential for employing plants as a soft capping for earthen sites in the open air from the function method.

Keywords Plant investigation, Impact, Soil properties, East city wall of the Sanxingdui site

Introduction

In southern China, a multitude of earthen sites have been preserved, distinguished by their diverse characteristics, long-term historical usage, and significant cultural value. However, the warm and humid climate in this region results in heavy rainfall year-round, leading to severe biodegradation of these sites. Conserving the earthen site in the open air is exceedingly challenging. While preservation techniques for dry-climate earthen sites have been developed, effective solutions for preserving earthen sites in humid environments are still lacking. The lush vegetation covering the earthen sites in humid environments not only slows down erosion but also obscures their appearance, posing a risk of biodegradation. Addressing how to fully harness the protective role of plants on these sites while minimizing negative impacts is an urgent issue that needs attention. This study focuses on the east city wall of the Sanxingdui site to investigate three specific issues: (a) the ecological characteristics of the plant communities in the east city wall of the Sanxingdui site and their significance on earthen site conservation, (b) the direct influence depth range of the existing plants on the east city wall, (c) within the influence range, the effects of plant community types on-site soil properties. The above issues are crucial for elucidating the weathering

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impact of vegetation on earthen sites and serve as important prerequisites for implementing vegetation soft capping technology in humid environments for earthen site conservation.

It is a common phenomenon for plants to grow on heritage sites in the open air, and utilizing plants to conserve these heritage sites is a new conservation approach that has been proposed in recent years. The traditional field of cultural heritage conservation believed that plants have a negative impact on sites in the open air [1–3]. As research into the value of cultural heritage and deterioration mechanisms deepens, scholars at Oxford University were the first to recognize that plants in outdoor sites play a dual role [4]. They have used plants to protect outdoor stone architecture through a method known as soft capping [5]. Extensive practical experience and long-term monitoring in Europe have shown that using plant soft capping can effectively mitigate the erosive effects of rainfall, regulate micro-environment humidity, and increase evaporation rates for conserving outdoor cultural relics [4–9]. This approach shows great potential as an environmentally friendly conservation method balancing both cultural heritage and ecological values. However, current experimental subjects primarily focus on stone architectures with relatively less research on using soft capping to conserve earthen sites. The interaction of plants on soil is complex. On one hand, plant stems and leaves can alleviate rainfall erosion while their evaporation action and reinforcing or anchoring action can enhance soil shear strength [10, 11]. On the other hand, plant root systems may induce crack development and rainwater infiltration leading to slope instability [12, 13]. Additionally, decomposition products from plant tissues can accelerate soil biodegradation [12, 13]. Currently, there is limited comprehensive study on these combined effects acting upon the same object.

From 2010, Chinese scholars conducted fundamental research on original plants for earthen sites in the arid region of northwest China [14–19]. The study proposed selection principles for plants used in soft capping in arid areas and conducted technical feasibility analysis for existing projects [1, 2]. In the southern part of China, with its humid climate and lush vegetation, the effects of vegetation on earthen sites are complex, and their interaction is unclear. The protective effects and destructive mechanisms are also unknown. There has been a lack of extensive vegetation surveys at earthen sites in humid environments. Uncontrolled vegetation growth at many open-air earthen sites affects their display. Some ongoing projects have cleared all existing plants and replanted lawns, significantly impacting the authenticity and ecological stability of these sites. Currently, most of the research on how the plants influence the earthen sites is aimed at the plants' deterioration and plant species and adopted method of case studies [14, 16–18], without delving into the mechanisms underlying plant–soil interactions. Mature conclusions have been drawn in the fields of soil and water conservation and engineering geology, regarding the role of plants and agricultural soil, along with engineering slopes [10, 11]. However, earthen sites are different from the usual research objects. On one hand, the earthen sites carry significant archaeological value, while the materials and construction techniques are tangible evidence of the ancient adaptation and transformation of the natural environment. On the other hand, concerning the demand for display utilization, open-air earthen sites should optimize the presentation of the site's form and orientation while ensuring its safety and interpreting its archaeological value. Therefore, research findings from other fields can only serve as a reference, rather than being directly applicable. The key to effectively utilizing soft capping for earthen site conservation lies in finding the optimal balance between aesthetics and maximizing plant protection effects. Understanding how plants influence the properties of the soil is essential for achieving this balance. This study established a correlation between ecological parameters of plants and soil properties at the earthen site, clarified an initial mechanism of plants in conserving earthen sites, and laid a foundation for further research into soft capping technology.

Study object

The Sanxingdui site is located in Guanghan, Sichuan Province, China, and was the capital of the ancient Shu (Fig. 1). The site originated in the late Neolithic period and lasted until the Shang and Zhou dynasties, and it is the largest and best-preserved pre-Qin period site in the upper reaches of the Yangtze River in China. The site encompasses an area of approximately 12 square kilometers, with the Sanxingdui ancient city serving as its core. The city's layout exhibits an irregular trapezoidal shape, wider towards the south and covering around 3.6 square kilometers in total. It comprises city walls, substantial architectural foundations, sacrificial sites, and various other relics [20]. The initial archaeological excavation was conducted during the 1930s. Subsequent excavations in the sacrificial area took place in 1986 and from 2019 to 2022, unearthing a significant multitude of ivory, bronze, gold, and jade artifacts that serve as crucial tangible evidence attesting to the advanced ancient Shu civilization [21].

The city wall consists of the east city wall, west city wall, south city wall, the Yueliangwan City Wall, the Sanxingdui City Wall, and the Cangbaobao city wall (Fig. 2) [20]. Among them, only the profile of the Yueliangwan city

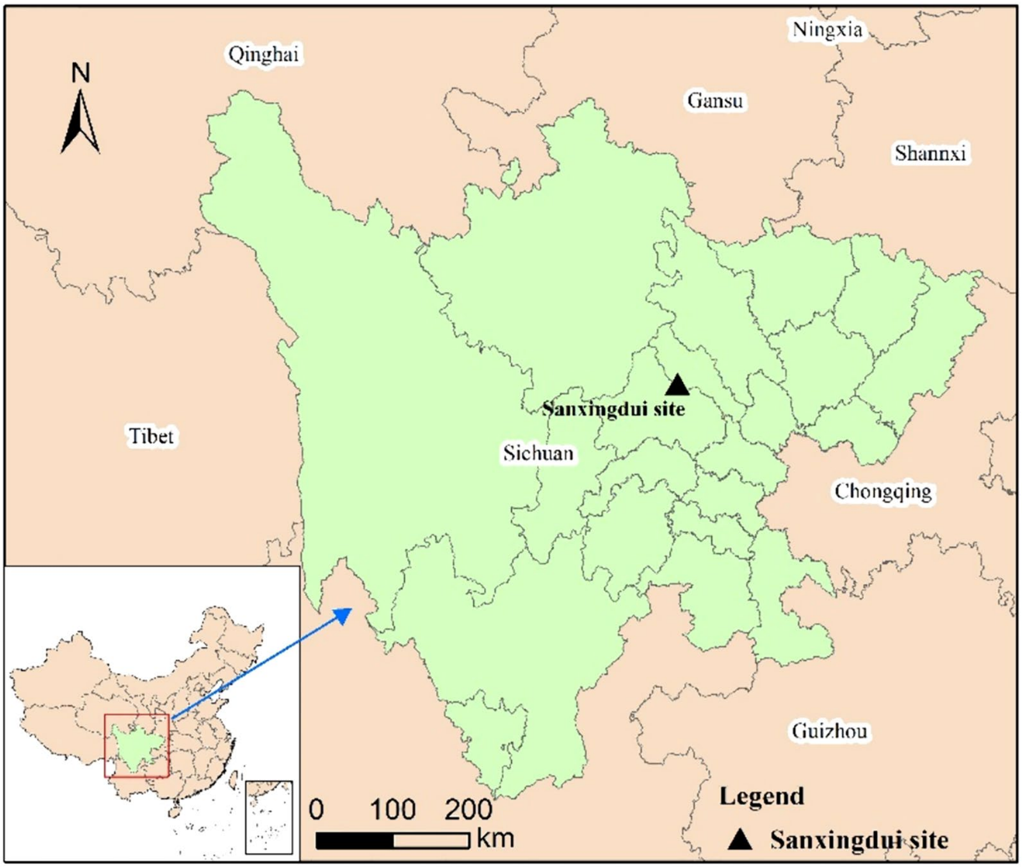

Fig. 1 Location of the Sanxingdui site

wall has been built a protective construction for protection and display, and the rest is open display. The site area is of abundant rainfall throughout the year, and the climate is mild, so the plants growing on the surface of the city wall are very lush, and the vegetation coverage is very high. This has two influences. On the one hand, the vegetation reduces the erosion of the wall by abundant rainfall, which is a key reason why most of the earthen sites in southern China have been preserved to this day. On the other hand, the extremely high vegetation coverage obscures the shape of the wall, making it impossible to show the original shape of the site, destroying the archaeological value and aesthetic character (Fig. 3). Most of the earthen sites in the open air in southern China face the same situation. The city wall of the Sanxingdui site is the typical representative. This investigation aims at the currently well-preserved east city walls of the Sanxingdui site.

The climate in Guanghan is a typical continental monsoon climate. Spring exhibits lower precipitation levels, while summer brings high temperatures and frequent rainstorms. Autumn is characterized by continuous rainfall, whereas winter tends to be dry yet warm with foggy conditions. Based on meteorological data, the annual average temperature in this region stands at 16.3 °C, peaking in July and August and reaching its lowest point in January. The average annual precipitation measures 890.8 mm, primarily concentrated during the summer months of July and August. Additionally, the average annual relative humidity reaches 82%, with monthly averages ranging between 75 and 85%.

This research selected the exposed section of the east city wall in the Sanxingdui site as the research object. The site depicted in Fig. 2 is encompassed by permanently designated arable land located within the central conservation zone. The east city wall is located on the eastern side of the site, oriented northeast-southwest (14° southwest), and spans approximately 400 m in length [20]. As depicted in Fig. 4, an orthophoto reveals that the east city wall is encompassed by farmland on all sides, while being divided into three segments by roads and canals within its central portion. The wall exhibits a stepped profile, with a width ranging from about 20–30 m at its upper part, 30–40 m at its lower part, and standing at a height between 3 and 5 m [20]. Adjacent to the eastern side of the wall lies a trench extending over 40 m wide along

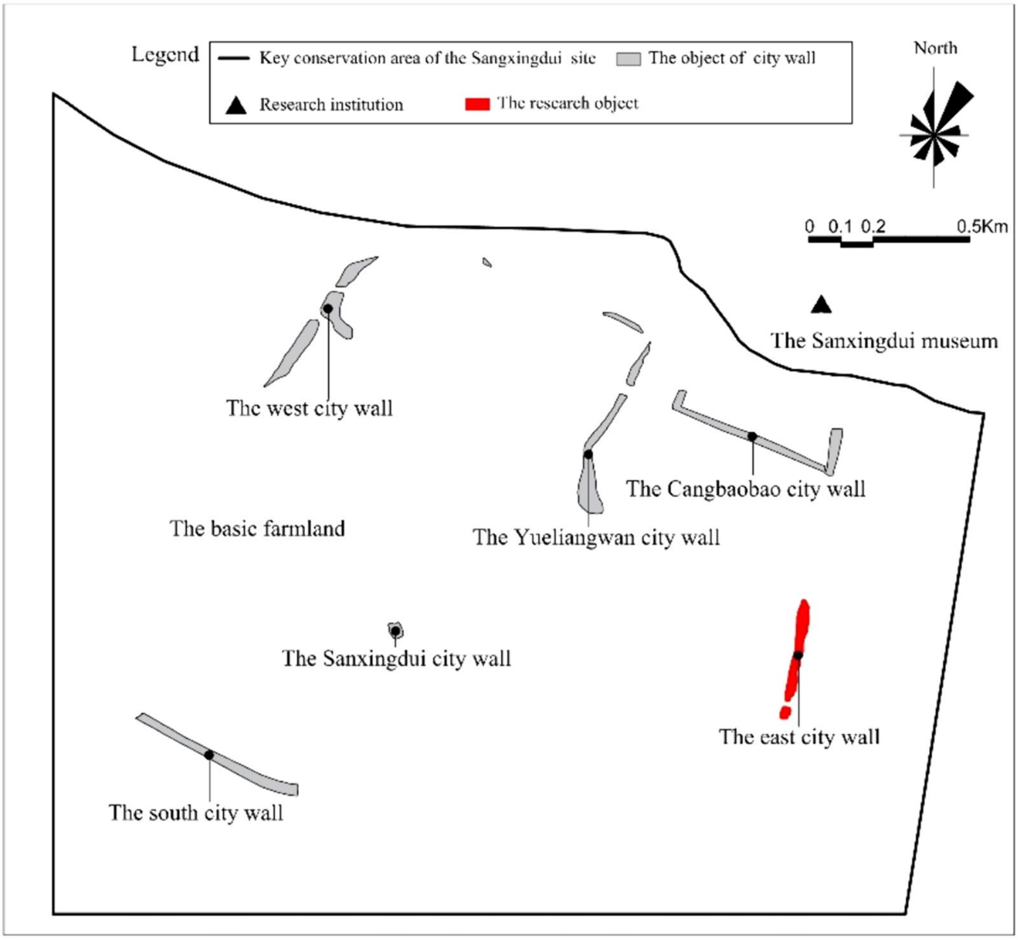

Fig. 2 Distribution of the city wall in the Sanxingdui site

Fig. 3 Plants cover the city wall (**a**: The northern facade of the southern section of the east city wall. **b**: The south side of the east city wall)

its direction. The city walls were composed of a central main wall and auxiliary walls on both the inner and outer sides (Fig. 5). The main wall was constructed horizontally in layers, while the auxiliary walls exhibited an angled construction technique, with evidence of brick usage found in certain areas [20]. This architectural approach distinguishes it from contemporaneous wall-building techniques observed along the Yellow River and lower reaches of the Yangtze River in China, showcasing a pronounced regional characteristic.

Method

The study was conducted in the following steps: firstly, the authors employed the method of plant ecology investigation to understand the basic data of native vegetation on the east city wall of the Sanxingdui Site, and then the significance of ecological parameters for earthen site conservation was explained accordingly. Based on this, we investigated the direct influence range of plant roots on the east city wall. Finally, we explored the impact and variation characteristics of different community types on soil properties at the site.

Sample plot setting

Based on a comprehensive investigation, following the typical ecological plot survey method, the plots in the east city wall were consistently divided into 30 m×20 m sections with a 10 m interval between adjacent plots. Following Wu's classification and naming principles [22], the community's name is determined by the dominant species found within the surveyed area. According to a preliminary study [23, 24], the east city wall was divided into 12 sample plots representing three community types, as presented in Table 1.

The plant community parameters investigated in this study encompassed the number of families, genus, and species, the species importance value, and the biodiversity index. The Chinese Biological Species Catalogue classification system was utilized to compile the vascular plant catalog within the sample plot. For plants that could not be identified on-site, researchers take photos and collect specimens for identification by referencing the Flora of China and other relevant data sources. Importance value was used to characterize relative species importance, expressed through formula (1) [25].

$$I = \frac{D(\%) + F(\%) + T(\%)}{300} \tag{1}$$

Fig. 4 The orthophoto of the east city wall

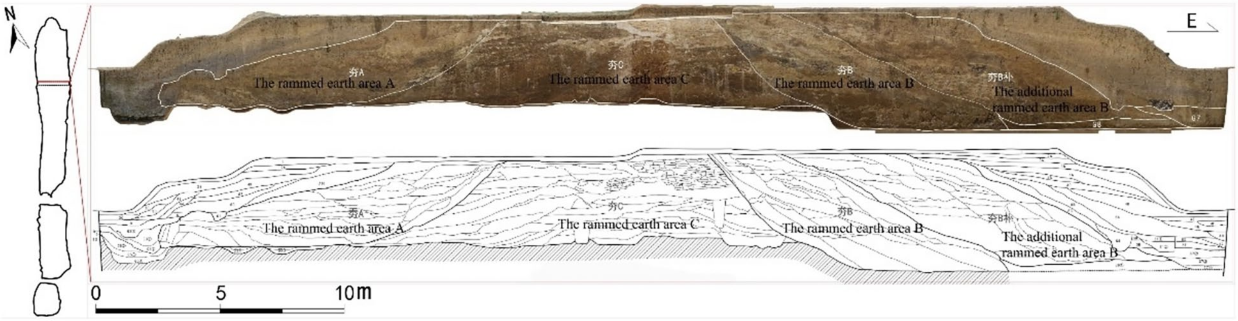

Fig. 5 Archeological cross-section of the east city wall

Table 1 Community of each plot

Community type	E-1	E-2	E-3
Number of plots	NO. 1, NO. 2, NO. 11, NO. 12	NO. 3, NO. 8, NO. 9, NO. 10	NO. 4, NO. 5, NO. 6, NO. 7

E-1: Ass. *Broussonetia papyrifera-Albizia kalkora* community, E-2: Ass. *Imperata koenigii-Symphyotrichum subulatum* community, and E-3: Ass. *Centella asiatica-Symphyotrichum subulatum* community

In formula (1), I represent importance value, D (%) denotes relative density, F (%) indicates relative frequency, and T (%) signifies relative significance.

The expression of species diversity represents the level of biodiversity. The plant community in the east city wall of the Sanxingdui Site is representative of the homogeneous habitat. In this study, we employed the Shannon–Wiener index (H), Simpson index (D), Pielou index (J_{sw}), and species richness index (S) to characterize α diversity within the community. The calculation formulas are presented from Formula (2) to Formula (5) [25].

$$H = -\sum_{i=1}^{S} P_i \log_2 P_i \tag{2}$$

$$D = 1 - \sum_{i=1}^{S} (N_i/N)^2 \tag{3}$$

$$J_{SW} \equiv H/\ln S \tag{4}$$

$$S = species\ richness\ in\ a\ plot \tag{5}$$

In these formulas, N_i denotes the number of individuals belonging to the ith species, N represents the total number of individuals across all species, S indicates the total number of species in the sample plot, and P_i signifies the proportion of individuals belonging to species i among all individuals.

Soil sample collection and property testing

Soil samples were collected in August 2023 (the most concentrated rainfall period in a whole year). To minimize intervention in the site, soil sample collection and archaeological probing were carried out at the same time. This sampling method can minimize the impact of rainwater backflow into the interior of the site. One exploratory hole was drilled in each plot. In the soil taken out by the probe shovel, samples are taken at a vertical interval of 10 cm, and the sampling range is 10–100 cm, for a total of 10 sets of depths and 120 samples (Fig. 6). Due to the special sampling method, the amount of soil samples involved in this study is very limited, while the engineering property tests of soil often require a large number of samples, which need two-to-three-kilogram soil in one sample. Therefore, this study does not involve the engineering property tests of soil.

The literature research suggests that root content serves as a conventional indicator, reflecting the direct impact of plants on soil [10, 11]. Organic content, pH value, soil macro-aggregates content, permeability coefficient, and grain size distribution are key factors influencing soil erodibility. Due to limitations in sampling volume, this study only examined root content, pH value, organic matter content, and grain size distribution [10, 11, 19]. The pH value is measured using an ion-selective electrode method; organic matter content is determined through potassium dichromate oxidation-external heating method; root content (dry weight) is assessed via weighing method; and the soil particle size analysis is conducted using a combination of sieve analysis and laser particle size analyzer. The obtained test results were subjected to a one-way analysis of variance and nonparametric tests to evaluate the impact of community types on soil properties. Additionally, Pearson correlation analysis was conducted to establish relationships between soil properties and ecological parameters. Data analysis was performed using SPSS software while Origin software was utilized for data visualization.

Result

Plant ecological investigation

The family, genus, species, and important value

The east city wall of the Sanxingdui site in summer comprises three community types: E-1 Ass. *Broussonetia papyrifera-Albizia kalkora* community, E-2 Ass. *Imperata koenigii-Symphyotrichum subulatum* community, and E-3 Ass. *Centella asiatica-Symphyotrichum subulatum* community (Table 2 and Fig. 7). The investigation result reveal that the E-1 community consists of an arbor

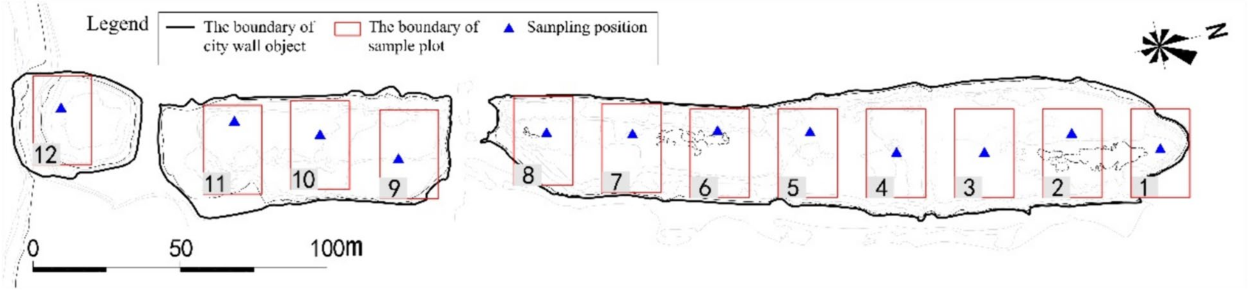

Fig. 6 Sampling plot and location

Table 2 The plant family, genus, and species in the east city wall

Plant layer	E-1			E-2			E-3		
	Family	Genus	Species	Family	Genus	Species	Family	Genus	Species
Arbor	10	11	11	/	/	/	/	/	/
Shrub	13	17	17	/	/	/	/	/	/
Herb	17	35	40	12	28	30	13	32	37
Total	40	63	68	12	28	30	13	32	37

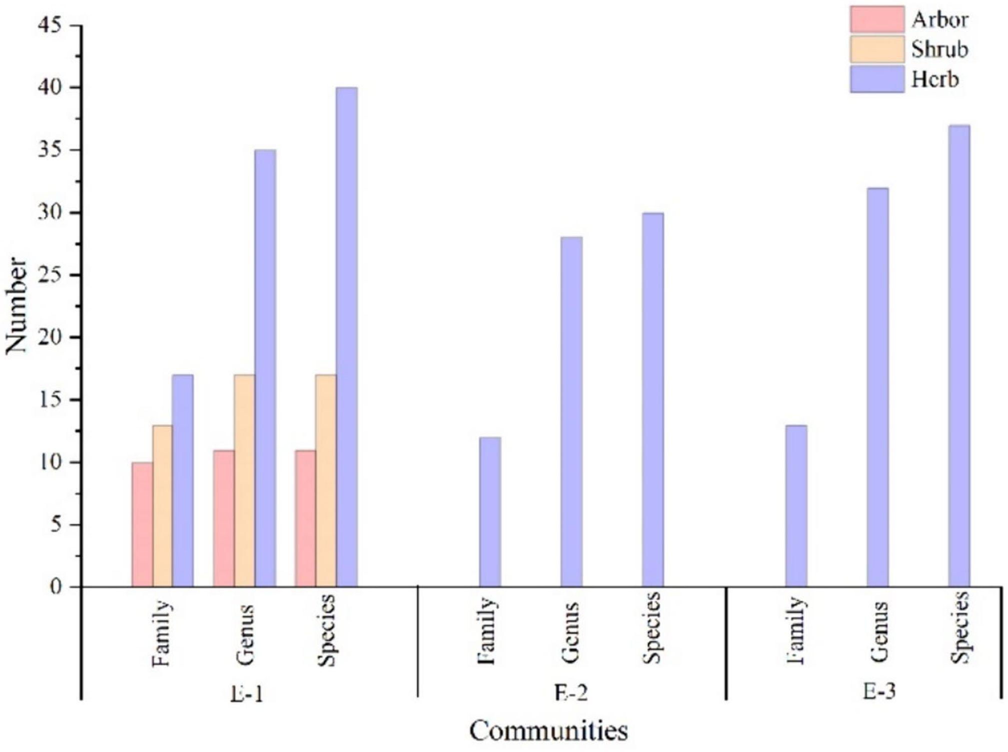

Fig. 7 The family, genus, and species of three communities

layer, shrub layer, and herb layer, while the E-2 and E-3 communities solely consist of an herb layer. Notably, the number of families, genus, and species observed in the herb layer is higher in the E-1 community compared to both the E-2 and E-3 communities; conversely, the lowest counts are recorded for families, genus, and species within the E-2 community.

The importance values of each species in the three communities were calculated using formula (1), and the results are presented in Table 3. The results indicate that *Broussonetia papyrifera* and *Camptotheca acuminata Decne* are the dominant species in the arbor layer of community E-1, while both *Broussonetia papyrifera* and *Nerium indicum* dominate the shrub layer. In addition, *Imperata koenigii* is identified as the dominant species in the herb layer in E-1. The dominant species in the herb layer of E-2 and E-3 communities were *Imperata koenigii*, *Symphyotrichum subulatum,* and *Centella asiatica.*

Species diversity

Species diversity in ecology has two meanings. On the one hand, it is the number of species. The second is the evenness of species, which reflects the evenness of the distribution of the number of individuals of each species [25, 26]. The four parameters in Table 4 used in this study are commonly used in ecology to characterize species diversity, and the larger the parameter value, the greater the species diversity. The four parameters in Table 4 were calculated from Formula (2) to Formula (5). Calculation results showed that among the plants in the herbaceous

Table 3 Importance Value of plant species in the east city wall

Community type	Plant layer	Importance value
E-1	Arbor	*Camptotheca acuminata* (0.236) + *Broussonetia papyrifera* (0.184) + *Albizia kalkora* (0.178) + *Eucalyptus robusta* (0.162) + *Koelreuteria bipinnata* (0.074)
	Shrub	*Broussonetia papyrifera* (0.677) + *Nerium indicum* (0.081) + *Albizia kalkora* (0.069) + *Camptotheca acuminata* (0.044) + *Rubus niveus* (0.020)
	Herb	*Arthraxon hispidus* (0.198) + *Imperata koenigii* (0.161) + *Chrysanthemum indicum* (0.156) + *Cirsium arvense var. integrifolium* (0.043) + *Spermacoce alata* (0.041)
E-2	Herb	*Imperata koenigii* (0.669) + *Symphyotrichum subulatum* (0.033) + *Vigna vexillate* (0.032) + *Centella asiatica* (0.031) + *Artemisia argyi* (0.028)
E-3	Herb	*Centella asiatica* (0.158) + *Symphyotrichum subulatum* (0.101) + *Artemisia argyi* (0.070) + *Justicia procumbens* (0.069) + *Cirsium arvense var. integrifolium* (0.060)

Table 4 Plant communities biodiversity index in the east city wall

Plant layer	Community type	H	D	S	J_{sw}
Arbor	E-1	1.082 ± 0.142	0.594 ± 0.054	5.750 ± 1.500	0.630 ± 0.074
Shrub	E-1	0.787 ± 0.412	0.267 ± 0.243	8.000 ± 2.828	0.374 ± 0.149
Herb	E-1	2.130 ± 0.536 b	0.775 ± 0.155 b	22.500 ± 3.416ab	0.685 ± 0.156 b
	E-2	0.823 ± 0.219 a	0.291 ± 0.074 a	17.750 ± 3.304 a	0.286 ± 0.063 a
	E-3	2.362 ± 0.0978 b	0.849 ± 0.021 b	24.250 ± 2.217 b	0.742 ± 0.026 b

Different letter show significant difference ($P < 0.05$)

layer of the east city wall, the four parameters of different communities were significantly different, with species diversity E-3 > E-1 > E-2, and the results showed that the E-3 community was richer in species and had stronger species uniformity.

Soil property tests

Root content, pH value, organic content

According to the literature review [10, 14, 27], there are three function modes of plants on soil, including the mechanical reinforcement by the root system, the hydrological effect by the stems and leaves, and the transpiration effect by the plant. Among them, mechanical reinforcement is the direct function, therefore, the root content of the site soil is used to characterize the direct influence range of the plant roots on the soil. In the field of traditional heritage conservation, it is believed that during the process of growth and development, plants produce organic acids which can alter the pH value and organic content of the soil, thereby influencing its weathering degree [1, 2, 12]. Consequently, the range of biological weathering is characterized by variations in pH value and organic content. The raw data are presented in the Additional file 1. A non-parametric test (Kruskal–Walli's method) was used to analyze the trend of root content of soils at different depths in 12 sample plots, and ANOVA was used to analyze the trend of pH value and organic content of soils at different depths in 12 sample plots. The analysis results are shown in Table 5 and Fig. 8.

The results indicate a significant decrease in root content across the 12 plots with increasing soil depth ($p < 0.01$). Plant roots were predominantly concentrated within the 10–20 cm soil layer, while root content data for the surface layer of 0–10 cm exhibited strong variability. Root content data for the 20–30 cm soil layer gradually stabilized, and below 40 cm, root content approached zero. The data presented above indicate that the root content of different community types may vary in the surface soil layer (0–20 cm). The pH values across 12 plots at varying depths exhibit minimal fluctuations, transitioning from weak acidity to neutrality with increasing depth. Below a depth of 40 cm, the pH remains stable and unchanged, yielding significant results ($p < 0.01$). Organic content decreases significantly with increasing depth across all 12 plots; notably, organic content is significantly higher in the surface layer (0–20 cm) than in deeper layers (20–40 cm). However, below a depth of 40 cm, organic content stabilizes and remains constant with significant results ($p < 0.01$). Based on these three analyses, we conclude that plant roots have a direct effect on soil within a range of 0–40 cm along the east city wall.

Table 5 Root content, pH value, and organic content in different depth

Depth	Non-parametric test	ANOVA		
	Root content (Median)	**pH value (Mean ± SD)**	**Organic content (Mean ± SD)**	
0–10 cm (*n* = 12)	1.540	5.86 ± 0.36	22.80 ± 3.47	
10–20 cm (*n* = 12)	0.425	6.28 ± 0.40	12.95 ± 3.79	
20–30 cm (*n* = 12)	0.060	6.53 ± 0.33	8.81 ± 2.31	
30–40 cm (*n* = 12)	0.015	6.80 ± 0.34	6.13 ± 2.07	
40–50 cm (*n* = 12)	0.010	6.88 ± 0.31	5.71 ± 1.93	
50–60 cm (*n* = 12)	0.010	6.89 ± 0.30	4.93 ± 1.45	
60–70 cm (*n* = 12)	0.000	6.88 ± 0.35	4.68 ± 2.00	
70–80 cm (*n* = 12)	0.000	6.86 ± 0.35	4.25 ± 1.30	
80–90 cm (*n* = 12)	0.000	6.86 ± 0.35	4.50 ± 1.90	
90–100 cm (*n* = 12)	0.000	6.86 ± 0.33	4.62 ± 2.19	
Kruskal–Walli's test *H* value	74.061	*F*	12.191	74.110
p	0.000**	*p*	0.000**	0.000**

**p* < 0.05; ***p* < 0.01

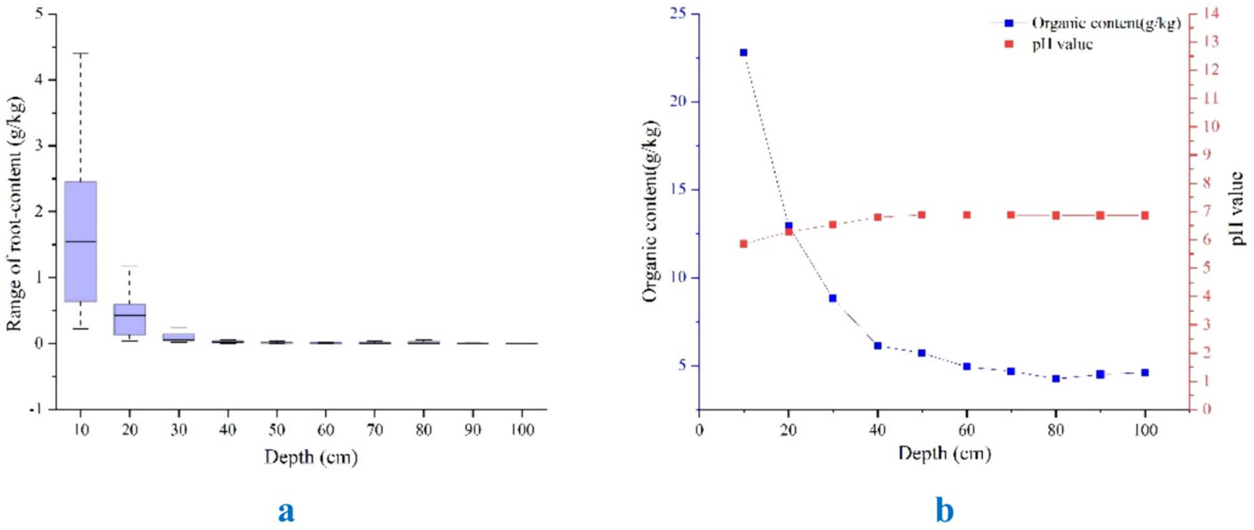

Fig. 8 Variation trend of root content, pH value, and organic content at different depths (**a**: Root content—Depth. **b**: pH value—Depth, Organic content—Depth)

Soil particle size

According to Table 5 and Fig. 8, the results indicate that plant roots have a direct influence on the soil within a range of 0–40 cm in the surface layer. Consequently, a comparative analysis is conducted between the particle composition of soil within the root depth range (0–40 cm) and outside this range (40–100 cm).

The results of grain size analysis and descriptive statistics of site soils are shown in Table 6. More than 90% content of all samples were fine-grained soils. The clay content of soils within the range of root depths (0–40 cm) was at about 10–40%, and the silt content was at about 60–80%. The above data fluctuated in a wide range, but the data of silt content at the same depths were more stable. Outside the root depth range (40–100 cm) the clay content is in the range of about 25–60%, and the silt content is in the range of about 35–70%, and the data fluctuation is large. All the samples showed that the silt content was significantly larger than the clay content. Most of the samples had less clay content within the root depth range than outside the root depth range, and more silt content than outside the root depth range.

Table 6 Particle size analysis of soil

Plot number		Within the root depth range (0–40 cm)		Outside the root depth range (40–100 cm)	
		Clay content % (≤ 5 μm)	Silt content % (5–75 μm)	Clay content % (≤ 5 μm)	Silt content % (5–75 μm)
NO. 1		27.03	71.04	42.04	57.25
NO. 2		9.66	86.01	42.82	53.11
NO. 3		52.58	47.42	63.56	36.44
NO. 4		36.34	63.67	36.76	60.14
NO. 5		33.60	62.79	38.59	59.75
NO. 6		43.54	56.46	25.58	74.43
NO. 7		35.26	63.06	28.02	71.99
NO. 8		42.73	55.73	46.99	52.04
NO. 9		32.61	67.39	33.85	66.16
NO. 10		40.10	59.91	39.26	60.75
NO. 11		22.12	77.89	41.13	55.03
NO. 12		30.59	62.05	41.17	56.51
Descriptive statistics	*Mean*	33.85	64.45	39.98	58.63
	SD	11.09	10.27	9.63	9.90
	CV	0.33	0.16	0.24	0.17

Discussion

Significance of ecological parameters to earthen sites

According to the results presented in Table 2, from the perspective of community hierarchical structure, the E-1 community exhibits a rich and complex composition comprising an arbor layer, shrub layer, and herbaceous layer. Amongst E-1, E-2, and E-3 communities, E-1 possesses the highest number of genera, species, and families. Based on the species importance values, the dominant species in the canopy layer of the E-1 community include *Camptotheca acuminata* (0.236), *Broussonetia papyrifera* (0.184), *Albizia kalkora* (0.178), *Eucalyptus robusta* (0.162). In terms of the shrub layer within this community, *Broussonetia papyrifera* stands out as the dominant species with an importance value of 0.677. Furthermore, *Arthraxon hispidus* (0.198), *Imperata koenigii* (0.161), and *Chrysanthemum indicum* (0.156) are identified as dominant species within its herbaceous layer. The E-2 and E-3 communities consist of single herbaceous plants, exhibiting a simple hierarchical structure. However, the E-3 community demonstrates greater richness in terms of genera, species, and families compared to the E-2 community. *Imperata koenigii* dominates the composition of the E-2 community with an importance value of 0.669, establishing its absolute advantage within the community. In contrast, *Centella asiatica* (0.158) and *Symphyotrichum subulatum* (0.101) are dominant species in the E-3 community. Considering community diversity, both species diversity and uniformity among species of the E-3 community are higher than E-2 communities due to the robust reproductive ability, environmental adaptability, and rapid growth of *Imperata koenigii*. *Imperata koenigii (Poaceae Barnhart, Imperata Cyr.)*, is recognized as one of the world's ten most detrimental weeds [28]. The plant exhibits dense and rigid scales at the tip of its root stems, rendering it exceptionally resilient and highly invasive. Its adaptability to various soil types and growing conditions significantly hampers the beneficial growth of other plant groups, thereby impeding ecological community diversity and stability [29, 30]. Consequently, this leads to diminished diversity and uniformity within the E-2 community, which adversely affects water and soil conservation and overall ecological stability at the site.

According to the preliminary study [23, 24, 27], the greater the number of family species and the higher the diversity index, the more stable the ecological dynamics within a community become, thereby enhancing soil resilience against external impacts. In conjunction with the present study, most of the dominant species in the E-1 community, such as *Broussonetia papyrifera* and *Camptotheca acuminata Decne*, exhibit a tree height exceeding 3 m. Due to resource distribution within the community, both the shrub layer and herb layer under the E-1 community are relatively sparse while deadwood thickness measures approximately 10 cm. The complex community structure during rainfall weakens soil erosion caused by kinetic energy while water retention on the soil surface is prolonged due to deadwood presence thereby accelerating biodegradation. The E-2 and E-3 communities exhibit a simple hierarchical structure with limited multi-level allocation of rainfall. The absence of arbors or shrubs occupying ecological niches within the community is notable. The dominant species in the herbaceous layer, *Imperata koenigii* and *Symphyotrichum subulatum*, typically reach heights from 80 to 180 cm. The restricted retention of rainfall by these dominant species is influenced by leaf morphology, suggesting that the rainfall buffering effect of the E-2 and E-3 communities on the site soil may be weaker than that of the E-1 community in theory. According to the existing analysis results, due to the relatively intricate community structure and diverse species, it is expected that the E-1 community would exhibit superior soil and water conservation effects compared to the E-2 and E-3. However, no significant differences in site soil deterioration were observed among the different communities during investigations. Notably, typical rain erosion phenomena such as gullies, erosion, desiccation cracking, and other deterioration were not evident in the entire east city wall. This phenomenon indicates that arbor community (E-1) and herbaceous communities (E-2 and E-3) provide similar conservation effects against local natural rainfall, and the native herbaceous community can achieve effective protection of the east city wall. The city wall of the Sanxingdui Site is being planned to be transformed into an archaeological site park for the public, to serve as a tangible medium for conveying the profound spiritual connotation embedded within the ancient Shu civilization and traditional Chinese culture. However, the presence of tall trees and dense dominant species obscures the visibility of the site, rendering it unrecognizable within its surrounding environment and significantly impeding its display. Considering site aesthetics and visual impact, both the tall trees and the lush *Imperata koenigii* and *Symphyotrichum subulatum* have significantly compromised their aesthetic appeal (Fig. 9), it is recommended to eliminate the arbor layer and species such as *Imperata koenigii* and *Symphyotrichum subulatum* from the native plant community, as this measure would not compromise the protective effect of the plants on the east city wall. This recommendation aligns with the guidance provided by the University of Oxford regarding the use of soft capping for stone architectures [4–6, 8].

Variation of root content, pH value, and organic content with depth in site soils of different communities

The plants function directly on the soil through the root-soil interaction zone. Root content, pH value, and organic content are three key indicators of the direct function of plant roots on soil. In this research root content, pH value, and organic content did not show statistically significant differences between community types and different depths. This is because all samples were collected from soils brought out by the probe shovels, and the differences in root content between soil samples from different communities were not significant due to the volume and number of soils. Descriptive statistics of the base data in the Attachment revealed that the standard deviations and coefficients of variation of the three parameters of soils at different depths in a total of 12 sample plots from the three communities (4 sample plots/colonies) were relatively small, and to explore the trends of the three soil properties with depth in the different communities, line plots were made using the mean values of the soil properties of the four sample plots at the same depths (Fig. 10).

In Fig. 10, the graph shows that the root content from 0 to 20 cm is E-3 > E-2 > E-1. Between 20 and 40 cm, all three communities exhibit a significant decline in root content. Below 40 cm, root content stabilizes and approaches zero. The variation in root content among the three communities is influenced by the root system characteristics of plants as well as the sampling method employed. The root system of *Broussonetia papyrifera* primarily consists of a taproot, three to five primary roots, numerous secondary roots, and fine hair roots arranged radially (Fig. 11). Surface roots are relatively thick, with their number decreasing and fineness increasing with depth. According to this survey, *Broussonetia papyrifera* has a horizontal root spread of approximately three meters and can grow up to a vertical depth of one meter (Fig. 11). Due to the dominance of *Broussonetia papyrifera* in the E-1 community, the shrubs and herbs in this area exhibit relatively reduced height compared to those in the E-2 and E-3 communities. The root system of the herbs is comparatively less developed, and there is a slightly lower root content on the surface of the site (0–20 cm) than that of the E-2 and E-3 communities. The dominant species in E-2 and E-3 communities are *Imperata koenigii* and *Symphyotrichum subulatum*, which exhibit environmental adaptability, rapid growth rates, and occupy a wide ecological niche. In the absence of competition for resources from arbors and shrubs, they have a higher likelihood of becoming dominant compared

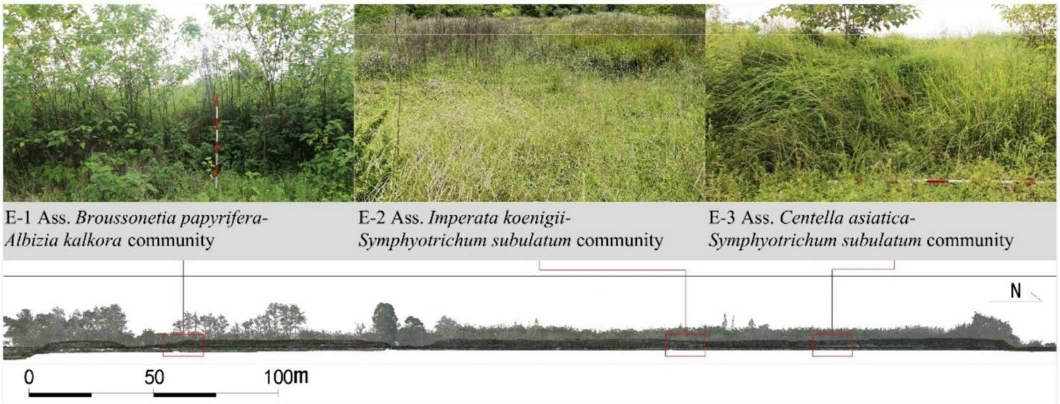

Fig. 9 The presence of towering trees and luxuriant herbaceous plants obscures the visibility and the aesthetic of the city walls

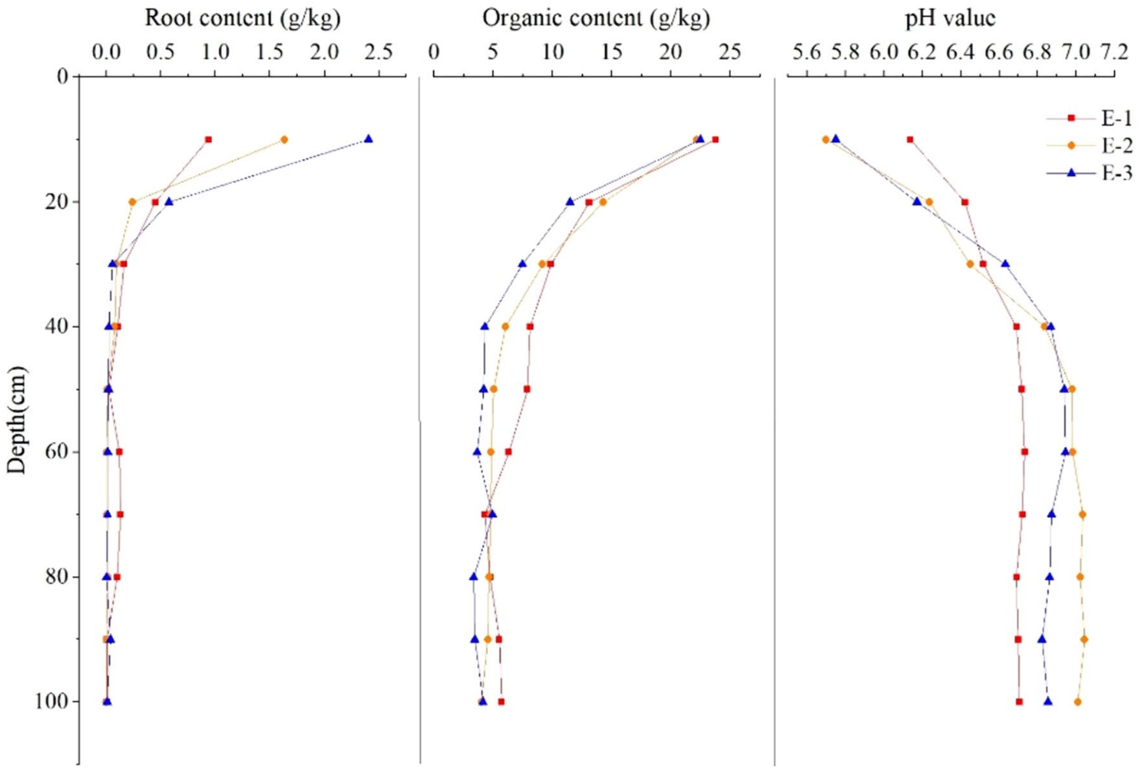

Fig. 10 Variation of root content, organic content, and pH value with depth of different communities

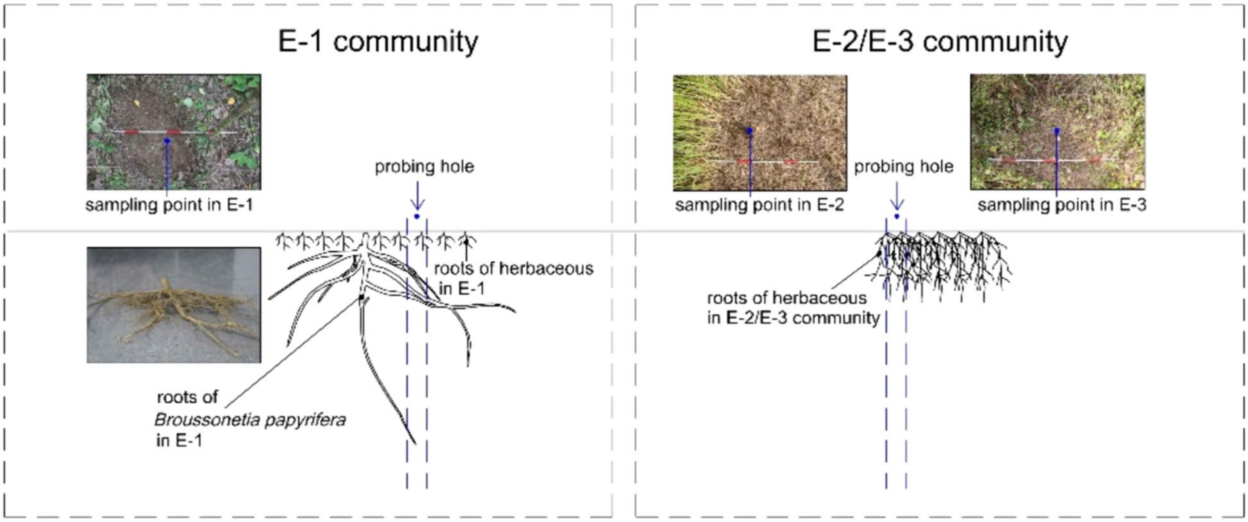

Fig. 11 Sampling method sketch map

to other herbaceous plants. The survey revealed that these two species reached above-ground heights ranging from 80 to 180 cm, with their underground root systems consisting of thick interwoven roots. Consequently, the E-2 and E-3 communities exhibited relatively high root contents within the 0–20 cm depth range. On the other hand, the E-1 community exhibited minimal root content in the upper 20 cm of soil, while root content data displayed fluctuations within the 60–90 cm range. This occurrence is attributed to both the morphological characteristics of the root system of *Broussonetia papyrifera* and the vertical sampling method employed. Soil samples were collected beneath dominant species as closely as possible to the surface of the site (after removing surface litter) (Fig. 11), using a vertical drilling technique with a 5 cm diameter, and samples were taken at 10 cm intervals. The vertical sampling approach may have led to probe shovel penetration through the surface root system of *Broussonetia papyrifera* (Fig. 11), resulting in lower root content in superficial soil samples. However, due to the morphological characteristics of the root system of *Broussonetia papyrifera*, some vertically growing roots in deeper soil were also captured by the probe shovel, leading to a slight increase in the root content data in deep soil.

The pH-depth graph revealed that the E-2 and E-3 herb communities exhibited weakly acidic soil with a pH range of 0–20 cm, while the arbor community of E-1 had significantly higher pH values than both E-1 and E-2 communities. According to the literature review [28–30], *Imperata koenigii* rhizomes contain secondary metabolites such as alcohols, terpinols, sterols, and acids which contribute to soil acidity reduction. Between 20 and 40 cm depth, the pH value of E-2 and E-3 communities increased rapidly to reach a neutral level (pH = 7), whereas the pH value of the arbor community in E-1 increased gradually but steadily. Below 40 cm depth, all three communities stabilized at a similar pH range between 6.7 and 7 due to soil-forming factors dominating below this depth; indicating that plant root biological weathering affects surface layers from depths ranging from 0 cm up until approximately 40 cm deep. The dominant species within the herb community (E-2), *Imperata koenigii* was found to increase soil acidity levels resulting in decreased soil pH values.

The organic content-depth profile indicates no significant difference among the three communities within the 0–40 cm range, with a decrease in content observed as depth increases. Below a depth of 40 cm, the E-1 community exhibits higher organic content compared to the E-2 and E-3 communities. A notable observation is that within the 0–20 cm soil on the surface of the site, while the root content of the E-1 community is lowest among all three communities, its organic content is higher. These two parameters briefly demonstrate a negative correlation temporary. This is due to the fact that the organic matter in the uppermost layer of soil originates from both above-ground and below-ground parts of deceased plants. The dominant species in the E-1 community are arbors, and the above-ground litter biomass of arbors surpasses that of herbaceous plants. Consequently, despite the low root content in the 0–20 cm upper layer of soil, the E-1 community still exhibits a high organic content. Below a depth of 40 cm, soil organic content primarily relies on underground components. As the root systems of dominant species in E-2 and E-3 communities are predominantly concentrated in the 0–20 cm layer, these two communities display low organic content beyond 40 cm depth. However, *Broussonetia papyrifera*, which is the dominant species in the E-1 community, possesses a root system that can extend up to approximately one meter or more; henceforth resulting in higher organic content for E-1 compared to E-2 and E-3 beyond 40 cm depth.

The above three graphs reveal a significant correlation between the root content, pH value, and organic content of the soil. To analyze the relationship further, a Pearson correlation analysis was performed on these parameters within the three communities using SPSS software. The corresponding results are presented in Table 7.

The correlation analysis results indicate a significant negative correlation ($p < 0.01$) between the pH value and root content of the three communities, while a significant positive correlation ($p < 0.01$) exists between organic content and root content. Organic matter is a crucial constituent of soil, derived from the deceased and decomposed tissues of plants and animals that undergo reassembly to form relatively stable polymeric compounds under microbial decomposition processes. The observed positive correlation between organic content and root content supports the hypothesis that the organic matter of soil in the east city wall of the Sanxingdui site originates from plant biological tissues. From an agricultural perspective, organic matter serves as a crucial indicator of soil fertility, while high vegetation coverage signifies the presence of suitable organic matter content for plant growth at the east city wall. Over time and exposure to open air conditions, plants continuously modify the properties of the soil through their metabolic processes and growth and development. From an engineering standpoint, organic matter contributes to increased soil aggregate content and enhances resistance

Table 7 Pearson correlation coefficient of root content, pH value, and organic content

E-1	Root content	E-2	Root content	E-3	Root content
pH value	– 0.962**	pH value	– 0.870**	pH value	– 0.919**
Organic content	0.954**	Organic content	0.914**	Organic content	0.972**

*$p < 0.05$; **$p < 0.01$

against erosion. However, it also exerts negative effects on soil's engineering properties; thus, more is not necessarily better in this case. The pH value of the soil at the site demonstrates a negative correlation with root content, specifically indicating that higher root content corresponds to lower pH values approaching weak acidity levels. This phenomenon arises from microorganisms decomposing plant residues to generate organic acids within the soil matrix. These findings validate the traditional belief in cultural heritage conservation that plant weathering leads to the degradation of mineral components in rocks and soils [1, 2, 4, 13]. Based on the specific impacts of pH value and organic matter on soil, this study posits that an appropriate level of vegetation coverage is necessary for earthen site conservation. The utilization of indigenous plants to conserve the earthen site should consider both their positive effects, such as enhancing soil aggregate structure and erosion resistance, as well as their influence on soil engineering properties and landscape aesthetics. In terms of soil engineering properties, insufficient vegetation coverage can lead to erosion, while excessive coverage can elevate organic matter content and lower pH levels, resulting in weak acidity within the site soil. From a landscape perspective, excessive vegetation cover may obscure the site's appearance and hinder its display ability. Therefore, experimental research should be conducted to determine a balanced point of vegetation coverage suitable for different climatic conditions; one that achieves soil conservation benefits alongside aesthetic appeal while maintaining favorable soil engineering properties.

Influence of community types on soil particle composition at the site

The composition of soil particles exerts a significant influence on engineering properties. Previous studies have demonstrated that the soil particle composition within the rooting range of plants is influenced by the plant communities [31]. Grouping the data on soil particle composition in Table 6 according to community type, we can investigate how community type affects soil particle composition both within and outside the rooting range. To examine the impact of community type on soil particle composition within the rooting range (0–40 cm), a one-way ANOVA was performed. As for data outside the rooting range (40–100 cm) which does not follow a normal distribution, non-parametric tests were employed. The analysis results are presented in Table 8.

The non-parametric test results presented in Table 8 indicate that the community type does not exert a significant influence on soil particle composition beyond the root depth range of 40–100 cm. However, within the root depth range of 0–40 cm, the analysis of variance reveals a significant impact of community type on clay and silt contents in the soil ($p < 0.01$) (Fig. 12). Specifically, for silt content, E-1 > E-3 > E-2; whereas for clay content, E-2 > E-3 > E-1. Notably, there exists a complementary trend between clay and silt contents across all three community types. In terms of community types, the clay content in the E-2 and E-3 communities exceeds that of the E-1 community, while the silt content is lower than that of the E-1 community. Literature reviews illustrate that soil erodibility is significantly influenced by the clay and silt content, with a negative correlation observed between clay content and soil erodibility, while a positive correlation exists between silt content and soil erodibility [32–34]. Proper clay content in the soil facilitates the formation of a surface crust during rainfall, thereby decreasing runoff and soil erosion [10, 11]. In comparison to the E-1 community, the higher clay content in the E-2 and E-3 communities suggests that the underlying soil is less prone to rainfall erosion. This finding aligns with

Table 8 Soil particles of different community types

		ANOVA				
		Communities (Mean ± SD)			***F***	***p***
		E-1 (*n* = 4)	**E-2 (*n* = 4)**	**E-3 (*n* = 4)**		
Within the root range (0–40 cm)	Clay content % (≤ 5 μm)	22.35 ± 9.14	42.01 ± 8.25	37.18 ± 4.38	7.367	0.013*
	Silt content % (5–75 μm)	74.25 ± 10.18	57.61 ± 8.33	61.50 ± 3.38	4.929	0.036*
		Non-parametric test				
		Median (P_{25}, P_{75})			**K-W test *H***	***p***
		E-1 (n = 4)	**E-2 (n = 4)**	**E-3 (n = 4)**		
Outside the root range (40–100 cm)	Clay content % (≤ 5 μm)	41.605 (41.1,42.6)	43.125 (35.2,59.4)	32.390 (26.2,38.1)	5.692	0.058
	Silt content % (5–75 μm)	55.770 (53.6,57.1)	56.395 (40.3,64.8)	66.065 (59.8,73.8)	4.308	0.116

*$p < 0.05$; **$p < 0.01$

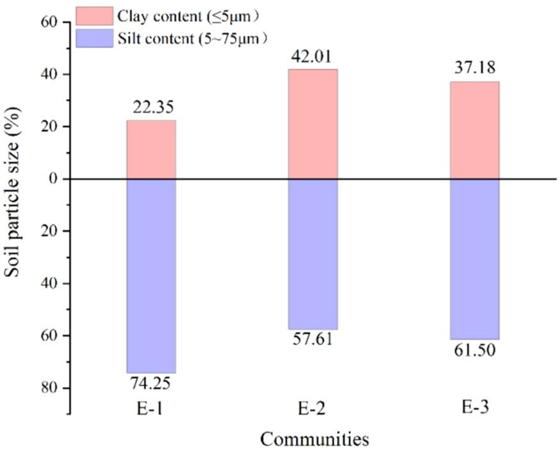

Fig. 12 Different communities impact the soil particles within the root range

references in the soil and water conservation field [31–33] and corresponds with the deterioration investigation indicating that there are no significant differences in typical rainfall erosion among these three communities.

Utilizing natural vegetation as a soft capping for earthen sites is an approach that effectively balances the ecological environment and the authenticity of cultural heritage, offering considerable potential. The crux of this conservation strategy lies in achieving a harmonious equilibrium between the soil conservation function of plants, the biological weathering process on earthen sites, and the desired landscape effect. This study elucidates the significance of ecological parameters within plant communities for earthen site conservation. It suggests that to ensure ecological stability and promote soil conservation effectively, it is necessary to shift from traditional single-species planting methods towards establishing plant ecological communities. Actually, in early earthen conservation practice in the Sanxingdui city wall, grass-like herbaceous plants were initially planted on the surface of the Sanxingdui City Wall for temporary coverage purposes. However, after 3–5 years, most of these plants perished or were replaced by local dominant species, failing to achieve the intended landscape effect (Fig. 13a–c). This maintenance cost associated with lawns is exorbitant while their ecological stability as single-species stands remains inadequate; thus, rendering this method unsuitable for long-term display and utilization of earthen sites. Building an ecological community with native plant species can ensure community diversity and ecological stability, which is beneficial for subsequent maintenance and earthen site conservation. The selection of native species should consider variations in water and soil conservation effects as well as landscape impacts resulting from different plant configurations and planting densities, necessitating further experimental research in later stages. Research findings demonstrate that three plant communities have a significant biological weathering effect on the east city wall of the Sanxingdui Site, primarily within a range of 0–40 cm. Dominant herbaceous plants release root exudates containing organic acids, leading to weakly acidic soil conditions at the site. This accelerates the decomposition of native minerals into secondary minerals while increasing organic content levels. Vegetation configuration within the ecological community should account for its influence on the engineering properties of the site's soil; however, higher vegetation coverage may not always be preferable. In later stages, on-site experiments and numerical simulations should be conducted to study plant species and coverage configurations that meet both water and soil conservation needs while maintaining desired engineering properties and landscape effects.

This study represents an initial endeavor to investigate the relationship between plants and earthen sites from the perspective of influence mechanisms. However, certain limitations such as the sampling method and soil sample amount have resulted in several deficiencies within this study. The limited sampling method has led to a limited amount of site soil, thereby preventing concurrent testing on the engineering properties of site soil. Consequently, it remains unclear how different plant

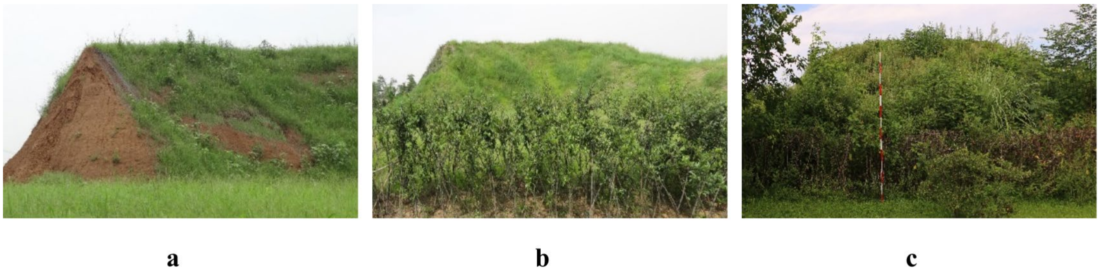

Fig. 13 The succession process of a plant community following artificial grass planting on the Sanxingdui city wall (**a**: In 2013, 1 year after the herbaceous was planted. **b**: In 2014, 2 years after the herbaceous was planted. **c**: In 2021, 9 years after the herbaceous was planted)

communities affect the engineering properties of soil within this study. Additionally, the limited amount of soil samples raises concerns regarding the potential underrepresentation of root content in comparison to actual conditions. The findings from the plant ecology survey indicate that *Broussonetia papyrifera*, *Imperata koenigii*, and *Symphyotrichum subulatum* predominantly possess underground root systems concentrated at depths exceeding 40 cm; however, they can extend as deep as 60–80 cm. Therefore, conclusions drawn regarding the direct impact range of plants on site soil based solely on these sampled tests may be more conservative than the actual situation. In this particular study design encompassing three communities with a total of 12 plots, vertical collection intervals for soil samples were set at every 10 cm per plot. Nevertheless, due to insufficient sample size, statistical significance cannot be attributed to depth's influence on soil biological weathering parameters within each community setting. Thus, further data is required for additional support.

Conclusion

According to plant investigation, soil properties test, and data analysis, the following conclusions were drawn:

1. There are three plant communities present in the east city wall of the Sanxingdui site. The E-1 (*Albizia kalkora—Broussonetia papyrifera)* community exhibits higher species diversity and better community stability, contributing to soil and water conservation. However, it significantly impacts the landscape effect of the site display and hinders its utilization. On the other hand, the E-2 (*Imperata koenigii -Symphyotrichum subulatum*) community displays the lowest species number and diversity with a single-species composition. This results in poor ecological stability and diversity, as well as accelerated biological weathering of the site soil due to dominance by sedge species, leading to an unfavorable landscape effect. Therefore, the removal of dominant species from both E-1 and E-2 communities is recommended. In contrast, the E-3 (*Centella asiatica -Symphyotrichum subulatum*) community demonstrates relatively balanced species diversity without tall trees obstructing views. The plants in this community moderately contribute to the biological weathering of soil. Considering removal of dominant *Symphyotrichum subulatum* species while retaining low-growing species as a soft capping layer could be considered.
2. Based on the special soil sample collection method, the findings from the analysis of soil root content, pH value, and organic content in 12 plots across three communities indicate that the direct impact of vegetation on the east city wall of the Sanxingdui site varies between 0 and 40 cm. However, there is no significant influence observed below a depth of 40 cm about community types and plant root systems on the soil at this site.
3. Plants exert a significant biological weathering impact on the east city wall of the Sanxingdui site. The biological weathering effect varies slightly among different plant communities. Through their root systems, plants influence the pH value and organic content within a depth range of 0–40 cm in the soil. The root content shows a positive correlation with organic content while exhibiting a negative correlation with pH value. Arbor communities exhibit relatively minor biological weathering effects on earthen sites, whereas herbaceous plant communities demonstrate higher root content within the 0–40 cm range, weakly acidic pH values, increased clay particle content in the soil, and more pronounced biological weathering effects.

Abbreviations

ANOVA	Analysis of variance
SD	Standard deviation
CV	Coefficient of variation
K–W test	Kruskal–Wallis' test

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40494-024-01451-7.

Additional file 1.

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Author contributions

XY, FZ, and YWW designed the research project; XY participated in soil sample collection and was responsible for data analysis and completing this manuscript; FZ and RH were responsible for the investigation, data collection, soil properties test, and data visualization; JFH was responsible for plant investigation and ecological parameters calculation. All authors read and approved the final manuscript.

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Availability of data and materials

The data used in this research are published in this paper, and they are available from the corresponding author upon reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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