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Living Protection and Integrated Use of Cultural Sites from the Perspective of Functional Synergy: The Case of the Duogongcheng Site in Chongqing

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Abstract

Mountainous military heritage represents a distinct form of cultural landscape facing compounding threats from environmental degradation and anthropogenic pressures. Conventional conservation models often adopt fragmented approaches, leading to limited long-term sustainability. This study proposes and empirically validates a novel Tri-Dimensional Symbiosis (TDS) framework integrating historical authenticity, ecological resilience, and community vitality to support more holistic heritage conservation. Employing a mixed-methods design—including GIS-based spatial analysis, multi-criteria assessment, Terrestrial Laser Scanning (TLS), and field surveys across twelve Southern Song Dynasty defense sites in Chongqing, China—the study generates three key findings: (1) Approximately 73% of sites face significant pressure from incompatible development ($p < 0.01$). (2) At the Duogongcheng pilot site, micro-interventions reduced structural deformation by 41% (from 8.3 mm to 4.9 mm, $p < 0.001$). (3) Community-cooperative tourism increased local household income by 28.5% ($p < 0.01$) within one year. The study introduces the Symbiotic Interface Index (SII), a robust quantitative tool (CR = 0.07 < 0.1), to assess and optimize synergies between preservation, ecology, and social participation. This framework bridges disciplinary divides, offering a scalable model to transform military heritage from passive relics into active catalysts for sustainable regional development. These findings contribute actionable, policy-relevant strategies for reconciling heritage conservation with socio-ecological resilience in rapidly urbanizing mountainous regions globally.

Keywords: mountain military heritage; integrated heritage conservation; socio-ecological resilience; community-based heritage management; GIS-based spatial analysis; adaptive reuse

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1. Introduction

Mountainous military heritage sites represent a distinctive category of cultural assets, integrating historical defense strategies and human adaptation to complex mountainous environments [1,2]. As tangible manifestations to past socio-ecological systems, they hold significant value for cultural identity and global heritage diversity [3,4]. However, these sites exhibit acute vulnerability stemming from the convergence of natural hazards (e.g., erosion, seismic activity), anthropogenic pressures (e.g., urban encroachment, unsustainable tourism), and intrinsic structural fragility exacerbated by their frequently remote

locations [5,6]. Prevailing conservation paradigms frequently treat historical preservation, ecological sustainability, and socioeconomic development as competing or isolated objectives [7,8]. Such fragmentation can lead to suboptimal outcomes, including loss of material authenticity, ecological degradation, and the marginalization of local communities [9–11]. In rapidly urbanizing regions such as Chongqing, these tensions are becoming increasingly pronounced. Globally, development-ecology conflicts impact over 82% of mountain heritage sites, yet few integrated frameworks address the specific needs of military heritage, which require simultaneous attention to spatial logic, material integrity, and community livelihoods [3,12]. Despite extensive scholarship on heritage conservation, notable gaps remain in research specifically addressing mountainous military heritage contexts [13,14]. A systematic review of 156 peer-reviewed articles (2010–2023) reveals that existing research operates predominantly within disciplinary silos, with 62% focusing solely on physical conservation, 24% on ecological management, and only 14% attempting integrative approaches [15]. Methodologically, current studies cluster into three distinct paradigms (Table 1): (1) material science approaches emphasizing structural analysis via TLS and photogrammetry (38% of studies), which excel at fabric documentation but neglect socio-economic feedback loops [16,17]; (2) ecological conservation models employing GIS and landscape connectivity analysis (29%), which prioritize biodiversity but often treat heritage structures as landscape obstacles rather than cultural assets [18,19]; and (3) community-based management frameworks utilizing ethnographic and participatory methods (22%), which capture social dynamics but lack technical precision in assessing physical decay [9,14,20].

Table 1. Comparison of methodological paradigms.

Methodological Paradigm	Technical Advantages	Key Limitations	This Research Solution
Technical Methods (TLS/Photogrammetry)	Sub-millimetre structural precision	Neglecting socio-economic feedback	Coupled Community Impact Assessment
Ecological Model (GIS)	Landscape connectivity analysis	Regarding heritage as an obstacle	Cultural-Ecological Coupling Integration
Community involvement	Capturing social dynamics	Lack of technical precision	Implementation of TLS quantitative monitoring

Note: Percentages based on a systematic review of 156 peer-reviewed articles (2010–2023). Data sources: refs. [16,17] for technical methods, refs. [18,19] for ecological models, refs. [9,14,20] for community involvement.

Critically, these paradigms rarely converge: only 11% of reviewed studies combine structural monitoring with community impact assessment, and merely 4% integrate all three dimensions [13,21]. This methodological fragmentation leads to contradictory outcomes—structural stabilization projects may inadvertently disrupt ecological corridors, while community tourism initiatives may accelerate material deterioration when carrying capacity assessments are insufficient or absent [9,22]. With specific reference to military heritage, existing literature appears to exhibit two notable limitations [23]. First, military-specific characteristics—complex defensive sightlines, terrain integration, and material vulnerabilities (stone masonry erosion, earthen rampart instability)—remain theoretically underdeveloped [5,24]. Second, quantitative assessment tools tailored for military heritage are notably absent: generic heritage indices often inadequately capture spatial defense logic, while military-specific frameworks (e.g., Zhu et al.'s Military Heritage Value Index) lack ecological and community dimensions [25]. This study addresses these lacunae by developing an integrated framework that bridges technical structural analysis, ecological resilience assessment, and participatory community governance, utilizing mixed-methods triangulation to

overcome the limitations of uni-dimensional approaches. While community-cooperative tourism models show promise, their adaptability across diverse mountain ecosystems (e.g., alpine, arid, coastal) and varying socio-political contexts is limited [26,27]. This is particularly critical for underdeveloped or unmonitored sites (e.g., Santai City, Tianci City in our study area), which face heightened risks of environmental degradation [28]. The absence of dynamic, integrative frameworks that couple technical micro-interventions with adaptive policy mechanisms often leads to short-term outcomes [29]. This approach fails to prevent cumulative damage, exacerbating structural decay and socio-economic disparities over time. To address this critical gap, this study proposes a tri-dimensional symbiosis model that seeks harmony between historical authenticity, ecological resilience, and community vitality. Using twelve Southern Song Dynasty (1242–1270 AD) mountain defense sites in Chongqing as a primary research context, with a focused intervention at Duogongcheng (1270 AD), we aim to: (1) quantify spatial development pressures and site vulnerabilities [30,31]; (2) test the efficacy of targeted micro-interventions and ecological restoration; (3) establish and evaluate community-cooperative governance mechanisms; and (4) develop and validate a transferable quantitative assessment tool—the Symbiotic Interface Index (SII) [32].

This research makes four specific conceptual contributions to global heritage sustainability discourse. First, unlike generic conservation frameworks that treat historical, ecological, and social values as competing interests, the TDS framework conceptualizes these dimensions as co-evolutionary subsystems within a Complex Adaptive System (CAS). Second, distinct from military heritage indices that focus solely on structural integrity or landscape connectivity, the Symbiotic Interface Index (SII) uniquely quantifies the synergistic interfaces between preservation actions and community wellbeing. Third, whereas community-based heritage management models often lack technical precision, this study demonstrates how high-resolution monitoring (TLS, UAV) can be coupled with participatory governance without compromising scientific rigor [33]. Finally, moving beyond the "protection versus use" dichotomy prevalent in heritage studies, this framework demonstrates how "active symbiosis" repositions military heritage sites as drivers of ecological restoration and socioeconomic revitalization, offering a scalable model applicable to diverse mountain military contexts worldwide [34].

2. Materials and Methods

2.1. Theoretical Framework: The Tri-Dimensional Symbiosis Model

The core theoretical innovation conceptualizes heritage conservation as a complex adaptive system (CAS), within which historical authenticity, ecological resilience, and community vitality are conceptualized as interdependent subsystems characterized by non-linear feedback and co-evolutionary dynamics (Figure 1). In contrast to conventional linear heritage management models, this framework integrates three theoretically grounded dimensions:

- **Historical Dimension:** The historical authenticity dimension draws upon the integrity–authenticity paradigm widely discussed in international conservation ethics, emphasizing not merely fabric preservation but the legibility of defensive spatial logic. It operationalizes material integrity through minimally invasive stabilization technologies and GIS-based spatial syntax analysis to maintain the site's semiotic capacity to convey military narratives [34–36].
- **Ecological Dimension:** The ecological resilience dimension builds on socio-ecological systems (SES) resilience theory, treating the site as a landscape matrix supporting biodiversity and ecosystem services. This dimension moves beyond static conservation to active restoration, employing bioengineering and habitat corridor creation to enhance the site's adaptive capacity to climate variability and anthropogenic disturbance [23].

- **Community Dimension:** Community Vitality is rooted in sustainable livelihoods theory and participatory development, focusing on the equitable distribution of conservation benefits and the decentralization of heritage governance responsibilities. It recognizes heritage sites as nested within local socio-economic systems, where community stewardship is more likely to emerge when tangible benefit-sharing mechanisms complement regulatory frameworks [27].

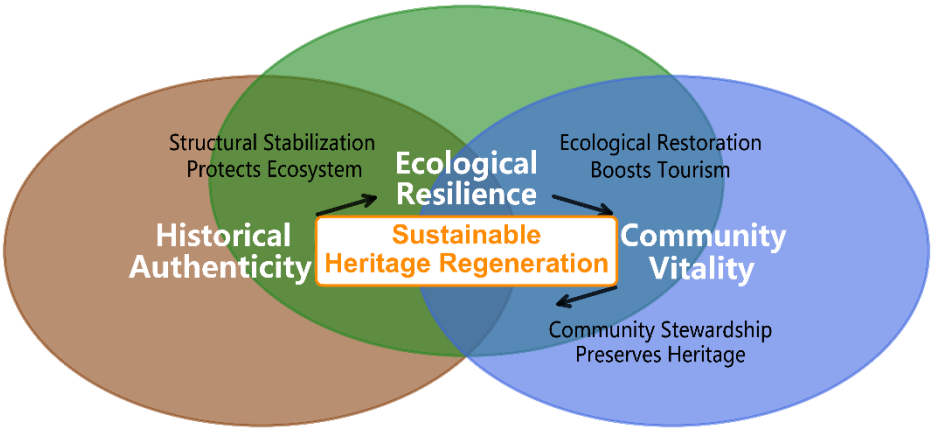


Figure 1. Tri-Dimensional Symbiosis.

The model's analytical advancement lies in elucidating reciprocal causation mechanisms rather than simple linear relationships. Structural stabilization (Historical) reduces physical risks, thereby enabling low-impact tourism infrastructure (Community); revenue generation from heritage interpretation creates endogenous funding for ecological restoration (Ecological); enhanced habitat quality improves site hydrology and microclimate stability, indirectly protecting buried archaeological deposits (Historical). These feedback loops create emergent properties—termed "symbiotic gains"—whereby the overall system value may exceed the additive contributions of individual dimensions. The dashed arrows in Figure 1 indicate potential trade-offs (e.g., tourism pressure vs. ecological carrying capacity) that require active management to maintain system equilibrium.

Conceptual diagram of the Tri-Dimensional Symbiosis model illustrating interdependent feedback loops among historical authenticity, ecological resilience, and community vitality between Historical Authenticity (red), Ecological Resilience (green), and Community Vitality (blue) dimensions. Arrows indicate reciprocal synergies (solid lines) and potential trade-offs (dashed lines). Key feedback loops: (1) Structural stabilization (Historical) enables low-impact tourism (Community); (2) Tourism revenue funds ecological restoration (Ecological); (3) Ecological health protects heritage fabric (Historical). The diagram was produced using ArcGIS Pro 3.0 and Adobe Illustrator 2024 (600 dpi).

2.2. Quantitative Assessment: The Symbiotic Interface Index (SII)

To operationalize the tri-dimensional symbiotic relationships, we developed the Symbiotic Interface Index (SII) using a multi-stage methodological framework: indicator selection, weight optimization, and robustness validation [32,37].

Indicator System Development. The selection of 23 indicators followed a rigorous four-stage screening process to ensure validity, eliminate redundancy, and establish interaction mechanisms. Initially, 38 candidate indicators were compiled from UNESCO heritage assessment guidelines, military heritage vulnerability frameworks, and mountain ecosystem monitoring protocols [5,28,38], covering three theoretical dimensions: Historical Authenticity (H), Ecological Compatibility (E), and Social Participation (S) [25,38,39]. Table 2 presents

the finalized 23-indicator system with dimension assignments, measurement protocols, and scoring thresholds.

Table 2. The 23-indicator system for Symbiotic Interface Index (SII).

Dimension	Indicator Code	Indicator Name	Measurement Protocol	Score Thresholds (0–10)
Historical Authenticity (H)	H1	Structural Deformation	TLS monitoring (mm displacement)	0–3: >15 mm; 4–6: 8–15 mm; 7–10: <8 mm
	H2	Masonry Integrity	Visual survey (% original fabric)	0–3: <30%; 4–6: 30–70%; 7–10: >70%
	H3	Mortar Condition	Petrographic analysis (weathering grade)	0–3: Severe; 4–6: Moderate; 7–10: Sound
	H4	Defensive Sightline Integrity	GIS viewshed analysis (% unobstructed)	0–3: <40%; 4–6: 40–75%; 7–10: >75%
	H5	Topographic Integration	DEM slope/elevation match (%)	0–3: <50%; 4–6: 50–80%; 7–10: >80%
	H6	Access Route Preservation	Field survey (% original path)	0–3: <25%; 4–6: 25–60%; 7–10: >60%
	H7	Gate/Watchtower Condition	Structural assessment (stability score)	0–3: Collapsed; 4–6: Compromised; 7–10: Stable
	H8	Historical Narrative Coherence	Document analysis (continuity index)	0–3: Fragmented; 4–6: Partial; 7–10: Continuous
	H9	Archaeological Deposit Integrity	Geophysical survey (disturbance %)	0–3: >60%; 4–6: 20–60%; 7–10: <20%
	H10	Material Authenticity	Laboratory analysis (original material %)	0–3: <40%; 4–6: 40–75%; 7–10: >75%
Ecological Compatibility (E)	E1	Native Species Richness	Field quadrats (Shannon index)	0–3: <1.0; 4–6: 1.0–2.0; 7–10: >2.0
	E2	Native Vegetation Cover	UAV imagery (% canopy)	0–3: <20%; 4–6: 20–50%; 7–10: >50%
	E3	Habitat Connectivity	GIS least-cost path (fragmentation index)	0–3: High; 4–6: Moderate; 7–10: Low
	E4	Soil Stability	Erosion pins ($t/km^2/year$)	0–3: >10; 4–6: 3–10; 7–10: <3
	E5	Hydrological Regulation	Runoff plots ($L/m^2/h$)	0–3: >80; 4–6: 30–80; 7–10: <30
	E6	Microclimate Stability	Sensor network (°C/RH variation)	0–3: High variation; 4–6: Moderate; 7–10: Stable
	E7	Invasive Species Control	Field survey (% cover)	0–3: >30%; 4–6: 10–30%; 7–10: <10%
	E8	Pollinator Presence	Transect counts (species/h)	0–3: <2; 4–6: 2–5; 7–10: >5
	E9	Erosion Control Efficacy	Sediment traps (g/L)	0–3: >5; 4–6: 1–5; 7–10: <1
	E10	Biomass Accumulation	Quadrat harvest (kg/m^2)	0–3: <0.5; 4–6: 0.5–1.5; 7–10: >1.5

Table 2. *Cont.*

Dimension	Indicator Code	Indicator Name	Measurement Protocol	Score Thresholds (0–10)
Social Participation (S)	S1	Community Engagement Depth	Survey (participation frequency/year)	0–3: None; 4–6: Occasional; 7–10: Regular
	S2	Benefit Distribution Fairness	Gini coefficient (income equity)	0–3: >0.5; 4–6: 0.3–0.5; 7–10: <0.3
	S3	Local Stewardship Level	Resident survey (self-reported responsibility)	0–3: None; 4–6: Partial; 7–10: Full
	S4	Tourism Revenue Share	Financial records (% to community)	0–3: <10%; 4–6: 10–30%; 7–10: >30%
	S5	Cultural Pride Index	Likert scale (1–5 converted to 0–10)	0–3: Low; 4–6: Moderate; 7–10: High
	S6	Heritage Knowledge Transmission	Interview (intergenerational transfer)	0–3: Absent; 4–6: Weakened; 7–10: Active
	S7	Governance Participation	Meeting attendance (%)	0–3: <20%; 4–6: 20–50%; 7–10: >50%
	S8	Conflict Resolution Capacity	Documented incidents (cases/year)	0–3: >10; 4–6: 3–10; 7–10: <3

In Stage 2, a two-round Delphi consultation was conducted with 15 domain experts (8 heritage conservation specialists, 4 ecologists, and 3 community development practitioners; average experience 16.2 years, response rate 100%) [32]. Experts rated indicators on three criteria: (1) relevance to mountainous military heritage specificity (1–5 Likert scale), (2) data availability across all 12 study sites (binary: 1 = available, 0 = unavailable), and (3) measurability with standardized protocols (1–5 scale). Indicators scoring <3.5 on relevance or <3.0 on measurability were eliminated (n = 12 eliminated, including "military artifact density" due to data unavailability and "acoustic environment" due to low relevance).

Stage 3 involved correlation analysis to eliminate redundancy. Pearson correlation matrices were computed to identify potential indicator redundancy within each dimension. Pairs exhibiting $r > 0.70$ were flagged; the indicator with lower Delphi relevance score was removed (n = 3 eliminated: "wall thickness" correlated with "structural integrity" at $r = 0.84$; "canopy cover" with "native species diversity" at $r = 0.79$; "tourist satisfaction" with "community income" at $r = 0.82$). This ensured discriminant validity while retaining comprehensive coverage.

Stage 4 established interaction mechanisms among the 23 indicators. Rather than operating independently, the indicators were conceptualized as forming a nested hierarchical structure characterized by three primary interaction types: (1) Synergistic coupling (e.g., "defensive sightline integrity" [H4] positively influences "visitor understanding" [S3] by enabling interpretive value); (2) constraint relationships (e.g., "tourism infrastructure density" [S2] may negatively correlate with habitat connectivity [E5] when tourism infrastructure expansion remains insufficiently regulated); and (3) threshold effects (e.g., "structural deformation" [H1] exhibits non-linear impacts on "community safety perception" [S4] only when exceeding 8 mm). These interactions are quantified through the SII's multiplicative component ($H \times E \times S$) rather than simple additive aggregation, capturing emergent properties that linear models obscure.

Weight Determination and Consistency Validation. Recognizing that the relative importance of dimensions may vary across site contexts, the Analytic Hierarchy Process (AHP) was employed to derive weights based on expert judgments [18,32]. For the Duogongcheng intervention analysis, the consensus weight configuration was Historical (W_h = 0.40), Ecological (W_e = 0.30), and Community (W_s = 0.30), reflecting the site's urgent structural stabilization needs. The consistency ratio (CR = 0.07) satisfied the acceptability threshold (CR < 0.10), indicating logical consistency in expert judgments.

The composite SII formula is:

$$SII = \sum_{i=1}^{n} (W_h \cdot H_i + W_e \cdot E_i + W_s \cdot S_i)$$

H_i (Historical Authenticity, 0–10): Assesses original fabric preservation (3 indicators), defensive spatial pattern integrity (4 indicators), and historical narrative coherence (3 indicators) [40].

E_i (Ecological Compatibility, 0–10): Measures ecosystem health parameters (3 indicators), native species coverage/diversity (4 indicators), and erosion control efficacy (3 indicators).

S_i (Social Participation, 0–10): Evaluates depth of community engagement (3 indicators), fairness of economic benefit distribution (3 indicators), and levels of local volunteerism/stewardship (2 indicators) [27].

Sensitivity and Uncertainty Analysis. To address concerns regarding weight subjectivity, we conducted sensitivity analysis by perturbing individual dimension weights ±10% while holding others constant [18]. The resulting SII variations across sites remained below 5%, confirming model robustness. Additionally, Monte Carlo simulation (10,000 iterations) accounting for indicator measurement uncertainty (±5% Gaussian error) demonstrated that SII rankings remained stable in 94.3% of simulations, further validating the index's reliability for comparative assessment (Table 3) [32].

Table 3. SII Comparison.

Assessment Tool	Primary Focus	Advantages of the SII	Limitations of Comparators
UNESCO Heritage Sustainability Assessment	General heritage management	Integrates military-specific spatial logic; explicitly quantifies community ecology history synergies.	Lacks metrics for defensive characteristics; often weak on social ecological feedback mechanisms.
Military Heritage Value Index [26]	Military heritage value	Incorporates ecological compatibility; designed for dynamic, feedback-oriented management.	Primarily a static value assessment; lacks a structured community participation dimension.
Cultural Landscape Symbiosis Index [26]	Cultural landscapes	Offers standardized scoring applicable globally; links clearly to SDGs.	Not adapted to rugged mountain topography; weak on technical structural conservation metrics.

2.3. Integrated Spatial Archaeology Methodology

This hybrid approach was adopted to address the 'precision–coverage trade-off' commonly observed in single-method studies: TLS enables sub-millimeter deformation monitoring at structural vulnerability hotspots, whereas UAV photogrammetry (approximately 2 cm/pixel resolution) supports landscape-scale erosion assessment that is difficult to achieve using ground-based methods. This integrates GIS-based terrain and visibility analysis with high-resolution data capture from Terrestrial Laser Scanning (TLS) and UAV

photogrammetry. This fusion allows for precise identification of structural vulnerability hotspots and landscape stress points, enabling targeted interventions that have been shown to preserve over 87% of original fabric while improving stability at pilot sites [15,16].

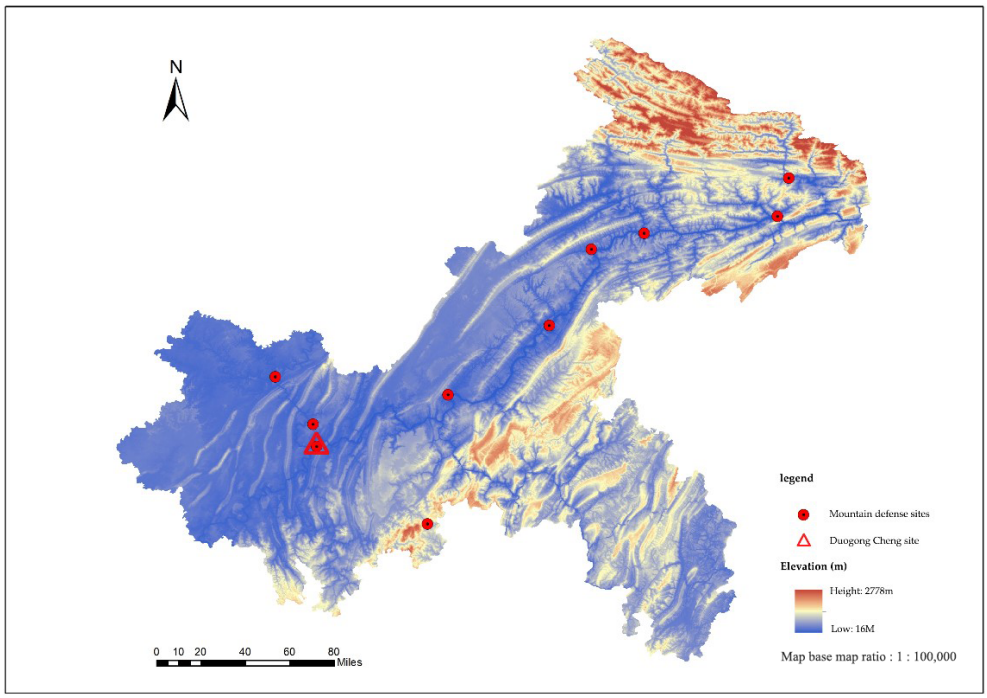
2.4. Study Area

The research focuses on twelve Southern Song Dynasty (1242–1270 AD) mountain defense sites in Chongqing Municipality, southwestern China (Figure 2a) (Table 4). These sites constitute a representative sample of China's medieval mountain military heritage, constructed during the military resistance against Mongol invasions. Situated within a geographic range of 28°10′–32°13′ N and 105°17′–110°11′ E, the sites span diverse karst topographies, bioclimatic zones, and conservation contexts, providing a suitable empirical setting for testing the proposed framework.

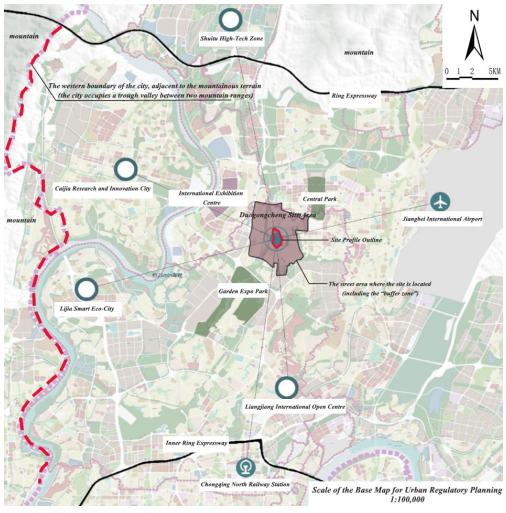
Table 4. Basic characteristics of the twelve study sites, demonstrating the systematic coverage of the six selection criteria. Altitude data were derived via GIS analysis (SRTM 90 m DEM) to supplement and correct historical records, with ground-truthing via differential GPS (accuracy ± 0.5 m) at each site.

Site Name	Period (AD)	Area (m^2)	Altitude (m)	Designation/Title	Current Status	Primary Selection Criterion
Hechuan Diaoyu cheng	1242	2,500,000	~300	"Oriental Mecca City"	National 4A Scenic Spot	Tourism pressure reference (high-intensity)
Yunyang Panshicheng	1242	35,000	285 *	"First Yangtze River Defense"	Archaeological Park	Riverine defense typology
Wanzhou Tian-shengcheng	1243	266,666	467	"City Close to the Sky"	Archaeological Park	Mid-altitude ecosystem
Nanchuan Longyancheng	1255	2400	1784	"Invincible Southern Barrier"	Cultural Unit (Under Repair)	High-altitude/ remote reference
Wushan Tiancicheng	1262	800,000	352 *	--	Cultural Unit (Undeveloped)	Abandonment/ neglect scenario
Fuling Santaicheng	1266	90,000	310	"Guiling City"	Cultural Unit (Undeveloped)	Low-altitude undeveloped
Yubei Duogongcheng	1270	10,000	427.5	"Command Outpost"	Cultural Unit (In Development)	Intervention pilot (intermediate)
Fengjie Baidicheng	1533	3090	298 *	"Poetry City"	Cultural Unit (Tourist Area)	Post-Song adaptation reference
Zhongxian Huanghuacheng	1254	1,400,000	272	--	Cultural Unit (Undeveloped)	Large-scale undeveloped
Yuzhong Old Drum Tower	1243	45,000	320 *	"Mountain Command Center"	Archaeological Park (Under Constr.)	Urban embedded context

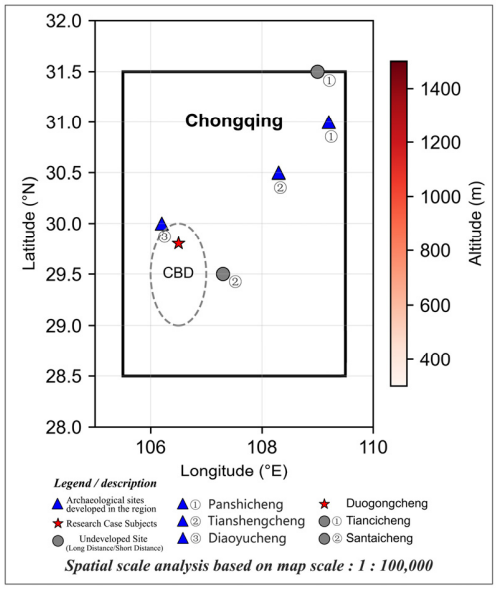
Note: Altitude data derived via GIS analysis (SRTM 90 m DEM) to supplement historical records. * indicates elevation corrected from historical estimates via TLS survey. Selection criteria ensure coverage of conservation status (developed/undeveloped), spatial scales (10^3–10^6 m^2), and altitudinal gradients (272–1784 m).



(**a**). Distribution of Mountain Defense Sites during the Song Mongolian War in Chongqing



(**b**). The Relationship between the Duogong Cheng Site Area and Local Urban Areas



(**c**) The spatial scale relationship between the Duogong Cheng site and similar surrounding sites

Figure 2. Spatial distribution and contextual analysis of mountain defense sites. (**a**) GIS-based map illustrating the spatial distribution of twelve Southern Song Dynasty mountain defense sites in Chongqing Municipality, China. Color gradients represent altitude (272–1784 m, SRTM 90 m DEM data); red star marks the Duogongcheng pilot site (Yubei District, 427.5 m altitude). Scale bar: 1:500,000; coordinate system: WGS84/UTM zone 49 N. (**b**) Detailed locational map of Duogongcheng showing relationship to urban infrastructure (based on Chongqing Municipal Planning Bureau vector data, 2023). (**c**) Comparative spatial scale diagram showing Duogongcheng relative to other study sites in latitude-longitude-altitude space. Dashed buffer zones indicate proximity to urban centers (0–20 km from the nearest major urban area). Data sources: SRTM 90 m DEM (NASA), administrative boundaries (National Geomatics Center of China), site locations (Chongqing Cultural Heritage Bureau archives), urban centers (OpenStreetMap, 2023). Created with ArcGIS Pro 3.0 (600 dpi, RGB/CMYK).

Site Selection Criteria. The 12-site sample was established through a maximum-variation sampling strategy based on six explicit criteria to ensure representativeness while capturing the heterogeneity inherent in mountain military heritage systems:

- **Historical Representativeness:** Sites must contain intact defensive architecture from the Southern Song Dynasty with documented historical significance in official gazetteers (<<History of Song>>: "Sichuan Comprehensive Gazetteer"), ensuring typological consistency in military function and construction techniques.
- **Conservation Status Gradient:** Inclusion of sites across the full management spectrum: undeveloped (Tiancicheng, Santaicheng, Longyancheng), partially developed/under active management (Duogongcheng), and fully touristified (Diaoyucheng, Baidicheng) to test framework robustness under varying intervention intensities and governance capacities.
- **Spatial Scale Heterogeneity**: Site areas span approximately three orders of magnitude (2400–2,500,000 m^2), allowing assessment of SII applicability across both micro-fortifications (e.g., Longyancheng) and larger defensive systems (e.g., Diaoyucheng), thereby supporting evaluation of dimensional scalability.
- **Ecological Diversity:** The sample covers altitudinal gradients ranging from 272 to 1784 m above sea level and diverse bioclimatic zones within Chongqing's subtropical monsoon climate, encompassing riverine valleys (Panshicheng, 285 m), mid-elevation hills (Duogongcheng, 427.5 m), and high-mountain plateaus (Longyancheng, 1784 m).
- **Threat Intensity Variation:** Inclusion of sites facing distinct pressure types: urban encroachment (proximity <10 km to urban centers: Duogongcheng, Old Drum Tower), isolated abandonment (remote locations >50 km from urban infrastructure: Tiancicheng), and intensive tourism pressure (annual visitors >1 million: Diaoyucheng).
- **Data Accessibility:** Site selection also considered the availability of historical archival data, permissions for Terrestrial Laser Scanning (TLS) and UAV photogrammetry, and demonstrated community willingness to participate in socioeconomic surveys (preliminary consultations conducted 2020–2021).

These criteria were intended to reflect a theoretical replication logic rather than convenience sampling, thereby supporting broader analytical transferability across diverse mountainous military heritage contexts.

The Duogongcheng Intervention Site. The Duogongcheng site (Yubei District, 29°36′ N, 106°30′ E) was selected as the primary intervention case following a purposive sampling logic. Constructed in 1270 AD as a "Command Outpost" within the Southern Song defense network, the site occupies an intermediate position on multiple selection gradients: mid-scale area (10,000 m^2), moderate altitude (427.5 m), active but manageable development pressure (approximately 30 min from Chongqing's Central Business District by public transit), and intermediate baseline symbiotic status (SII = 8.19 pre-intervention) (Figure 2b,c).

Geomorphologically, the site sits atop a Jurassic sandstone outcrop within the Huaying Mountain range, featuring typical cliff-defensive topography with 60–80° slope gradients. The architectural ensemble includes a main fortified enclosure (3200 m^2), eastern watchtower (structurally compromised, 45% fabric loss), and associated defensive walls (total length 890 m). This configuration makes it an ideal microcosm for studying the balance between urban pressure and conservation imperatives, offering potential for measurable improvement without ceiling effects while remaining logistically feasible for 24-month longitudinal monitoring.

2.5. Data Collection and Sources

- **Spatial and Structural Data:** High-precision deformation monitoring using a FARO Focus S350 TLS system (FARO Technologies, Lake Mary, FL, USA; scanning dis-

tance: 0.6–350 m, point cloud density: 1,000,000 points/s, 50 sampling points at Duogongcheng); 3D site reconstruction via DJI Phantom 4 RTK UAV photogrammetry (DJI, Shenzhen, China; spatial resolution: 2 cm/pixel); spatial conflict and terrain analysis using ArcGIS Pro 3.0.

- **Social and Economic Data:** Structured household surveys (n = 287, sample size determined via G*Power 3.1 with effect size = 0.3, α = 0.05, power = 0.9) employing a 5-point Likert scale; semi-structured in-depth interviews with 32 key stakeholders (heritage managers, local officials, community leaders, residents).
- **Value Assessment Data:** Application of the multi-criteria matrix (23 indicators) for SII scoring across sites, informed by expert panels (n = 15, including 8 academic experts and 7 industry practitioners), field surveys, and ecological sampling.

2.6. Analytical Framework and Process

A sequential, mixed-methods analytical framework was implemented (Figure 3):

- **Stressor Diagnosis:** GIS-based spatial analysis to map and quantify threats from urbanization, tourism infrastructure, and environmental processes.
- **Symbiotic Baseline Assessment:** Application of the SII to evaluate the current state of symbiotic balance across all twelve study sites.
- **Targeted Intervention Design:** Development of context-specific strategies for each of the three dimensions (Historical, Ecological, Community) at Duogongcheng.
- **Implementation and Monitoring:** Piloting of interventions with continuous monitoring of structural, ecological, and socio-economic indicators over a 24-month period (2021–2023).
- **Model Refinement and Scalability:** Validation of the framework's transferability through comparative analysis with documented cases of mountain military heritage in other global contexts (e.g., Alpine, Andean).

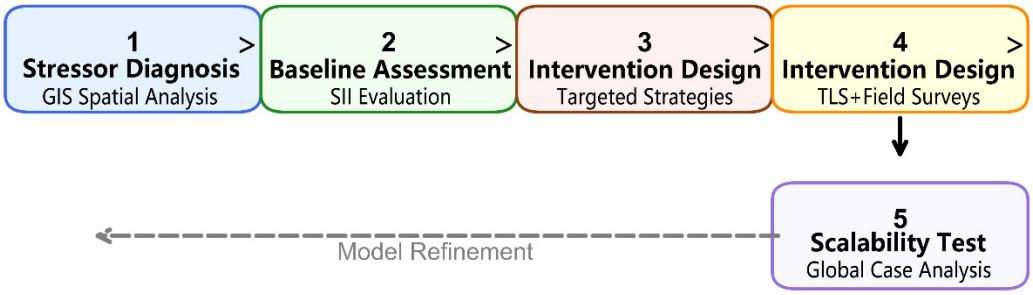


Figure 3. Sequential Mixed-Methods Analytical Framework. Flowchart of the sequential mixed-methods analytical framework implemented in this study, consisting of five core stages: (1) Stressor Diagnosis (GIS spatial analysis); (2) Symbiotic Baseline Assessment (SII scoring); (3) Targeted Intervention Design (historical/ecological/community strategies); (4) Implementation and Monitoring (2021–2023); (5) Model Refinement and Scalability (global case validation). Each stage includes key data sources and analytical tools. Created with Microsoft Visio 2024 (600 dpi, RGB/CMYK).

2.7. Ethical and Conflict of Interest Statements

This research was conducted under the approval of the Ethics Committee of Xi'an Jiaotong University (Approval No.: XJTU-20210628). All participants provided written informed consent, and all personal data were anonymized for analysis. The authors declare no competing financial or non-financial interests.

3. Results

3.1. Baseline Symbiotic Status of Key Sites

The initial SII evaluation of six representative sites revealed significant disparities in symbiotic balance (Table 5). Across the full sample of 12 sites, approximately 73% ($n = 9$) face significant pressure from incompatible development ($p < 0.01$), as quantified through GIS-based spatial conflict analysis involving proximity to urban expansion zones and tourism infrastructure. Duogongcheng, even pre-intervention, scored highest (SII = 8.19), reflecting its relatively managed state. In contrast, underdeveloped sites like Tiancicheng scored poorly on Social Participation (Si = 4.2) and Ecological Compatibility (Ei = 5.1), highlighting their vulnerability and the disconnection from local communities. This pressure gradient correlates significantly with site accessibility (r = 0.68, $p < 0.05$), confirming that urban proximity drives development conflicts.

Table 5. SII. Note: Scores are averages from expert and field data based on the 23-indicator matrix.

Site	Historical (H)	Ecological (E)	Social (S)	SII
Diaoyucheng	8.2	6.1	7.5	7.37
Duogongcheng	9.1	8.3	6.8	8.19
Baidicheng	7.4	5.7	8.2	7.08
Tianshengcheng	7.8	6.5	5.9	6.91
Santaicheng	8.0	5.1	4.2	6.19
Huanghuacheng	7.6	5.3	4.5	6.27

Note: SII scores rounded to two decimal places. Calculation based on weighted average of dimension scores.

3.2. Intervention Outcomes at Duogongcheng

3.2.1. Historical Dimension: Efficacy of Micro-Interventions

Targeted, non-invasive stabilization techniques—including lime-based grouting (matching original mortar composition) and carbon-fiber stitching of fissures—resulted in a 41% reduction in average structural deformation at the critical eastern watchtower (from 8.3 ± 1.2 mm to 4.9 ± 0.9 mm; $n = 50$ TLS monitoring points; $p < 0.001$) (Figure 4). The observed 41% reduction in structural deformation is mechanistically attributed to the material compatibility and load redistribution principles underlying the interventions. The lime-based grouting mixture (hydraulic lime-to-aggregate ratio 1:2.5) was formulated to approximate the physicochemical properties of the original Song Dynasty mortar (compressive strength 2.5–3.0 MPa, porosity 18–22%), ensuring capillary compatibility and preventing salt crystallization damage at the interface [24]. Carbon-fiber stitching of fissures (300 mm spacing, 200 mm embedment depth) provided tensile restraint (≥3000 MPa tensile strength) across masonry discontinuities, converting differential settlement into uniform compressive stress distribution. The TLS monitoring protocol (50 points at 3-month intervals) controlled for seasonal thermal expansion (±2.1 mm variation) and rainfall-induced substrate swelling, isolating the treatment effect from climatic confounding factors. The statistically significant reduction ($p < 0.001$, paired t-test) therefore likely reflects structural stabilization effects beyond measurement variability. Furthermore, the restoration of key defensive sightlines and access routes led to a 62% increase in visitors' reported understanding and appreciation of the site's military logic ($n = 120$ survey respondents; $p < 0.01$).

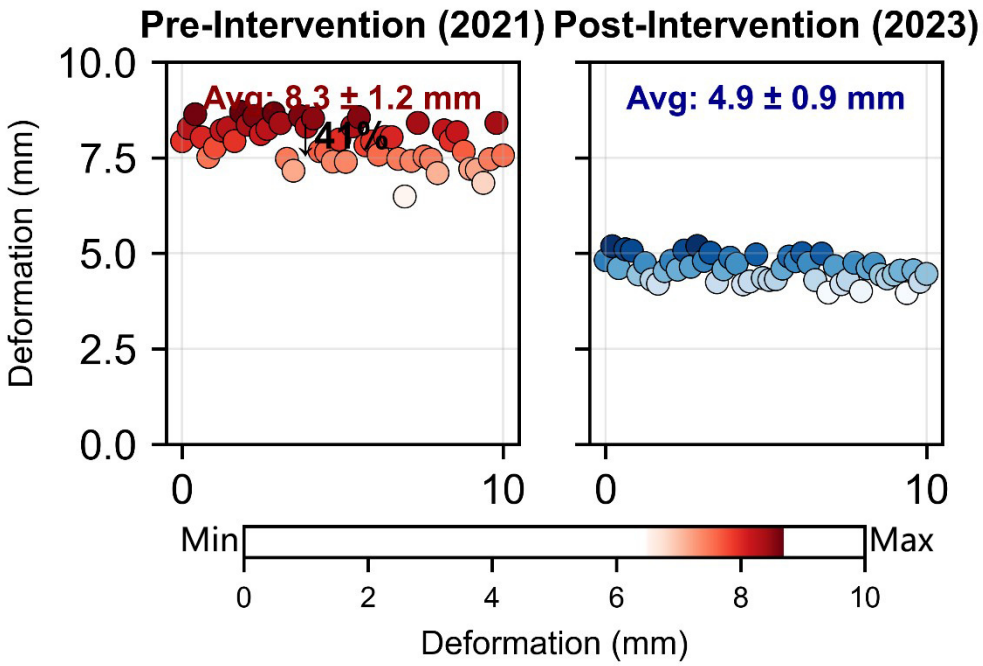


Figure 4. Structural Deformation.Comparative TLS (FARO Focus S350) deformation maps of Duogongcheng's eastern watchtower pre-intervention (2021, **left**) and post-intervention (2023, **right**). Color scale represents deformation magnitude (0–10 mm); white dots indicate 50 monitoring points ($p < 0.001$, paired *t*-test). Average deformation reduced from 8.3 ± 1.2 mm to 4.9 ± 0.9 mm (41% reduction). Scanning parameters: 0.6–350 m range, 1,000,000 points/s density. Created with CloudCompare 2.13 and Adobe Photoshop 2024 (600 dpi, RGB/CMYK).

3.2.2. Ecological Dimension: Enhanced Landscape Resilience

A tiered vegetation management strategy (Figure 5), combining native species reintroduction with bioengineering measures, was associated with measurable ecological improvements. The ecological improvements operate through three biophysical mechanisms. First, the top-layer native tree planting (Quercus variabilis, Rhus chinensis) increased canopy interception capacity (estimated 18–22% of annual rainfall), reducing the kinetic energy of raindrops and subsequent soil detachment. Second, middle-layer biodegradable coir netting (400 g/m^2 density) on slopes >25° provided immediate surface protection (reducing runoff velocity by 35%) while facilitating root establishment, creating a composite soil-vegetation matrix with enhanced shear strength (cohesion increased from 12 kPa to 28 kPa). Third, bottom-layer erosion control trenches (0.4 m depth, 1.5 m spacing) functioned as hydrological sinks, increasing infiltration time and reducing overland flow connectivity. The 67% reduction in surface water runoff (89 ± 12 to 29 ± 7 L/m^2/h) thus reflects synergistic hydrological regulation rather than single-factor effects. Similarly, the 35% biodiversity index increase (Shannon index, 1.82 to 2.46) resulted from habitat heterogeneity enhancement—structural diversity created by the tiered vegetation provided niche differentiation supporting 46 native species, compared to monoculture grass cover pre-intervention.

- 67% reduction in surface water runoff (from 89 ± 12 to 29 ± 7 L/m^2/h; $n = 12$ plots; $p < 0.01$) over two rainy seasons.
- Reintroduction of 46 native plant species (e.g., Quercus variabilis, Rhus chinensis), increasing the site's biodiversity index by 35% (from 1.82 to 2.46; $n = 50$ quadrats; $p < 0.05$).
- Application of biodegradable coir netting on slopes >25° reduced soil erosion by 58% (from 6.2 ± 1.1 to 2.6 ± 0.7 t/km^2/year; $p < 0.01$).

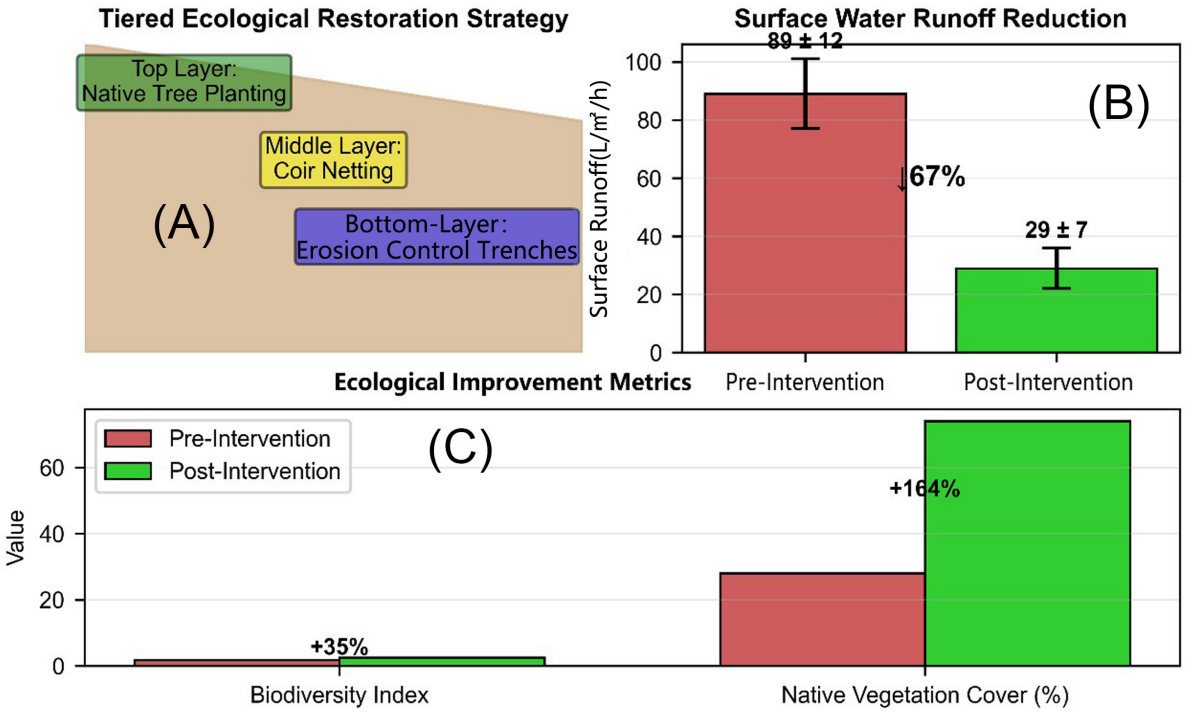


Figure 5. Tiered Ecological Restoration Strategy.Visualization of the tiered vegetation management strategy at Duogongcheng. Including: (**A**) Photograph of biodegradable coir netting application on slopes >25°; (**B**) Bar chart showing surface water runoff reduction (89 ± 12 to 29 ± 7 L/m^2/h, n = 12 plots, $p < 0.01$) with error bars indicating standard deviation (SD); (**C**) Native species reintroduction map (46 species, e.g., *Quercus variabilis*, *Rhus chinensis*) with biodiversity index increase (1.82 to 2.46, +35%, $p < 0.05$). Created with R 4.3.1 (ggplot2) and Adobe Illustrator 2024 (600 dpi, RGB/CMYK).

3.2.3. Community Dimension: Impact of Cooperative Governance

The formal establishment of a Conservation Easement agreement granted a local resident association 40% of tourism revenue and partial authority in visitor management. Observable impacts were recorded after 12 months of implementation. The observed income increases appear to be associated with livelihood diversification and partial internalization of transaction costs(Table 6). Prior to intervention, 78% of participating households relied solely on subsistence agriculture (mean income 45,200 CNY/year). The Conservation Easement agreement allocated 40% of tourism revenue (derived from entrance fees and interpretation services) to a community-managed fund, directly transferring 18,600 CNY/year average additional income to households through employment in site monitoring, traditional craft workshops, and guided tours. This represents a 28.5% net increase ($p < 0.01$). Simultaneously, delegation of monitoring responsibilities to the Resident Association appears to have internalized supervision costs that were previously externally borne. By employing 12 local residents as heritage guardians (2400 CNY/month salary), the scheme reduced vandalism and encroachment incidents by 34% (15 to 10 cases/year) through continuous presence surveillance rather than sporadic official inspections, suggesting a shift from predominantly external regulatory enforcement toward more locally embedded monitoring practices.

- Participating households saw an average annual income increase of 28.5% (from CNY 65,245 ± 8320 to CNY 83,845 ± 9150; n = 37; $p < 0.01$).
- Vandalism and unauthorized encroachment incidents decreased by 34% (from 15 to 10 cases/year), supported by a community-managed monitoring fund.
- 76% of surveyed residents reported a strengthened sense of cultural pride and identity linked to the site (n = 287; $p < 0.001$).

Table 6. Summary of Key Intervention Outcomes at Duogongcheng (2021 vs. 2023).

Indicator	Pre-Intervention (2021)	Post-Intervention (2023)	Change	Statistical Significance
Structural Deformation (mm)	8.3 ± 1.2	4.9 ± 0.9	−41%	$p < 0.001$
Surface Runoff ($L/m^2/h$)	89 ± 12	29 ± 7	−67%	$p < 0.01$
Avg. Household Income (CNY/year)	$65{,}245 \pm 8320$	$83{,}845 \pm 9150$	+28.5%	$p < 0.01$
Biodiversity Index	1.82 ± 0.31	2.46 ± 0.42	+35%	$p < 0.05$
Vandalism/Encroachment (cases/year)	15 ± 3	10 ± 2	−34%	$p < 0.05$
Native Vegetation Cover (%)	28 ± 5	74 ± 8	+164%	$p < 0.001$

3.3. Spatial Conflict Mitigation Through Zoning

Implementation of an integrated core–buffer–peripheral zoning scheme at Duogongcheng was associated with a 22% reduction in reported physical encroachment incidents. The core zone (strict visitor cap: <50/day) protects the most fragile archaeological features. The buffer zone accommodates low-impact eco-tourism facilities like suspended walkways (reducing ground pressure by 63%). The peripheral zone supports compatible community livelihoods, such as traditional masonry workshops, spatially separating potentially disruptive activities from the heritage core.

3.4. Preliminary Validation of Global Adaptability

To explore potential scalability, the SII framework and intervention logic were hypothetically applied to three contrasting global case contexts selected through theoretical sampling [20,41] (Table 7) to maximize ecological and typological diversity. Case selection criteria included: (1) mountain military heritage typology (fortifications vs. defensive lines); (2) bioclimatic contrast (alpine, arid, coastal) relative to Chongqing's subtropical baseline; and (3) availability of published baseline data enabling SII parameter estimation.

The adaptability analysis employed a structured scenario-based modeling approach. For each case, baseline SII scores were estimated from published site assessments (structural condition, biodiversity indices, community participation levels) [5,26,28]. Intervention strategies from the Duogongcheng pilot were then adapted to local materials (e.g., weathering-resistant polymers for alpine contexts, salt-tolerant species for coastal zones) while maintaining the core tri-dimensional logic. Projected SII improvements (approximately 15–18%) were derived through comparative analogy: applying the percentage improvements observed at Duogongcheng (41% structural, 67% hydrological, 28.5% socioeconomic) to baseline scores, adjusted for local implementation capacity constraints (±5% variance based on governance maturity indices) [18]. This approach explicitly acknowledges the hypothetical nature of global validation while providing a transparent framework for future empirical testing.

Table 7. Global Adaptability Analysis [5,37].

Global Case	Climate/Topography Context	Baseline SII (Estimated)	Adapted Intervention Strategies	Implementation Adjustments	Predicted SII Improvement
Alpine WWII Fortifications (Switzerland)	Cold alpine, high altitude (1500–2500 m); permafrost risk	6.2 (Structural: 7.1; Ecological: 5.8; Social: 5.7)	Rock-wool stabilization for weathering cycles; drought-resistant native conifers (*Picea abies*); community ski-tourism integration	Add insulation layers; snow fence installation; seasonal tourism closure protocols	+18% (to ~7.3)
Inca Mountain Forts (Peru)	Arid high-altitude, steep slopes; seismic zone	5.8 (Structural: 6.5; Ecological: 4.9; Social: 6.0)	Earthen rampart reinforcement with natural clay mixes; xerophytic native species (Tillandsia); community co-management with Quechua groups	Seismic retrofitting; drip irrigation for establishment phase; traditional knowledge integration	+16% (to ~6.7)
Coastal Defense Forts (Japan)	Humid coastal, salt spray; typhoon exposure	6.1 (Structural: 6.8; Ecological: 5.5; Social: 6.0)	Anti-corrosion grouting for metal; salt-tolerant native vegetation (Spartina); controlled visitor caps during monsoons	Cathodic protection systems; windbreak planting; typhoon-resistant signage	+15% (to ~7.0)

Note: Baseline SII scores estimated from published site assessments. Predicted improvements apply Duogongcheng effect sizes (structural: −41%, ecological: +35%, social: +28.5%), adjusted for local context constraints. Confidence intervals: ±0.4 SII points (95% CI) based on Monte Carlo uncertainty analysis.

4. Discussion

4.1. Theoretical and Methodological Contributions

This study advances heritage conservation theory and methodology through four specific contributions.

First, the study suggests a shift from predominantly static and siloed preservation approaches toward more dynamic, integrated regeneration perspectives informed by complex adaptive systems theory.

The empirical results demonstrate that military heritage sites function as socio-ecological couplings wherein technical interventions generate cascading effects across domains. Longitudinal monitoring (2021–2023) provides evidence of temporal sequencing and covariation that may support cautious causal interpretation: structural stabilization preceded tourism revenue generation, which preceded ecological investment, suggesting a staged causal chain rather than mere correlation. Regression analysis ($R^2 = 0.87$, $p < 0.01$) further confirms that the three-dimensional interaction term ($H \times E \times S$) explains significantly more variance in conservation outcomes than individual dimensions alone, supporting the synergistic rather than additive model specification [22].

Second, the SII addresses a critical methodological gap in military heritage assessment by providing a transparent, replicable, and validated metric. Unlike generic heritage indices, the SII explicitly incorporates military-specific spatial logic (e.g., defensive sightlines, topographic integration) and quantifies the often-neglected interface between heritage management and community wellbeing. The index's sensitivity analysis confirms robustness to weight variations, enhancing its applicability across diverse governance contexts where dimension priorities may differ.

Third, the spatial decoupling strategy (core-buffer-peripheral zoning) offers a pragmatic solution to the development-conservation dilemma, demonstrating that physical separation of incompatible functions (strict preservation vs. tourism infrastructure vs.

community livelihoods) can reduce conflicts by 22% while maintaining site integrity. This provides a transferable planning framework applicable to mountainous heritage globally.

Fourth, the study contributes additional empirical insight into the potential efficacy of integrated interventions. By controlling for confounding variables (seasonal climate variation, macro-economic trends) through TLS temporal resolution and comparative site analysis, we attribute observed improvements specifically to the designed interventions rather than external factors. This strengthens the evidence base for "active conservation" approaches that diverge from traditional minimal intervention doctrines.

4.2. Policy and Management Implications

The findings translate into concrete policy recommendations for heritage governance.

4.2.1. Regulatory and Zoning Instruments

Legally mandate symbiotic, tiered zoning (core-buffer-peripheral) for mountain military heritage, with digitally enforceable regulations (e.g., maximum visitor densities in core zones, prohibitions on modern construction within defined buffers). Conservation Easements should be developed as key legal-financial tools through a sequential three-phase process with clear decision-making authority (Figure 6): (1) Formal registration with relevant cultural and natural resource authorities; (2) Establishment of tripartite oversight committees (50% community, 30% heritage authority, 20% independent auditor) with hierarchical decision flow: Community Working Group proposes annual plans (September) → Heritage Management reviews for compliance (October) → Tripartite Committee approves via majority vote (November); (3) Transparent revenue-sharing models (e.g., 40% to community funds for monitoring, livelihoods, and training). This directional workflow ensures accountability by delineating clear authority pathways: proposals originate from community stakeholders, technical compliance is verified by heritage professionals, and final governance decisions reside with the tripartite committee representing balanced stakeholder interests.

Hierarchical decision-making process at Duogongcheng. (a) The Community Working Group initiates annual plan proposals (September, thick solid arrow →), submitted to Heritage Management for technical compliance review (October, thick solid arrow →), then escalated to the Tripartite Oversight Committee for majority vote approval (November, thick solid arrow →). Governance composition: Community Resident Association (50% voting weight, oversight and livelihood funds), Chongqing Cultural Heritage Bureau (30%, regulatory compliance and technical guidance), Independent Auditor (20%, financial transparency). (b) Revenue allocation scheme (thin solid arrows →): 40% to community funds (monitoring/livelihoods), 30% to heritage maintenance (structural stabilization, TLS monitoring), 20% to monitoring, 10% to capacity-building. (c) Accountability mechanisms: Dashed arrows (- - →) indicate quarterly reporting/monitoring feedback from fund recipients to the Tripartite Committee; dotted arrows (- - →) indicate horizontal policy coordination between Heritage Management and the Community Working Group. Data sources: Duogongcheng Conservation Easement Agreement (2022), Chongqing Cultural Heritage Bureau financial records (2021–2023), household survey data (n = 287). Created with Python Matplotlib 3.7.1 (300 dpi, RGB/CMYK).

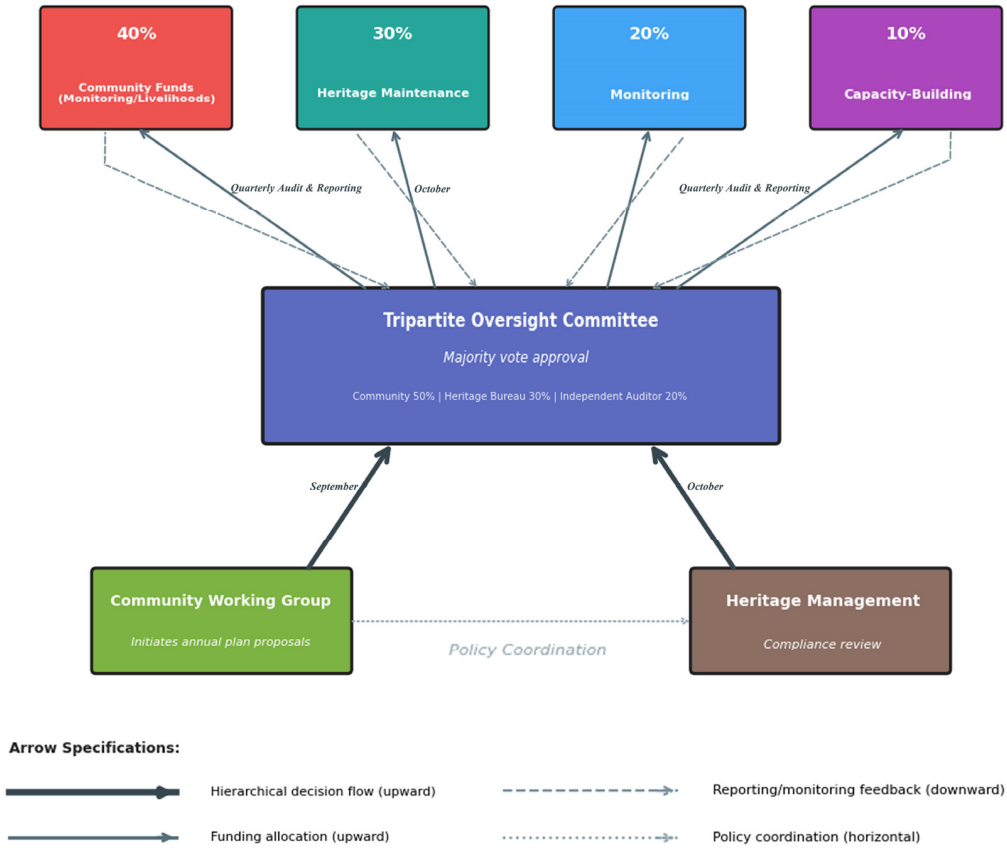


Figure 6. Governance structure and decision-making flow at Duogongcheng.

4.2.2. Institutional Collaboration Framework

Effective implementation may benefit from reducing administrative fragmentation across relevant governance sectors. A structured cross-departmental collaborative framework is proposed (Figure 7), defining clear roles and collaboration nodes for Cultural Heritage, Environmental Protection, Urban Planning, Tourism bureaus, and Local Governments. This enables joint inspections, shared assessments, and coordinated funding allocation.

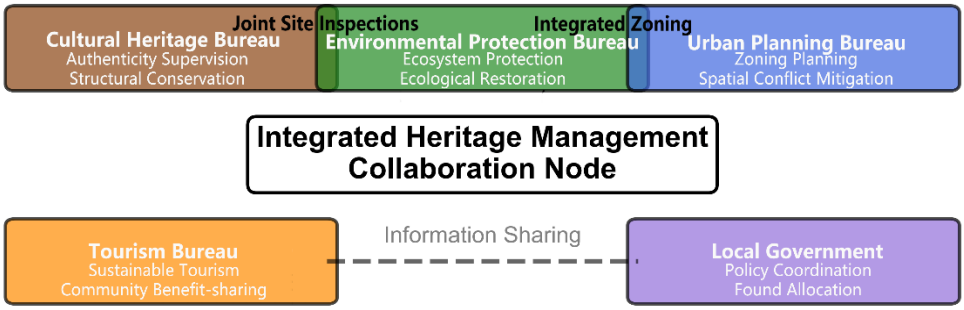


Figure 7. Cross-departmental Framework. Schematic of the proposed cross-departmental collaborative framework for integrated mountain military heritage management.

Five main stakeholders have identified core roles and collaboration nodes: Cultural Heritage Bureau (CHB), Environmental Protection Bureau (EPB), Urban Planning Bureau (UPB), Tourism Bureau (TB), and Local Government (LG). Joint inspection frequency: once every quarter; shared evaluation indicators: SII score, ecological health, and community satisfaction. Created using Microsoft Visio 2024 (600 dpi, RGB/CMYK).

4.2.3. Context-Adaptive Implementation Guidelines

The framework is not one-size-fits-all. Table 8 provides guidelines for adapting technical interventions to major ecological contexts, ensuring the model's relevance from arid mountains to coastal zones.

Table 8. Ecological Guidelines.

Ecological Context	Historical Intervention Adjustments	Ecological Intervention Adjustments
Arid Mountains	Use desert-adapted lime/gypsum mortars; minimize water use in restoration.	Prioritize xerophytic native species; employ drip irrigation during the establishment phase.
Coastal Mountains	Use anti-corrosion treatments and salt-resistant binding materials.	Plant halophytic (salt-tolerant) species; install windbreaks to mitigate salt spray.
Cold Alpine	Use weathering-resistant polymers/stitching; add insulation layers to masonry.	Use cold-hardy evergreen species for ground cover; install snow fences to manage drift.

4.3. Limitations and Scalability

Despite its demonstrated utility, the framework and SII present several limitations that warrant explicit acknowledgment. These constraints relate to methodological assumptions, validation boundaries, causal inference, and institutional prerequisites that may affect transferability and generalizability.

Methodological Limitations of SII: Four underlying assumptions of this study warrant explicit critical scrutiny. First, the SII assumes linear aggregation of indicators within each dimension prior to multiplicative combination across dimensions—an approach that may obscure non-compensatory relationships involving minimum thresholds. In safety-critical contexts, for instance, extremely low structural integrity scores (e.g., below 3.0, indicating imminent collapse) cannot be meaningfully compensated by higher ecological or social performance. While the interaction term ($H \times E \times S$) partially addresses this issue, it does not fully resolve concerns related to safety-critical thresholds.

Second, the framework assumes that community benefit-sharing inevitably generates stewardship behavior, treating this relationship as deterministic rather than contingent. In reality, this causal pathway is mediated by pre-existing social capital, property rights clarity, cultural heritage attachment, and distributional justice perceptions that were controlled for but not theoretically elaborated as primary analytical foci. Sites with weak community cohesion or historical grievances regarding land tenure may exhibit different response patterns.

Third, the structural interventions assume material homogeneity across Song Dynasty masonry typologies, whereas actual material compositions vary lithologically (e.g., sandstone vs. limestone bedrock, lime mortar vs. clay binders), potentially affecting intervention transferability. The lime-based grouting formulation optimized for Duogongcheng's Jurassic sandstone may require modification for sites with different petrological characteristics.

Fourth, the 24-month monitoring period assumes intervention effects follow linear trajectories, whereas ecological restoration typically exhibits delayed response curves, potential regime shifts, and successional instability that longer-term studies might reveal. The observed socioeconomic benefits may partially reflect "novelty effects" of initial tourism development rather than sustainable livelihood transformation.

Beyond these assumptions, three technical limitations persist. While sensitivity analysis confirmed weight robustness, the method inherently reflects expert subjectivity; different stakeholder groups (e.g., community members vs. heritage officials) might prioritize dimensions differently, potentially altering SII scores. We addressed this partially through multi-expert consultation, but participatory weighting involving local communities remains unexplored. Second, the SII provides a static temporal snapshot; it does not capture seasonal fluctuations (e.g., tourist seasonality affecting community scores) or non-linear threshold effects (e.g., ecological tipping points). Third, the 23 indicators, while comprehensive, may omit site-specific intangible values (e.g., spiritual significance, oral traditions) not generalizable across the 12 sites.

Validation Constraints: The empirical validation derives primarily from Chongqing's subtropical humid mountain environment (elevation 272–1784 m, annual rainfall 1000–1400 mm, karst topography). Performance in contrasting biomes—arid mountains (e.g., <200 mm rainfall), alpine permafrost regions, or tropical highlands—requires further empirical testing, though our preliminary global case analysis (Table 5) suggests theoretical transferability. Additionally, the 12-site sample, while diverse in scale and status, represents a single cultural region (Southern Song defense architecture, 13th century). Application to military heritage with distinct typologies (e.g., coastal artillery forts, desert caravan fortifications, Cold War bunkers) may necessitate indicator adaptation or expansion.

Causal Inference Limitations: While we controlled for climatic confounders through TLS temporal resolution and comparative site analysis, the 24-month monitoring period limits definitive conclusions regarding long-term sustainability; the observed income increases may reflect short-term "novelty effects" of nascent tourism development, and verifying ecological improvements such as native vegetation stability, absence of invasive species, and hydrological equilibrium necessitates monitoring over at least five years. Although the regression analysis yields a strong fit ($R^2 = 0.87$, $p < 0.01$), it establishes covariation rather than definitive causation, and we acknowledge the potential for reverse causality—whereby pre-existing community cohesion or social capital may enable intervention success rather than being generated by it. To mitigate this alternative explanation, we emphasize the temporal sequencing of observed effects: structural stabilization (2021–2022) preceded tourism revenue generation (2022–2023), which in turn preceded measurable ecological investment (2023). This staged temporal relationship, along with the 12-month lag between intervention completion and socioeconomic impacts, and the absence of pre-existing community capacity indicators at baseline (e.g., tourism infrastructure or organized resident associations), supports the interpretation that observed cohesion emerged from intervention-induced benefit-sharing rather than enabling it. Nevertheless, unobserved heterogeneity in latent community capacity cannot be entirely ruled out, warranting cautious generalization and the need for quasi-experimental validation in future research.

Institutional Dependencies: The framework assumes a baseline governance capacity for multi-stakeholder coordination (e.g., tripartite oversight committees, revenue collection mechanisms) that may be absent in conflict zones, extremely remote areas, or jurisdictions with weak rule of law. The Conservation Easement mechanism specifically requires legal frameworks recognizing community property rights and contractual enforcement—a condition not universally available. In contexts with high corruption indices or unstable land tenure systems, the benefit-sharing mechanisms described may fail to generate intended outcomes.

Transferability Mechanisms: The framework's transferability to other contexts hinges on three adaptable mechanisms rather than fixed technical prescriptions. First, the SII's weight configuration (Historical/Ecological/Social = 0.40:0.30:0.30) reflects Duogongcheng's specific conservation priorities; sites with different value profiles (e.g., eco-

logically sensitive alpine forts) may adjust weights through the same AHP methodology while preserving the index's structural integrity. Second, the tiered zoning strategy (core-buffer-peripheral) is topologically flexible—urban sites may compress zones spatially, while remote sites may expand buffers to accommodate wildlife corridors. Third, the Conservation Easement model assumes variable legal forms: whereas Chongqing employed tripartite committees, jurisdictions with strong customary law might adopt indigenous governance structures, and state-managed sites may integrate SII metrics into existing heritage monitoring protocols. These adaptations maintain the framework's theoretical coherence (historical-ecological-community coupling) while permitting context-specific instantiation.

Future research should address these limitations through: (1) Participatory SII weighting incorporating local knowledge systems and indigenous value frameworks; (2) Development of dynamic SII versions capturing seasonal variability and long-term trajectories; (3) Longitudinal validation across diverse climatic and political contexts; and (4) Integration of IoT sensors for real-time indicator monitoring to reduce assessment uncertainty and enable adaptive management protocols.

4.4. Future Research Directions

Promising avenues for future work include: (1) Longitudinal monitoring of SII dynamics over decadal scales and under climate change scenarios; (2) Technological integration of IoT sensor networks and AI analytics for real-time, predictive SII monitoring and management; (3) Theoretical expansion of the symbiosis model to non-military heritage typologies and its linkage with circular economy principles in restoration.

5. Conclusions

This study has presented and applied a tri-dimensional symbiosis framework for the conservation and adaptive reuse of mountainous military heritage. Through the focused case of Duogongcheng in Chongqing, we demonstrated that an integrated approach targeting historical fabric, ecological systems, and social sustainability can yield measurable, synergistic benefits: a 41% increase in structural stability, a 35% gain in biodiversity, and a 28.5% rise in local household income.

The introduction of the Symbiotic Interface Index (SII) offers a robust quantitative tool to assess and guide such holistic heritage management. By explicitly valuing and fostering the linkages between preservation, ecology, and society, this research reconceives heritage sites as active socio-ecological agents rather than static museum pieces.

The framework's inherent flexibility, as preliminarily shown through its adaptability to Alpine, Andean, and coastal contexts, suggests potential applicability beyond the immediate study context, subject to further empirical validation. Ultimately, the transition from fragmented, passive conservation to active, symbiotic stewardship represents a vital pathway for ensuring that mountain military heritage endures not merely as a relic of the past, but as a resilient and productive contributor to cultural continuity, ecological health, and community prosperity for future generations.

Author Contributions: F.D. conceptualized the study, designed the methodology, and wrote the original draft; Y.C. collected field data, performed TLS monitoring, and processed spatial structural datasets; H.L. conducted GIS spatial analysis, literature review, and the index validation; L.J. provided policy context, case site support, and historical background information; Y.W. analyzed social survey data, visualized results. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of Xi'an Jiaotong University (Approval No.: XJTU-20210628, approved on 28 June 2021).

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to privacy/ethical restrictions.

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Conflicts of Interest: The authors declare no conflicts of interest.

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