

ECO-GENE IDENTIFICATION AND ATLAS CONSTRUCTION OF HUIZHOU ARCHITECTURE FROM A MULTIDISCIPLINARY PERSPECTIVE

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Abstract: Traditional settlements worldwide constitute repositories of ecological wisdom accumulated through millennia of human-environment coevolution, yet the systematic decoding of ecological genes embedded within traditional architectural morphologies remains substantially underdeveloped, particularly within rigorous multidisciplinary frameworks. Huizhou architecture, an exemplary manifestation of Chinese vernacular heritage inscribed on the UNESCO World Heritage list, exemplifies a sophisticated teleological alignment between built form and ecological substrate; nevertheless, extant scholarship has predominantly remained at the descriptive and conservation-oriented level, lacking ontological precision in identifying and taxonomizing its constituent eco-genes. Addressing this epistemological lacuna, the present study develops an integrated multidisciplinary methodology for identifying, classifying, and visualizing eco-genes embedded within Huizhou architectural typologies. Drawing upon extensive field investigation, dialectical synthesis across philosophy, art theory, design science, and ecology, and GIS-based cartographic visualization, this research constructs a three-tier eco-gene taxonomy—encompassing macro-structural, meso-configurational, and micro-material genes—and proposes a comprehensive atlas framework for their spatial representation, combinatorial analysis, and evolutionary mapping across the Huizhou region. The findings reveal that Huizhou architecture embodies a complex ecological epistemology manifested through topological adaptation to mountainous terrain, thermodynamic optimization via grey-brick and black-tile envelopes, and synergistic hydrogeological integration through courtyard drainage systems. By advancing cultural landscape gene theory through ontological clarification of architectural eco-genes and epistemological standardization of identification protocols, this study contributes substantively to heritage conservation theory, enriches the conceptual vocabulary of cultural landscape studies, and provides a hermeneutic foundation for contemporary sustainable design practice.

Keywords: Huizhou architecture; Eco-gene; cultural landscape gene; Gene atlas; Multidisciplinary perspective; Traditional ecological knowledge

1 INTRODUCTION

1.1 Global Context of Cultural Heritage and Ecological Wisdom

The ontological status of cultural landscapes as palimpsests of human-environment coevolution has garnered increasing scholarly attention within the interdisciplinary nexus of heritage studies, landscape ecology, and architectural theory. Traditional settlements, constituting the material embodiment of millennia of ecological adaptation, function not merely as passive repositories of historical artifacts but as active, living systems encoding sophisticated traditional ecological knowledge (TEK) accumulated through iterative trial-and-error processes spanning successive generations [1]. This epistemological reconceptualization of vernacular architecture—from static monument to dynamic knowledge system—has been formally institutionalized through UNESCO's framework for safeguarding intangible cultural heritage and the Council of Europe (2000) European Landscape Convention, both of which underscore the dialectical interdependence between cultural identity and landscape morphology. Taylor (2012) further elaborates that landscape meaning emerges through the hermeneutic interplay of human perception, cultural narrative, and material environment, thereby establishing an interpretive framework wherein vernacular settlements are read as complex texts encoding multivalent ecological and social significations.

Contemporary discourse on sustainable development has witnessed a paradigmatic shift from technocratic solutions toward phenomenological engagement with historically evolved ecological wisdom embedded within traditional built environments. Antrop (2005) compellingly argues that landscapes of the past constitute indispensable reservoirs of ecological intelligence, offering teleological insights into how human societies have historically negotiated the tension between anthropogenic needs and environmental constraints. This hermeneutic perspective positions vernacular settlements as embodied texts requiring interpretive decoding rather than mere aesthetic appreciation. The crisis of cultural landscape identity, accelerated by rapid urbanization and the homogenizing forces of globalization, has precipitated an urgent imperative to develop systematic methodologies for extracting, formalizing, and transmitting the ecological knowledge encoded within traditional architectural morphologies before their irreversible erosion.

1.2 Huizhou Architecture: Cultural Significance and Ecological Sophistication

Situated within the mountainous topography of southern Anhui Province, China, Huizhou architecture represents one of the most refined and ecologically sophisticated manifestations of Chinese vernacular building tradition. Its distinctive formal vocabulary—characterized by grey-brick masonry, black-tile roofing, horse-head wall compositions (*matouqiang*), intricately carved timber structural elements, and precisely proportioned courtyard configurations—constitutes a cohesive morphological system that transcends mere stylistic convention to embody a deeply rooted ecological epistemology [2]. The iconic settlements of Hongcun and Xidi, inscribed on the UNESCO World Heritage List in 2000, exemplify this architectural tradition's extraordinary capacity for integrating built form with natural topography, hydrological systems, and microclimatic conditions.

The ecological sophistication of Huizhou architecture manifests across multiple scalar registers. At the macro-structural level, settlement patterns demonstrate meticulous topophilic adaptation to undulating mountainous terrain, with building orientations optimized for solar exposure, wind deflection, and drainage management. At the meso-configurational level, the prototypical courtyard-centered spatial organization—encapsulating the *tianjing* (skywell) system—functions as a sophisticated passive climate-modification apparatus, facilitating natural ventilation, daylighting modulation, and rainwater harvesting. At the micro-material level, the specification of local building materials, including porous grey brick, thermally massive stone foundations, and breathable timber joinery, reflects an empirically derived understanding of hygrothermal performance long predating modern building physics [3]. This multilayered ecological intelligence positions Huizhou architecture as an exceptionally fertile terrain for systematic eco-gene identification and analysis.

1.3 Research Gap: From Descriptive Analysis to Gene-Level Decoding

Notwithstanding the substantial scholarly attention directed toward Huizhou architecture over recent decades, extant research has predominantly operated within descriptive, conservation-oriented, or stylistic-analytical paradigms that fail to penetrate to the underlying genetic substratum of its ecological intelligence. Chen and Pintong (2024) have contributed valuable perspectives on Huizhou traditional dwellings through the lens of green architecture, while Song et al. (2025) have examined the sustainability of traditional Chinese villages from a broad environmental perspective. Similarly, Ma et al. (2025) and Zhang et al. (2022) have advanced digital preservation methodologies for architectural heritage through virtual and knowledge-visualization approaches. However, these studies remain fundamentally phenomenological in orientation, describing *what* ecological characteristics manifest rather than decoding *how* these characteristics function as discrete, heritable, and combinatorial genetic units within a broader architectural genotype.

The conceptual framework of the cultural landscape gene, initially theorized through seminal work on memetics and subsequently adapted to architectural and settlement studies [4], provides a promising theoretical foundation for transcending this limitation. Yet, the specific application of gene-level analysis to the ecological dimensions of traditional architecture—the identification, classification, and cartographic visualization of *eco-genes* as distinct units of ecological knowledge encoded in built form—remains conspicuously absent from the literature. There exists no systematic taxonomy of architectural eco-genes applicable to Huizhou architecture, no standardized epistemological protocol for their identification, and no integrated atlas framework for their spatial visualization and comparative analysis. This tripartite lacuna constitutes the central problematic motivating the present investigation.

1.4 Research Objectives and Contributions

In response to the identified research gaps, this study establishes three interconnected objectives. First, it seeks to develop a rigorous multidisciplinary theoretical framework for conceptualizing architectural eco-genes, synthesizing insights from philosophical ontology, art-historical morphology, design-science methodology, and landscape ecology to establish clear definitional and operational criteria for eco-gene identification. Second, it aims to construct a systematic three-tier taxonomy of eco-genes specific to Huizhou architecture, encompassing macro-structural genes (settlement patterns, topographical adaptation), meso-configurational genes (spatial organization, courtyard typologies), and micro-material genes (material specifications, construction techniques, ornamental motifs encoding ecological function). Third, it endeavors to develop a comprehensive GIS-based atlas framework capable of visualizing the spatial distribution, combinatorial relationships, and evolutionary trajectories of identified eco-genes across the Huizhou region.

The theoretical contribution of this study lies in advancing cultural landscape gene theory through the introduction and operationalization of the eco-gene concept—a hermeneutic and methodological innovation that bridges the gap between abstract gene theory and the concrete materiality of vernacular architecture. By demonstrating that ecological wisdom in traditional architecture is not merely a diffuse cultural attribute but a structurally organized system of discrete, identifiable, and mappable genetic units, this research provides a replicable epistemological template applicable to other vernacular traditions worldwide. The practical contribution resides in the atlas framework itself, which offers heritage conservation practitioners, urban planners, and sustainable designers a cartographic instrument for understanding, preserving, and strategically deploying traditional ecological knowledge in contemporary contexts.

1.5 Paper Structure Overview

The remainder of this paper is organized as follows. Section 2 develops the multidisciplinary theoretical framework, synthesizing perspectives from philosophy, art theory, design science, and ecology to establish the ontological and

epistemological foundations for eco-gene identification. Section 3 details the methodological protocols, encompassing field investigation procedures, interdisciplinary synthesis techniques, and GIS-based cartographic visualization methods. Section 4 presents the three-tier eco-gene taxonomy derived from systematic analysis of Huizhou architectural morphologies. Section 5 elaborates the atlas construction framework and demonstrates its application through selected case studies. Section 6 discusses the implications of the findings for cultural landscape gene theory, heritage conservation practice, and sustainable design. Section 7 concludes with a summary of contributions, limitations, and directions for future research. To address these gaps, this study develops a multidisciplinary theoretical framework that integrates ontological, epistemological, and phenomenological perspectives to establish rigorous criteria for identifying, classifying, and visualizing architectural eco-genes, as elaborated in the following section.

2 THEORETICAL FRAMEWORK

Building upon the identified research gaps, this section establishes the theoretical foundations that underpin the eco-gene identification and atlas construction of Huizhou architecture. The framework proceeds through four interconnected strata: first, the gene-metaphor lineage from Dawkins' meme theory to contemporary cultural landscape gene theory furnishes the analytical vocabulary for decoding heritable architectural knowledge; second, the ecological philosophy embedded in traditional Chinese architectural praxis provides the ontological grounding; third, a multidisciplinary epistemological integration synthesizes insights from phenomenology, art history, design studies, and ecology into a coherent methodological orientation; and fourth, these strands converge in the formulation of the eco-gene paradigm, a conceptual model that renders explicit the mechanisms through which ecological knowledge is encoded, transmitted, and expressed in built form.

2.1 Cultural Landscape Gene Theory

The application of biological metaphors to cultural analysis has undergone substantial refinement since Dawkins (1976) first proposed the meme as a unit of cultural transmission analogous to the gene. Dawkins' insight—that cultural information replicates, mutates, and undergoes selective pressure in manners parallel to biological evolution—established a conceptual foundation subsequently adapted by scholars of landscape studies. Chinese scholars, notably Liu et al. (2009), translated this metaphor into territorial analysis, proposing cultural landscape gene theory (*wenhua jingguan jiyin*), which treats settlement morphology, architectural typology, and spatial organization as heritable informational units subject to processes of identification, transmission, mutation, and selection.

The theoretical architecture of cultural landscape gene theory rests upon four core conceptual operations. Gene identification entails the systematic decomposition of settlement morphology into discrete, recurrent elements—architectural components, spatial configurations, and topographical adaptations—that retain sufficient stability across replication to constitute analytical units. Gene transmission addresses the mechanisms through which these units propagate across generations, encompassing both direct pedagogical transmission and indirect diffusion through migration and trade. Gene mutation captures the incremental modifications that occur as architectural genes are replicated under divergent environmental and sociocultural conditions, generating observed phenotypic diversity. Gene selection accounts for the differential persistence of variants, whereby configurations that enhance environmental fitness or symbolic efficacy achieve greater reproductive success within the cultural population.

The operationalization of this framework for traditional Chinese settlements has achieved notable maturity. Yang (2023) advanced a meme-based approach for knowledge mining and organization of traditional settlement culture, demonstrating that the cultural landscape gene concept can function as a generative framework for computational heritage analysis. Liu et al. (2023) examined environmental adaptation of settlement patterns through landscape gene mapping, establishing empirical correlations between topographical variables and the spatial distribution of architectural genes. Their research confirmed that settlement genes exhibit systematic spatial patterning governed by ecological fitness landscapes. Together, these contributions validate the analytical purchase of the gene metaphor, while underscoring the necessity of grounding abstract constructs in the material particularities of environmental adaptation.

2.2 Ecological Philosophy in Traditional Chinese Architecture

The ontological foundation of Huizhou architecture is rooted in the philosophical doctrine of *Tian Ren He Yi*, conventionally rendered as the "Unity of Heaven and Humanity." This cosmological proposition, central to Confucian, Daoist, and Neo-Confucian thought, posits a non-dualistic continuity between natural processes and human existence, establishing an ethical and aesthetic imperative for architectural practice to achieve harmonious integration with its environmental milieu. Unlike Western metaphysical traditions that have frequently construed nature as an objectified domain to be mastered, the *Tian Ren He Yi* framework situates human dwelling within the continuous field of cosmic processes, such that the built environment is conceptualized not as an artificial enclave carved from wilderness but as a cultivated continuation of natural order.

This philosophical orientation found its most concrete architectural expression in *Feng Shui*, a body of empirical ecological knowledge regulating site selection, orientation, and spatial configuration. Far from the caricature of superstitious geomancy, *Feng Shui* as analyzed by Han (2001), Mak and Ng (2008), and Bruun (2008) constitutes a sophisticated, observation-based framework for optimizing the relationship between built form and environmental variables. Han (2001) demonstrated that traditional site selection principles exhibit convergences with contemporary

ecological perspectives, particularly in microclimatic modulation and drainage management. Mak and Ng (2008) corroborated this through empirical surveys, revealing that *Feng Shui* principles retain functional relevance for contemporary design. Bruun (2008) contextualized the system within anthropological frameworks, arguing that *Feng Shui* operates as a culturally specific but empirically grounded mode of landscape reasoning encoding accumulated environmental knowledge in symbolic form.

The spatial organization of Huizhou architecture manifests Yin-Yang balance and the Five Elements (*Wuxing*) in its morphological grammar. Yin-Yang dialectics inform the alternation between enclosed, shaded courtyards and open, sun-exposed transitional spaces, generating thermal gradients that facilitate passive climate moderation. The Five Elements framework structures material selection: timber corresponds to Wood, fired brick and ceramic tile to Earth, metal fixtures to Metal, hearths to Fire, and water-management systems to Water. Xu (2003), in a doctoral investigation of *Feng Shui* and environmental principles, demonstrated that these cosmological categories function not merely as symbolic classifications but as operational heuristics guiding the integration of built form with regional ecosystems. Consequently, Huizhou architecture embodies environmental reasoning in which ecological functionality and cosmological signification are co-constitutively intertwined.

2.3 Multidisciplinary Epistemological Integration

The analytical comprehension of Huizhou architecture as a carrier of ecological knowledge demands an epistemological pluralism that transcends the methodological monism of any single discipline. The present framework therefore undertakes a strategic integration of four disciplinary perspectives—philosophy, art history, design studies, and ecology—each of which illuminates a distinct dimension of the architectural object while together constituting a comprehensive analytical aperture.

From the philosophical perspective, essay "Building Dwelling Thinking" furnishes the foundational phenomenological vocabulary for apprehending architecture not as a collection of physical artifacts but as the materialization of dwelling (*Wohnen*)—the mode of human existence that attunes itself to the particularities of place [5]. Heidegger's distinction between building as construction and building as cultivation resonates profoundly with the Huizhou tradition, wherein architectural production is inseparable from agricultural stewardship. The phenomenology of dwelling directs analytical attention toward experiential qualities: the way light filters through the *si shui gui tang* courtyard, the acoustic properties of timber-framed halls, the haptic memory of stone thresholds worn by generational passage. Ingold (2000), extending this tradition through ecological anthropology, emphasized that dwelling is not static occupancy but continuous engagement with the environment, a perspective that aligns with the dynamic, adaptive character of Huizhou architectural praxis.

Art historical analysis contributes an aesthetics of material expression that complements phenomenological description with iconographic interpretation. The distinctive grey-white-black chromatic palette of Huizhou architecture constitutes not merely a regional stylistic signature but a material poetics that indexes regional resource availability and the climatic necessity of high-albedo surfaces. Decorative programs, particularly wood carvings of flora and fauna, function as compendia of local ecological knowledge, encoding information about native species and seasonal cycles in a visual language simultaneously aesthetic and didactic. Lefebvre (1991), in his theorization of the production of space, provided critical tools for analyzing how such material expressions are implicated in the social production of spatial meaning and power relations.

Design studies contribute the concept of pattern languages, systematically articulated by Alexander (1977), which provides a generative framework for understanding architectural knowledge as a repertoire of combinatorial rules. Alexander's approach, wherein each pattern describes a recurrent design problem together with its solution, offers direct methodological affinities with the gene-metaphor framework. For Huizhou architecture, this reveals that diverse individual buildings are generated from a compact set of underlying patterns—courtyard configurations, structural bay modules, roofscape articulations—that recombine under varying contextual constraints. Rapoport (1969), in his foundational study of house form and culture, established that built form is shaped not merely by climate and technology but by culturally specific norms and cosmological beliefs, a principle that underwrites the present framework's insistence upon the inseparability of ecological and cultural analysis.

Ecology contributes the concepts of bioclimatic adaptation and ecosystem services, rendering measurable the environmental performance encoded in traditional form. McHarg (1969) argued that regional landscape processes should constitute the primary data for architectural decision-making—a principle Huizhou builders implicitly enacted centuries before its theoretical formulation. The ecosystem services framework permits quantification of benefits provided by traditional settlement patterns, including microclimatic regulation, stormwater management, and habitat provision. Berque (1995), synthesizing Eastern and Western landscape traditions, advanced landscape reasoning (*raison du paysage*) as a mode of thought mediating between human subjectivity and environmental materiality, providing a philosophical bridge between the *Tian Ren He Yi* tradition and contemporary ecological epistemology.

2.4 Conceptual Model: The Eco-Gene Paradigm

The convergence of the theoretical strands elaborated above—cultural landscape gene theory, traditional ecological philosophy, and multidisciplinary epistemological integration—yields the eco-gene paradigm, the central conceptual apparatus of this study. An eco-gene is defined as a heritable unit of ecological knowledge encoded in built form,

transmitted across generations through processes of architectural replication and pedagogical apprenticeship, and subject to selective pressure from environmental, social, and symbolic fitness landscapes. This definition preserves the analytical utility of the biological gene metaphor while rejecting the reductionist implication that cultural evolution is mechanistically determined by biological analogues; rather, eco-genes are understood as informational regularities that achieve persistence through their capacity to mediate efficaciously between human dwelling requirements and environmental conditions.

The eco-gene paradigm is structured along three analytic dimensions: Material, Process, and Meaning. The Material dimension encompasses the physical substrate of architectural genes: the selection and processing of regional materials (grey brick, black tile, timber, stone), the dimensional and proportional parameters of structural components, and the chromatic and textural properties of surfaces. Material eco-genes encode empirical knowledge about local resource availability, mechanical properties, weathering behavior, and thermal performance. The Process dimension addresses the operational sequences through which architectural form is produced and maintained: construction techniques, maintenance regimes, adaptive modifications, and the ritual practices that punctuate the building lifecycle. Process eco-genes embody knowledge about energy flows, labor organization, and the temporal rhythms of material transformation. The Meaning dimension, finally, encompasses the semiotic and symbolic content invested in architectural form: cosmological orientation, decorative iconography, spatial hierarchies, and the narratives through which buildings are integrated into communal memory and identity. Meaning eco-genes encode the cultural values, cosmological beliefs, and social norms that govern the appropriateness and desirability of particular morphological configurations.

The relationship between these dimensions is not merely additive but generative. Following the genotype-phenotype distinction adapted from biology, eco-genes operate at two interconnected levels. The genotype comprises the latent design principles—rules of composition, proportional systems, material specifications, and spatial scripts—that constitute the architectural equivalent of genetic code. These principles are not always explicitly articulated in textual form; more frequently, they are encoded in craft knowledge, embodied in the trained dispositions of builders, and implicit in the morphological regularities of existing buildings. The phenotype, conversely, comprises the observable built artifacts: the individual courtyard house, the ancestral hall, the water-management channel, the defensive wall. The analytical task of eco-gene identification is precisely the inferential reconstruction of genotype (design principles) from phenotype (built artifacts), a hermeneutic operation that demands simultaneous attention to material traces, technical procedures, and symbolic contexts.

The conceptual model comprises a multi-layered structure. At the foundational stratum lies the environmental matrix—topography, climate, hydrology, and biota—that constitutes the selective pressure field within which eco-genes evolve. The second stratum contains the gene pool: the repertoire of heritable design principles distributed across the Huizhou settlement network. The third stratum comprises the expression mechanisms—craft traditions, construction practices, and ritual protocols through which genotypic principles are actualized as phenotypic form. The fourth stratum encompasses the built environment in its totality. This model is dynamic; eco-genes circulate, mutate, and recombine within the gene pool, while selective pressures continuously filter architectural variants, driving the co-evolution of built form and ecological knowledge.

3 METHODOLOGY

Grounded in the theoretical framework elaborated above, the research methodology integrates qualitative and quantitative approaches within an explicitly interdisciplinary design. The methodological architecture reflects the epistemological commitment that the identification and mapping of architectural eco-genes cannot be accomplished through any single disciplinary lens but requires the coordinated deployment of architectural documentation, environmental measurement, spatial analysis, and interpretive hermeneutics. This section details the research design, data collection procedures, the four-step eco-gene identification protocol, and the atlas construction methodology.

3.1 Research Design: Mixed-Method Interdisciplinary Approach

The research adopts a mixed-method design combining qualitative and quantitative modalities to achieve complementary analytical depth. The qualitative component encompasses systematic literature review, sustained field observation, and semi-structured expert interviews. The literature review surveys architectural history, landscape ecology, and heritage studies to establish the state of knowledge. Field observation employs visual ethnography and architectural phenomenology, documenting the spatial experience of Huizhou settlements and the ongoing practices of maintenance and adaptation. Expert interviews engage architectural historians, conservation specialists, and traditional craftsmen to access tacit knowledge preserved in professional expertise and communal memory.

The quantitative component comprises spatial analysis, climatic measurement, and GIS-based mapping. Spatial analysis employs morphometric techniques to quantify geometric properties of settlement plans, building footprints, and courtyard proportions, generating datasets that permit statistical comparison across sites and the identification of recurrent patterns. Climatic measurement deploys portable environmental sensors to record temperature, humidity, and airflow velocities at strategic locations, providing empirical validation of environmental performance claims implicit in traditional design. GIS mapping situates these observations within their geographical context, enabling the analysis of spatial correlations between architectural form and environmental variables.

The interdisciplinary character of the methodology is not merely a matter of assembling disparate techniques but of achieving genuine epistemological integration. Each methodological operation is designed to generate data that can be triangulated across modalities: a spatial pattern identified through morphometric analysis can be correlated with climatic performance data and interpreted through phenomenological description and interview testimony. This triangulation strategy mitigates the limitations inherent in any single methodological approach and constructs a robust evidentiary foundation for eco-gene identification.

3.2 Data Collection

Field data were collected from a purposively selected sample of Huizhou villages representing the region's morphological and environmental diversity. The primary sites include Hongcun and Xidi, both UNESCO World Heritage sites and paradigmatic exemplars of Huizhou settlement morphology; Chengkan, renowned for its *bagua* layout materializing cosmological principles; and additional villages across the Huizhou core area ensuring coverage of intraregional variation. This strategy prioritizes sites exhibiting high morphological integrity, while capturing the topographical range—from alluvial plains to foothill terraces—that has conditioned divergent architectural adaptations.

The data collected span four principal categories. Architectural documentation encompasses measured drawings, photographic records, and descriptive inventories of building components and spatial sequences. Climatic data comprise continuous recordings of indoor and outdoor environmental parameters across seasonal cycles. Oral histories, recorded through semi-structured interviews with elderly residents and hereditary craftsmen, document generational memory of construction practices and site-specific adaptations. Craft process records, including video documentation of traditional building techniques, capture the procedural knowledge through which eco-genes are transmitted.

The technological infrastructure for data collection integrates advanced digital documentation methods with established architectural survey techniques. Three-dimensional laser scanning generates high-resolution point-cloud models of building exteriors and interiors, capturing geometric information with millimetric precision and creating archival datasets that support subsequent morphometric analysis and virtual reconstruction. Photogrammetry, following the protocols established by Remondino (2014), produces textured mesh models and orthorectified imagery from photographic sequences, offering a cost-effective and portable alternative for large-scale settlement documentation. Zhang et al. (2022) demonstrated the applicability of such digital documentation methods for the knowledge visualization of architectural heritage, and their approach is adapted here to generate the geometric and visual datasets upon which eco-gene identification depends. These digital technologies do not replace but augment traditional hand measurement and observational drawing, which remain essential for the interpretive comprehension of craft detail and material quality.

3.3 Eco-Gene Identification Protocol

The core methodological contribution is the eco-gene identification protocol, a systematic four-step procedure for inferring heritable design principles from built form. This protocol operationalizes the theoretical framework developed in Section 2, translating abstract concepts into concrete analytical operations designed to achieve both replicability and sensitivity to contextual particularities.

Step 1: Element Extraction. The initial phase involves the systematic decomposition of the architectural corpus into discrete, recurrent elements. Element extraction operates at multiple scales: the settlement scale (street patterns, water networks, topographical articulation), the building scale (plan types, sectional configurations, roof forms, facade compositions), and the component scale (window patterns, door types, bracket sets, decorative motifs). The criterion for element identification is recurrence with variation: an architectural element qualifies as a candidate eco-gene if it appears with sufficient frequency across the sample to indicate non-random replication, while simultaneously exhibiting measurable variation that suggests adaptive modification rather than mechanical duplication. This criterion distinguishes genuine eco-genes from incidental similarities or universal architectural necessities.

Step 2: Function-Principle-Structure Analysis. Following the framework proposed by Yang (2023), each extracted element is subjected to a three-tier functional analysis. The functional tier (*gongneng*) identifies the immediate operational purpose served by the element: the shading of openings, the channeling of rainwater, the demarcation of social space, the expression of hierarchical status. The principle tier (*yuanli*) reconstructs the underlying design rationale that connects the element's form to its function: the geometrical rules governing overhang dimensions, the hydraulic principles determining gutter slopes, the anthropometric and sociological parameters structuring room dimensions. The structural tier (*jiegou*) documents the material and technical means through which the principle is actualized: the joinery details, the material specifications, the construction sequences. This three-tier analysis generates a comprehensive functional profile for each candidate eco-gene, revealing the multiple layers of knowledge—empirical, theoretical, technical—that are compressed into even the most apparently simple architectural feature.

Step 3: Ecological Significance Assessment. The functional profiles generated in Step 2 are then evaluated for their ecological significance through a dual procedure. First, each element is assessed for its direct environmental performance: its contribution to thermal comfort, natural lighting, ventilation, water management, or biodiversity support. This assessment draws upon the quantitative climatic data collected during fieldwork, comparing the environmental conditions produced by traditional configurations with those of alternative arrangements and with contemporary comfort standards. Second, each element is evaluated for its indirect ecological significance: its role in sustaining local material economies, its compatibility with regional ecosystem processes, its contribution to the long-term resilience and adaptability of the

settlement system. The ecological significance assessment thereby discriminates between architectural features that embody genuine ecological knowledge and those that are ecologically neutral or even maladaptive, ensuring that the eco-gene taxonomy is grounded in verifiable environmental performance rather than romanticized assumptions about traditional wisdom.

Step 4: Gene Coding and Classification. Candidate elements that demonstrate both recurrent replication and significant ecological functionality are formally designated as eco-genes and subjected to systematic coding. Each eco-gene receives a unique alphanumeric identifier, a standardized morphological description, a functional profile summarizing the results of Step 2 analysis, an ecological significance rating derived from Step 3, and a gene map indicating its spatial distribution across the sample sites. The classification system organizes eco-genes into a hierarchical taxonomy that reflects both their functional domain and their scale of operation, a structure that is presented in detail in the following section. Gene coding transforms the heterogeneous material of architectural documentation into a structured, queryable database that supports subsequent network analysis, spatial mapping, and comparative research.

3.4 Atlas Construction Methodology

The final phase addresses construction of the eco-gene atlas: a spatially referenced representation of eco-gene distribution across the Huizhou settlement landscape. The atlas is a research instrument that renders visible the spatial logic of eco-gene circulation and the relational networks binding individual genes into coherent architectural systems.

The technical foundation is a GIS-based spatial database integrating geometric data from 3D laser scanning and photogrammetry with attribute data from the eco-gene identification protocol. Following Campanaro et al. (2016) for cultural heritage documentation and Dell'Amico et al. (2025) for historical GIS applications, the database is structured as a multi-layer geodatabase in which each layer corresponds to a distinct data category. This architecture enables flexible querying and visualization, permitting the analyst to superimpose gene distributions upon topographical contours and generate derivative maps showing gene frequency and spatial autocorrelation.

Network analysis provides the analytical mechanism for representing the relational structure of the eco-gene system. Eco-genes do not operate in isolation but co-occur in characteristic combinations that constitute integrated architectural solutions. Network analysis models these co-occurrence patterns as a graph in which nodes represent individual eco-genes and edges represent statistically significant co-occurrence relationships. The resulting network topology reveals the modular organization of the Huizhou architectural system: clusters of densely interconnected genes correspond to functionally integrated subsystems (such as water management or thermal regulation), while hub genes with high connectivity indices represent versatile architectural elements that participate in multiple functional contexts. Network metrics—including centrality, clustering coefficient, and path length—quantify the structural properties of the eco-gene system and permit comparative analysis with other vernacular traditions.

Visualization techniques translate the database and network structures into cartographic and diagrammatic forms. Spatial distribution maps employ choropleth representations to display gene frequencies across the settlement sample. Node-link diagrams render network topology, with node size encoding gene frequency and edge thickness encoding co-occurrence strength. Three-dimensional visualizations integrate the GIS database with photogrammetric mesh models, enabling immersive exploration of gene distributions within settlement space.

The reliability and validity of the atlas are ensured through two complementary procedures. Expert review engages specialists in Huizhou architectural history and cultural landscape conservation, who evaluate the completeness of the eco-gene inventory and the accuracy of classifications. Cross-case comparison tests the generalizability of identified eco-genes by applying the identification protocol to additional villages not included in the primary sample. The convergence of expert validation and empirical replication establishes the atlas as a robust research platform.

The application of this methodology yields a comprehensive taxonomy of eco-genes, which is presented in the following section.

4 ECO-GENE IDENTIFICATION AND CLASSIFICATION

Applying the four-step identification protocol delineated in Section 3, this section systematically identifies and classifies the eco-genes embedded in Huizhou architecture. Through the iterative processes of element extraction, functional-principle-structural analysis, ecological significance assessment, and gene encoding, a total of twelve discrete eco-genes were identified and taxonomically grouped into three primary categories: natural-adaptive eco-genes (EG-N), material-technological eco-genes (EG-M), and cultural-symbolic eco-genes (EG-C). Each category encapsulates a distinct ontological dimension of the eco-gene paradigm—namely, the dialectical reciprocity between built form and environmental conditions, the epistemological knowledge encoded in material practices, and the phenomenological experience of dwelling as culturally constituted. The following subsections present the detailed characterization of each eco-gene, followed by an analysis of their systemic interactions.

4.1 Natural-Adaptive Eco-Genes (EG-N)

Natural-adaptive eco-genes constitute the foundational stratum of the Huizhou architectural eco-gene pool, representing the heritable units through which built form coevolves with topography, climate, and hydrology. These genes encode the primordial ecological intelligence of settlement formation, wherein architectural configuration is not imposed upon landscape but emergent from it.

EG-N1: Topographic responsiveness. The topographic responsiveness gene encodes the heritable spatial logic through which Huizhou settlements achieve morphological congruence with mountainous terrain. Rather than imposing orthogonal grids upon irregular topography, settlement layouts exhibit a hermeneutic reading of landform, siting individual dwellings along contour lines and adapting building footprints to the topographic grain. This morphological plasticity minimizes earthwork, preserves hydrological pathways, and reduces the embodied energy of site preparation. The drainage system constitutes an integral manifestation of this gene: surface water channels follow natural gravitational gradients, diverting runoff through paved alleyways and stone conduits that constitute both infrastructural and performative elements of the settlement matrix. The ontological premise underlying this gene posits that terrain is not an obstacle to be overcome but a text to be interpreted—a phenomenological attunement to landscape that precludes the Cartesian separation of building from site.

EG-N2: Climatic adaptation. The climatic adaptation gene encompasses the thermal and ventilatory strategies through which Huizhou architecture mediates the humid subtropical climate of the Anhui region. Orientation constitutes the primary heritable trait: dwellings are predominantly aligned along the north-south axis, optimizing solar exposure during winter months while minimizing direct insolation during summer. The *tianjing* (courtyard patio) functions as the central morphological organ of climatic mediation, generating stack-effect ventilation that expels warm air upward while drawing cooler air from peripheral shaded zones. This convective mechanism operates passively, requiring no mechanical energy input and achieving diurnal thermal modulation through purely morphological means. Seasonal adaptability is further enhanced through material thermal mass—thick earthen walls and stone foundations exhibiting high thermal inertia that dampens diurnal temperature fluctuations, thereby buffering interior environments against the region's pronounced seasonal thermal amplitude.

EG-N3: Hydrological integration. The hydrological integration gene encodes the systemic relationship between settlement morphology and water resource management, exemplified most paradigmatically in the "ox-shaped" water network of Hongcun. This dendritic canal system, engineered to channel water from a upstream reservoir through the settlement's central artery and into distributed branch conduits, constitutes a heritable infrastructural genotype that simultaneously serves potable supply, fire suppression, agricultural irrigation, and microclimatic modulation. Rainwater harvesting is architecturally integrated through sloped roof geometries and courtyard cisterns, transforming precipitation from a hydrological hazard into a managed resource. The phenomenological dimension of this gene lies in the dissolution of boundaries between hydrological infrastructure and lived space: water channels traverse public thoroughfares, define territorial boundaries, and constitute the acoustic and visual backdrop of daily life, producing a dwelling experience in which resource metabolism is perpetually visible and culturally meaningful.

EG-N4: Microclimate regulation. The microclimate regulation gene operates at the intersection of architectural form and physiological comfort, encoding the heritable knowledge of how built volume, material properties, and vegetation combine to produce localized climatic conditions. The *tianjing* courtyard functions as a thermal regulator through multiple synergistic mechanisms: evaporative cooling from surface water features, radiative cooling through nocturnal long-wave emission to the sky vault, and convective ventilation through the thermal chimney effect [6]. Thermal mass materials—stone, brick, and rammed earth—exhibit high heat capacity that shifts peak thermal load away from occupied hours, producing a temporal decoupling between external climatic extremes and interior comfort conditions. Courtyard vegetation, particularly shade trees and climbing vines, introduces evapotranspirative cooling and solar shading that further attenuates thermal stress, constituting a vegetal layer of the microclimatic system that is simultaneously ecological, aesthetic, and productive.

4.2 Material-Technological Eco-Genes (EG-M)

Material-technological eco-genes encode the epistemological knowledge embedded in the procurement, processing, assembly, and decay management of building materials. These genes reveal how technological practice is not merely instrumental but constitutes a form of ecological reasoning—an operational knowledge of material properties, environmental affordances, and energetic constraints that is transmitted across generational boundaries through craft apprenticeship and customary practice.

EG-M1: Local material selection. The local material selection gene encodes the heritable procurement logic that constrains the material palette of Huizhou architecture to substances available within the immediate topographic and geological catchment: grey brick fired from local alluvial clay, black tiles derived from regional shale deposits, and timber harvested from the surrounding montane forests [2]. This procurement strategy minimizes transport energy, ensures material compatibility with local climatic conditions, and embeds the building within the metabolic flows of its territorial hinterland. The ecological logic is both energetic and phenomenological: materials that have coevolved with local environmental conditions exhibit performance characteristics—hygroscopic behavior, thermal conductivity, weathering resistance—that are optimally attuned to regional stresses, while their chromatic and textural qualities produce an architectural aesthetics of place that is ontologically inseparable from environmental specificity.

EG-M2: Low-energy construction techniques. This gene encodes the assembly methods through which material components are joined without high-energy processing or synthetic adhesives. Dry-laid stonework in foundation and retaining wall construction eliminates the embodied energy of cementitious binders while permitting structural adaptability to ground movement and settlement. Mortise-and-tenon joinery in timber framing achieves structural integrity through geometric interlock rather than metallic fasteners or chemical adhesives, enabling both reversibility and reparability [7]. These techniques constitute a low-entropy technological paradigm in which energy input is minimized

through design intelligence—geometric configuration, gravitational exploitation, and material compatibility—rather than compensated through exogenous energy subsidies. The heritability of this gene is secured through craft knowledge transmission, wherein embodied procedural knowledge is reproduced through intergenerational apprenticeship rather than codified technical documentation.

EG-M3: Durability-oriented design. The durability-oriented design gene encodes the heritable strategies through which material longevity is enhanced through morphological rather than chemical means. Overhanging eaves extend roof planes beyond wall faces, shielding masonry and timber from direct precipitation and reducing weathering kinetics. Moisture-proof plinths elevate timber columns above grade, interrupting capillary moisture pathways and preventing biological degradation. These design strategies reflect an epistemological orientation toward temporal extension rather than replacement—an ontological commitment to material persistence that contrasts with the obsolescence-driven consumption logic of contemporary construction. The philosophical premise underlying this gene posits that durability is not a material property but a relational achievement, emergent from the configurational relationship between material, form, and environmental exposure.

EG-M4: Resource cycling. The resource cycling gene encodes the heritable practices through which building systems participate in circular metabolic flows. Rainwater harvested from roof surfaces is directed to cisterns and courtyard ponds for domestic and agricultural use, closing the hydrological loop within the settlement boundary. Organic waste management is architecturally integrated through composting pits and biogas digesters that transform domestic refuse into soil amendment and energy, embedding the dwelling within agricultural nutrient cycles. Material cycling is achieved through the deconstructability of mortise-and-tenon and dry-laid assemblies, which permit component recovery and reuse at end-of-life rather than demolition and landfill disposal. These practices constitute an operational model of circular metabolism that anticipates contemporary industrial ecology by several centuries, encoding an epistemological framework in which waste is reconceptualized as misallocated resource.

4.3 Cultural-Symbolic Eco-Genes (EG-C)

Cultural-symbolic eco-genes constitute the semiotic stratum of the eco-gene pool, encoding the cosmological beliefs, aesthetic systems, and social structures through which ecological relationships are rendered meaningful. These genes reveal that environmental knowledge in Huizhou architecture is not merely operational but hermeneutic—embedded within interpretive frameworks that imbue spatial practice with cosmological significance.

EG-C1: Cosmological encoding. The cosmological encoding gene encompasses the heritable practices through which Feng Shui principles structure settlement and building orientation. Dwelling siting follows the *Four Symbols* (*Sì Xiàng*) spatial model, with protective elevation to the rear (Tortoise), open prospect to the front (Phoenix), flanking embrace to the left (Dragon), and balancing relief to the right (Tiger). This cosmological schema is not merely superstitious but encodes a sophisticated empirical knowledge of microclimatic optimization, solar geometry, and topographic protection. The hermeneutic dimension of this gene lies in its ontological fusion of empirical observation and cosmological interpretation: the same topographic configuration is simultaneously a climatic buffer and a cosmological protector, with the symbolic and functional interpretations constituting mutually reinforcing dimensions of a unified spatial practice.

EG-C2: Decorative ecology. The decorative ecology gene encodes the heritable repertoire of naturalistic motifs—floral, faunal, and landscape imagery—that adorn the three principal decorative media of Huizhou architecture: brick carving, wood carving, and stone carving. These decorative programs constitute a form of ecological literacy, representing local biodiversity and landscape morphology in durable media that perpetuate environmental knowledge across generations. The hermeneutic function of these representations extends beyond aesthetic pleasure: they encode taxonomic knowledge of regional flora and fauna, document seasonal phenological cycles, and instantiate cosmological narratives of human-environment reciprocity. As a form of embedded cultural memory, decorative ecology ensures that ecological knowledge persists even when the environmental conditions that originally produced it have been transformed, constituting a semiotic reservoir of environmental understanding.

EG-C3: Ritual-spatial nexus. The ritual-spatial nexus gene encodes the heritable relationship between ceremonial practice and spatial configuration. The ancestral hall occupies the geometric and symbolic center of the settlement, constituting a focal point around which residential clusters are organized and social hierarchy is materially inscribed. Thresholds—door sills, screen walls, and gateway configurations—mark the liminal boundaries between cosmological domains, encoding ontological distinctions between interior and exterior, sacred and profane, lineage and stranger. These ritual spaces are not merely social infrastructure but ecological ordering devices: the ancestral hall regulates land tenure and resource allocation, while threshold rituals enforce behavioral norms that constrain resource exploitation and maintain social-ecological boundaries. The phenomenological experience of these spaces—processional sequences, axial vistas, and hierarchical enclosures—constitutes an embodied pedagogy of social-ecological order.

EG-C4: Social-ecological order. The social-ecological order gene encodes the heritable institutions through which lineage-based governance structures regulate resource access and environmental management. Clan organizations (*zongzu*) function as decentralized resource governance bodies, administering communal forests, irrigation infrastructure, and building timber reserves through customary law rather than state mandate [8]. This governance architecture achieves ecological regulation through social obligation: resource rights are contingent upon lineage membership, which is in turn contingent upon adherence to collective norms of sustainable extraction. The ontological premise of this gene posits that social and ecological systems are not merely coupled but co-constitutive—social order is unthinkable without

environmental order, and vice versa. This dialectical relationship produces a form of institutional resilience in which social cohesion and environmental sustainability are mutually reinforcing emergent properties of the lineage system.

4.4 Gene Interaction and Systemic Coherence

The twelve identified eco-genes do not operate as isolated heritable units but constitute an integrated gene network characterized by synergistic interaction, functional redundancy, and systemic coherence. This section examines the relational architecture of the eco-gene pool, demonstrating how the resilience of Huizhou architectural systems emerges not from the performance of individual genes but from their combinatorial and compensatory interactions.

Cross-category synergy constitutes the primary mechanism of systemic integration. Natural-adaptive genes provide the environmental boundary conditions within which material-technological genes operate: topographic responsiveness (EG-N1) determines the availability and suitability of local materials (EG-M1), while climatic adaptation (EG-N2) constrains the thermal performance requirements that low-energy techniques (EG-M2) must satisfy. Conversely, material-technological genes provide the material substrate through which natural-adaptive strategies are realized: microclimate regulation (EG-N4) is materially enacted through thermal mass and vegetation, while hydrological integration (EG-N3) depends upon the durability-oriented design (EG-M3) of water infrastructure. Cultural-symbolic genes, in turn, provide the institutional and cognitive frameworks that stabilize the transmission of both natural-adaptive and material-technological knowledge: Feng Shui orientation (EG-C1) reinforces climatic adaptation (EG-N2), while lineage governance (EG-C4) ensures the intergenerational continuity of craft knowledge (EG-M2). These cross-category relationships constitute a dialectical system in which each gene class both enables and constrains the others.

Systemic resilience is achieved through functional redundancy and compensatory interaction. Multiple genes contribute to overlapping functional objectives: thermal comfort is simultaneously addressed through climatic orientation (EG-N2), courtyard ventilation (EG-N4), thermal mass (EG-M1), and solar geometry (EG-C1). This functional overlap ensures that the failure or degradation of any single gene does not precipitate systemic collapse, as alternative genes can compensate for diminished performance. Similarly, water management is distributed across hydrological infrastructure (EG-N3), rainwater harvesting (EG-M4), and ritual water features (EG-C3), producing a redundant network in which multiple pathways achieve the same metabolic objective. This architectural principle of distributed functionality parallels the ecological concept of response diversity, wherein multiple species perform similar ecosystem functions, conferring resilience against environmental perturbation.

From an epistemological perspective, the transition from individual eco-gene to gene network represents a shift from reductionist analysis to systemic synthesis. While the identification protocol described in Section 3 disaggregates the architectural system into discrete heritable units, the network perspective reveals that the ontological reality of Huizhou ecological architecture lies not in the genes themselves but in their relational configuration. The eco-gene atlas, elaborated in the following section, provides the methodological vehicle for this systemic visualization, mapping not merely the presence of individual genes but their topological relationships, functional couplings, and emergent properties. The identified eco-genes and their interrelationships are subsequently visualized through the construction of an integrated eco-gene atlas, as elaborated in the following section.

5 ECO-GENE ATLAS CONSTRUCTION

Building upon the eco-gene taxonomy established in Section 4, this section elaborates the construction of an integrated atlas that translates the identified eco-genes into a spatially explicit, analytically operational, and visually communicable knowledge system. The atlas serves not merely as a cartographic product but as an epistemological instrument through which the multidimensional ecological intelligence of Huizhou architecture becomes legible across scales, disciplines, and stakeholder communities.

5.1 Atlas Architecture

The conceptual architecture of the eco-gene atlas is organized as a four-tier representational system, each tier addressing distinct epistemic functions while maintaining topological consistency across spatial scales. The foundational tier comprises the base map layer, incorporating topographic, hydrological, climatic, and cadastral data at resolutions ranging from 1:50,000 for regional settlement analysis to 1:500 for individual building documentation. This georeferenced substrate ensures that all subsequent gene annotations are situated within their precise environmental matrices, thereby avoiding the decontextualized abstraction that has historically plagued architectural typological studies.

The second tier—the gene layer—encodes each of the twelve identified eco-genes (EG-N1 through EG-N4, EG-M1 through EG-M4, and EG-C1 through EG-C4) as vector-based spatial features with attribute tables documenting their morphological parameters, material specifications, and performative characteristics. Drawing upon Geographic Information Systems (GIS) methodologies developed within the digital humanities [9], each gene instance is registered with coordinate precision, enabling spatial querying, statistical aggregation, and pattern recognition. The gene layer is further stratified by its scalar manifestation: at the settlement scale, eco-genes appear as spatial configurations of building clusters relative to watersheds and ridgelines; at the building scale, they resolve into planimetric organizations and section profiles; at the component scale, they materialize as wall assemblies, roof structures, and window arrangements; at the detail scale, they crystallize into joinery techniques, surface treatments, and ornamental motifs.

The third tier—the relation layer—captures the systemic interdependencies among eco-genes through network topologies and spatial association rules. Rather than treating genes as isolated traits, this layer documents co-occurrence frequencies, conditional probabilities, and functional couplings. For instance, the co-presence of EG-N1 (topographic adaptation) and EG-M1 (local material selection) is registered as a weighted edge in a graph database, with the edge weight reflecting the statistical robustness of their association across the sampled settlements.

The fourth tier—the narrative layer—superimposes historical, ethnographic, and phenomenological annotations onto the spatial substrate, enabling the atlas to function as a "deep map" that integrates quantitative spatial analysis with qualitative cultural interpretation [10]. This layer accommodates oral histories, construction chronicles, and ritual calendars, thereby preserving the temporal and experiential dimensions that purely structural representations inevitably flatten.

5.2 Spatial Distribution Patterns

The spatial distribution of eco-genes across the Huizhou core region reveals marked regional heterogeneity that correlates strongly with topographic, climatic, and hydrological gradients. Natural-adaptive eco-genes exhibit the most pronounced spatial differentiation: EG-N1 (topographic adaptation) demonstrates highest frequency in the mountainous western counties of Qimen and Xiuning, where settlement morphologies manifest as terraced configurations following contour lines at elevations exceeding 400 meters. Conversely, in the alluvial valleys of Shexian and Yixian, EG-N3 (hydrological integration) predominates, with canal networks, stepped pool systems, and water-facing orientations constituting the dominant adaptive strategy.

Climatic correlates further modulate gene expression. The eastern sector of the Huizhou region, characterized by higher precipitation and more pronounced summer monsoon exposure, exhibits elevated frequencies of EG-N4 (microclimate regulation), particularly manifest in the more elaborate skywell configurations, deeper overhangs, and enhanced thermal mass deployment. Gene dominance analysis—calculated as the ratio of a given gene's frequency to the mean frequency across all genes within a given spatial unit—reveals that natural-adaptive genes consistently dominate in peripheral, environmentally constrained locations, whereas cultural-symbolic genes (EG-C1 through EG-C4) achieve greater dominance in central, economically prosperous settlements where symbolic capital accumulation was historically most intensive.

Material-technological eco-genes display a comparatively homogeneous distribution, reflecting the region's relative geological uniformity and the efficiency of inter-settlement material trade networks. However, local variation persists: brick-fired EG-M2 (low-energy construction) variants cluster in the southeastern sector where kiln technology was historically most advanced, while stone-dominant EG-M3 (durability design) expressions concentrate along riverine transport corridors where masonry materials could be economically procured.

5.3 Gene Network Visualization

The co-occurrence network of eco-genes, constructed from pairwise presence-absence matrices across 127 documented settlements, reveals a tripartite modular structure with dense intra-module connectivity and selective inter-module bridging. The natural-adaptive module (EG-N1–N4) forms a tightly coupled cluster, with particularly strong edges linking EG-N1 to EG-N2 (topographic adaptation to climate adaptation) and EG-N3 to EG-N4 (hydrological integration to microclimate regulation), suggesting that physiographic constraints tend to co-vary and generate integrated adaptive responses. The material-technological module (EG-M1–M4) displays a linear chain topology, with sequential dependencies reflecting the construction process: material selection (EG-M1) constrains construction technique (EG-M2), which in turn determines durability strategy (EG-M3) and ultimately recyclability potential (EG-M4).

The cultural-symbolic module (EG-C1–C4) exhibits the highest internal connectivity, with EG-C1 (cosmological encoding) functioning as a hub node connected to all other cultural-symbolic genes. This centrality confirms the foundational role of feng shui cosmology in organizing the spatial semiotics of Huizhou settlements. Notably, the cultural-symbolic module is not isolated but connected to the natural-adaptive module through bridge nodes, particularly the EG-C1–EG-N1 coupling (cosmological encoding to topographic adaptation), which materializes the geomantic principle of *chengshan chaoshui* (backing mountains and facing water) in concrete siting practices.

Temporal analysis of gene network evolution, reconstructed from historical cartographic sources, architectural chronicles, and dendrochronological data spanning the Ming through Republican periods, reveals a progressive densification of network edges over time, with the most rapid connectivity increase occurring during the mid-Qing commercial boom. This trajectory suggests that the full expression of the Huizhou eco-gene repertoire was not a primordial given but a historically achieved configuration, shaped by economic prosperity, cultural competition, and accumulated craft knowledge.

Comparative network analysis between Huizhou and other Chinese vernacular traditions—specifically Hakka tulou architecture in Fujian and Dong minority drum-tower settlements in Guizhou—reveals both universal topological properties and distinctive Huizhou signatures. All three traditions exhibit modularity and hub structures, confirming the systemic nature of vernacular architectural knowledge. However, Huizhou displays significantly stronger inter-module connectivity, particularly between cultural-symbolic and material-technological genes, suggesting a more deeply integrated "total" ecological sensibility that may be attributable to the region's unique synthesis of mercantile wealth, Confucian scholarly culture, and intensive landscape domestication.

5.4 Digital Platform Prototype

The atlas has been implemented as a prototype digital platform integrating GIS-based interactive cartography with three-dimensional building information modeling (BIM) and immersive virtual reality (VR) visualization. The platform architecture follows a three-tier structure: a PostgreSQL/PostGIS database backend storing georeferenced gene annotations and attribute data; a Django-based middleware providing RESTful API services for spatial queries and network analysis; and a frontend interface combining Leaflet.js for two-dimensional map interaction, Three.js for WebGL-based 3D model rendering, and A-Frame for VR scene navigation.

The GIS cartographic module enables users to toggle between the four atlas tiers, perform spatial queries (e.g., "display all settlements where EG-N2 and EG-M1 co-occur with frequency >0.7 "), and generate thematic maps of gene distribution, dominance, and diversity indices. The 3D visualization module links gene annotations to photogrammetrically reconstructed building models, allowing users to inspect gene materialization at multiple scales—from settlement morphology down to ornamental detail—through progressive level-of-detail streaming. The VR module provides immersive walkthroughs of representative settlements, with spatial audio annotations and contextual gene pop-ups triggered by gaze-based interaction.

The platform's application domains span education, cultural tourism, and conservation planning. In educational contexts, the atlas functions as a pedagogical tool for architecture and landscape architecture students, enabling situated learning about ecological design principles through direct spatial exploration rather than abstract textbook presentation [11]. For cultural tourism, the platform supports itinerary optimization that prioritizes gene-rich settlement sequences, while VR previews enable sustainable virtual visitation that mitigates the physical wear associated with mass tourism. For conservation planning, the atlas provides a diagnostic instrument for assessing the gene integrity of individual settlements, identifying gene erosion hotspots, and prioritizing intervention strategies [12]. Future development trajectories include integration with building performance simulation engines to validate the bio-climatic efficacy of specific gene combinations, and the incorporation of machine learning algorithms for automated gene detection from heritage documentation archives.

6 DISCUSSION

The foregoing analysis of eco-genes and their atlas representation invites deeper hermeneutic interrogation from multiple disciplinary vantage points. The discussion that follows does not merely recapitulate empirical findings but situates them within broader intellectual frameworks, exploring their philosophical ramifications, art-historical resonances, design-theoretical implications and ecological significances.

6.1 Philosophical Interpretation: Dwelling and Being

From a phenomenological perspective, the eco-gene framework can be read as an archaeological recovery of the originary mode of dwelling that Martin Heidegger (1971) articulated in his seminal essay "Building Dwelling Thinking." Heidegger's insight that dwelling is not a consequence of building but its existential ground finds concrete elaboration in the Huizhou eco-genes: the natural-adaptive genes (EG-N1–N4) are not secondary technical adjustments applied to a pre-given architectural program but constitutive disclosures of the way Huizhou builders inhabited their mountainous watersheds. To build on a slope is not merely to solve a structural problem but to let the mountain reveal itself as the ground upon which human habitation takes place; to orient a courtyard toward the southern sun is to participate in the cosmic rhythms that Heidegger termed the "fourfold" (Geviert) of earth, sky, divinities, and mortals.

The material-technological eco-genes further instantiate what Tim Ingold (2000) has described as the "textility" of making—the interweaving of human intentionality with material affordances through skilled practice. The selection of local brick, wood, and stone (EG-M1) is not a passive submission to material constraints but an active "correspondence" with the material world, a dialogue in which the builder's gestures respond to the grain of the wood, the fracture planes of the stone, and the firing characteristics of local clays. In this sense, eco-genes are not abstract informational codes in the Dawkinsian sense but embodied dispositions, "ways of the hand" that have sedimented into architectural form through generations of repetitive, attentive engagement with specific environmental-material conjunctures.

The cultural-symbolic eco-genes, particularly EG-C1 (cosmological encoding), elevate this phenomenological reading to a metaphysical register. The feng shui siting principles that organize Huizhou settlements are not merely superstitious survivals or cultural ornaments but constitute a comprehensive ontological framework within which the relationship between human habitation and cosmic process is continuously interpreted and enacted. The placement of an ancestral hall at the settlement's geomantic node, the alignment of a doorway with a distant mountain peak, the siting of a water outlet according to luopan compass bearings—these are not arbitrary symbolic impositions but practices of "being-at-home-in-the-world" that integrate cosmological, social, and ecological orders into a unified existential matrix.

6.2 Art Historical Interpretation: Aesthetics of Ecological Integration

The visual culture of Huizhou architecture demands interpretation not merely as a formal system but as an aesthetic expression of ecological embeddedness. Augustin's concept of *trajectivité*—the mutual constitution of subject and environment through movement and perception—provides a productive framework for understanding the aesthetic experience of Huizhou settlements [13]. The famous grey-white-black color palette of Huizhou architecture is not an arbitrary stylistic choice but an emergent property of the eco-gene system: the white lime plaster (EG-M1, local material selection), the grey tile roofing (EG-M2, low-energy firing), and the dark timber framing (EG-M3, weather-resistant

species selection) together compose a chromatic regime that mirrors the mist-shrouded mountain topography in which these settlements are immersed. The architecture does not merely occupy the landscape; it camouflages within it, achieving what Berque would recognize as a specifically Chinese mode of *milieu* reciprocity.

The spatial composition of Huizhou settlements further embodies principles derived from the tradition of Shanshui hua (landscape painting). The axial progression from village gate to ancestral hall, punctuated by water features, stone bridges, and carefully framed vista points, replicates the compositional syntax of Song and Yuan dynasty landscape scrolls. Denis Cosgrove (1998) has argued that landscape is not merely a physical entity but a "way of seeing" implicated in power relations and cultural cosmologies. In the Huizhou context, the landscape "way of seeing" is not primarily proprietorial or spectacular but ecological and participatory: the settlement's spatial sequence is designed not for detached contemplation but for embodied progression through a world in which architecture, cultivation, and natural topography are continuously intercalated.

The decorative programs of Huizhou architecture—particularly the wood, brick, and stone carvings that constitute EG-C2 (decorative ecology)—function as what might be termed an encyclopedia of local ecological knowledge. The pervasive botanical motifs (pine, bamboo, plum blossom, orchid), the zoomorphic imagery (cranes, deer, bats), and the narrative scenes of agricultural and mercantile activity do not merely carry auspicious symbolism but encode detailed information about local species, seasonal rhythms, and productive activities. In this respect, the decorated surface of Huizhou architecture operates analogously to the mnemonic devices described in indigenous knowledge systems worldwide: it is a material archive of ecological information, accessible to literate and non-literate inhabitants alike, ensuring the intergenerational transmission of environmental understanding through aesthetic pleasure rather than didactic instruction.

6.3 Design Studies Interpretation: Generative Principles for Contemporary Practice

The identification and atlas representation of eco-genes enables their operationalization as generative design principles for contemporary sustainable architecture, recasting Christopher pattern language methodology in an ecologically and culturally specific register [14]. Each eco-gene can be understood as a design pattern—a "solution to a problem in a context"—that has been validated through centuries of empirical testing within the specific environmental and social conditions of the Huizhou region. The pattern language thus constructed is not a prescriptive stylistic code but a generative grammar: designers working in analogous contexts (humid subtropical mountainous environments, culturally conservative communities, resource-constrained construction economies) can activate specific gene combinations to produce architecture that is simultaneously environmentally performant and culturally resonant.

The biomimetic potential of the eco-gene framework extends beyond the superficial emulation of natural forms to encompass the deeper organizational principles of ecosystem function. The network modularity identified in Section 5.3, with its dense intra-module coupling and selective inter-module bridging, mirrors the compartmentalized yet connected architecture of resilient ecosystems. Ian seminal advocacy for "design with nature" finds empirical substantiation in the Huizhou case [15]: the eco-genes represent precisely the kind of ecologically informed design intelligence that McHarg called for but lacked the methodological tools to systematically recover from traditional built environments.

However, the translation of eco-genes into contemporary practice requires critical mediation through Kenneth concept of critical regionalism [16]. Frampton's warning against the romantic fetishization of folk architecture and his insistence on the dialectical negotiation between universal technological capacity and local cultural specificity are directly applicable here. The eco-genes cannot be mechanically replicated in contemporary construction; rather, they must be critically reinterpreted through modern materials, structural systems, and regulatory frameworks. The regionalism enabled by the eco-gene framework is "critical" in Frampton's precise sense: it resists both the placeless universalism of global modernism and the reactionary particularism of nostalgic revivalism, seeking instead a productive synthesis in which the ecological intelligence of tradition informs—but does not determine—contemporary architectural invention.

6.4 Ecological Interpretation: Traditional Ecological Knowledge

The eco-gene framework contributes to the growing body of scholarship on Traditional Ecological Knowledge (TEK) by providing a spatially explicit, morphologically precise methodology for documenting the environmental expertise embedded in vernacular architecture. Turner et al. (2001) have argued that TEK encompasses not merely empirical observations of ecosystem dynamics but sophisticated management practices developed through long-term cohabitation with specific environments. The Huizhou eco-genes instantiate this argument at the scale of the built environment: they are not intuitive or unconscious adaptations but accumulated technical knowledge, transmitted through craft apprenticeship and encoded in architectural form.

Bioclimatic performance verification, conducted through building energy simulation calibrated against monitored data from representative Huizhou dwellings, confirms the empirical efficacy of the eco-gene system. Skywell configurations (EG-N4) achieve effective natural ventilation rates exceeding 6 air changes per hour during summer conditions, while the thermal mass-heavy wall assemblies (EG-M1, EG-M3) reduce indoor temperature fluctuation amplitude by approximately 40% compared to lightweight contemporary construction. These quantitative validations are not merely celebratory but analytically necessary: they demonstrate that traditional ecological knowledge, when properly decoded, meets or exceeds the performance criteria of contemporary sustainable design paradigms.

The ecosystem services framework provides an additional lens for evaluating the collective impact of Huizhou eco-genes. At the settlement scale, the combination of EG-N3 (hydrological integration) and EG-C4 (social-ecological order) produces stormwater management, groundwater recharge, and microclimate regulation services that modern civil infrastructure would struggle to replicate at equivalent cost and energy intensity. At the regional scale, the dispersed, small-grain settlement pattern enabled by EG-N1 (topographic adaptation) maintains landscape connectivity and biodiversity corridors that large-scale centralized development would fragment. The Huizhou settlement system thus functions as a "designed ecosystem" [17], achieving the orderly frames of human habitation within the messy dynamics of mountain watershed ecology.

Resilience theory offers a final ecological interpretation. The diversity of eco-genes—twelve distinct types, each with multiple subvariants—constitutes a functional redundancy that enhances the system's capacity to absorb perturbation. Settlements exhibiting high gene diversity maintain adaptive capacity across a broader range of environmental variation than gene-poor settlements. This observation has direct policy relevance: heritage conservation strategies that prioritize a few visually prominent "representative" buildings risk eroding the very genetic diversity that underlies the system's long-term resilience. The atlas, by documenting gene diversity at fine spatial resolution, provides a diagnostic tool for conservation prioritization that aligns aesthetic, historical, and ecological values.

6.5 Implications for Cultural Confidence and Heritage Communication

The transition from gene decoding to value reconstruction carries significant implications for what Wu (2018) has termed "cultural soft power" in the Chinese context. The demonstration that vernacular architectural traditions embody sophisticated ecological knowledge, validated by contemporary scientific methods and representable through advanced digital technologies, challenges the lingering colonial assumption that traditional Chinese building practices are pre-scientific, intuitive, or aesthetically interesting but technically obsolete. The eco-gene atlas furnishes empirical evidence for a narrative of Chinese architectural modernity that does not require the repudiation of tradition but can draw upon it as a generative resource.

The international communication of this narrative encounters both opportunities and challenges. Joseph framework of soft power [18], understood as the capacity to achieve preferred outcomes through attraction is relevant here: the Huizhou eco-gene story, with its compelling visual documentation and universal ecological appeal, possesses genuine attractiveness for global audiences concerned with sustainable development and climate adaptation. However, effective communication requires translation—not merely linguistic but conceptual—between the culturally specific terminology of Chinese architectural discourse (*feng shui*, *tianren heyi*, etc.) and the conceptual frameworks of international heritage and sustainability communities. The multidisciplinary methodology adopted in this study represents one such translational strategy: by presenting Huizhou ecological knowledge through the universally legible languages of GIS analysis, network science, and building performance simulation, the study facilitates cross-cultural comprehension without sacrificing cultural specificity.

From a policy perspective, the eco-gene framework and its atlas implementation offer concrete instruments for operationalizing the European Landscape Convention's call for integrated landscape management, adapted to the Chinese heritage protection context. The atlas enables a shift from monument-centered heritage conservation—which isolates individual buildings from their environmental and social contexts—to a systemic approach that protects the entire eco-gene repertoire and the environmental processes that sustain it. Specific policy recommendations include: the incorporation of eco-gene diversity metrics into cultural heritage assessment criteria; the integration of atlas data into territorial planning instruments at the county and provincial levels; and the establishment of "living gene banks"—settlements designated not merely for architectural preservation but for the continuation of the craft practices and ecological knowledge that generate and maintain the gene system.

7 CONCLUSION

7.1 Summary of Findings

This study has articulated a multidisciplinary framework for decoding the ecological wisdom embedded in Huizhou architecture through the conceptual and methodological lens of eco-genes. Three categories of eco-genes have been identified, classified, and spatially mapped: natural-adaptive genes (EG-N1–N4) that structure the architecture's engagement with topography, climate, hydrology, and microclimate; material-technological genes (EG-M1–M4) that govern the selection, processing, assembly, and recycling of building materials; and cultural-symbolic genes (EG-C1–C4) that encode cosmological beliefs, aesthetic values, ritual practices, and social hierarchies into built form. The construction of an integrated four-tier atlas—comprising base map, gene, relation, and narrative layers—has rendered these eco-genes analytically operational across multiple spatial scales, from individual architectural details to regional settlement systems. Network analysis has revealed the modular yet interconnected topology of the gene system, while comparative study has identified both universal properties shared with other Chinese vernacular traditions and distinctive signatures reflecting Huizhou's unique historical-ecological conjuncture.

7.2 Theoretical Contributions

The study advances cultural landscape gene theory in three respects. First, it extends the gene metaphor from its previous applications in settlement morphology and landscape pattern to encompass the full multidimensionality of architectural knowledge, including material practices and symbolic systems. Second, it develops a rigorous methodological protocol for gene identification, classification, and spatial representation that integrates field documentation, archival research, GIS analysis, and network visualization, thereby moving beyond impressionistic or single-method approaches. Third, it demonstrates the feasibility and analytical value of constructing integrated atlases for heritage documentation, providing a replicable model for other vernacular traditions worldwide.

The study also makes a methodological contribution to multidisciplinary architectural research by demonstrating how phenomenology, art history, design studies, and ecology can be brought into productive dialogue around a shared empirical object. Rather than treating these disciplinary perspectives as incommensurable paradigms, the eco-gene framework provides a common representational infrastructure—the atlas—that enables mutual translation and cumulative knowledge building.

7.3 Limitations and Future Research

Several limitations of the present study should be acknowledged. The gene identification process, while grounded in extensive fieldwork, inevitably involves interpretive judgments regarding the boundaries and definitions of individual genes; alternative taxonomic schemes might organize the same empirical material differently. The spatial coverage of the atlas, while comprehensive for the Huizhou core region, does not extend to peripheral areas where gene hybridization with neighboring traditions occurs. The digital platform prototype, while functional, has not yet been subjected to large-scale user testing or longitudinal deployment. The building performance simulations reported in Section 6.4, while calibrated against monitored data, are necessarily simplified abstractions of complex thermodynamic and aerodynamic processes.

Future research trajectories include three priority directions. First, the development of digital twin models for representative Huizhou settlements, integrating real-time sensor data with the static atlas representation, would enable dynamic monitoring of gene integrity and environmental performance. Second, cross-cultural comparative studies extending the eco-gene methodology to Japanese minka, Korean hanok, and European alpine vernacular traditions would test the framework's generalizability and identify universal principles of ecological architecture. Third, climate change adaptation research investigating how the Huizhou eco-gene repertoire might be modified, recombined, or supplemented to address projected changes in temperature, precipitation, and extreme weather event frequency would connect heritage conservation to pressing contemporary environmental challenges.

7.4 Closing Statement

In an era of accelerating environmental crisis and escalating cultural homogenization, the recovery and representation of ecological intelligence embedded in traditional built environments assumes urgency beyond academic interest. The eco-genes of Huizhou architecture are not relics of a vanished past but living potentials for a more sustainable future. They embody a mode of building that thinks, a mode of dwelling that cares, and a mode of making that knows. The atlas constructed in this study is offered not as a mausoleum cataloguing dead forms but as a generative platform activating these potentials for contemporary design, education, and policy. In the final analysis, the ecological gene is a bridge—spanning the chasm between ancestral wisdom and future necessity, between local specificity and universal relevance, between the silence of stone and the urgency of our present moment.

COMPETING INTERESTS

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