An Ecological Sensitivity Design Framework: Optimizing Resident Behavior and Balancing Resources in Crowded Tourism Environments

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***Abstract*—Background and Gap: Rapid growth in international tourism has contributed to "overtourism," placing heavy pressure on local ecosystems in many destinations. Existing management is often reactive and lacks systematic, forward-looking measures. This study addresses how low-barrier, publicly available, or on-site data can be used to identify ecologically sensitive zones in a crowded historic town. It also examines whether combining multiple low-cost nudges can encourage more sustainable behavior among residents, with the goal of producing actionable guidance for resource allocation.Methodology: We adopted a systematic design and mixed-methods approach to develop an Ecological Sensitivity Design Framework built on three components: ecological sensitivity assessment (ESA), quasi-experimental nudge interventions, and Multi-Criteria Decision Analysis (MCDA). Importantly, the framework avoids expensive or high-tech data sources—such as mobile signaling or remote sensing—to improve accessibility, replicability, and real-world applicability.Implementation in Practice: A typical ancient water town in China's Jiangnan region served as the case site. We integrated publicly available visitor data, on-site observation records, and a stratified resident survey (N=120). The framework was validated through (1) spatial pattern analysis of ecological sensitivity, (2) quasi-experimental comparisons of resident behavior under different nudge-based design strategies, and (3) a reproducible MCDA process to support resource allocation decisions.Key Findings:Combining ESA with public-data-based visitor hotspot analysis enables accurate identification of priority spatial nodes for optimization.A composite nudge package—blending informational, economic, and environmental cues—shows a clear synergistic effect in promoting residents' sustainable behaviors.The MCDA approach effectively supports higher-order trade-offs, balancing tourism income, ecological footprint, and resident satisfaction.Significance: The proposed framework functions as a lightweight, deployable decision-support tool that helps destinations move from passive crowd control to proactive ecosystem coordination. It offers meaningful theoretical and practical value for tourist sites worldwide.**

Keywords—Ecological Sensitivity Design, Tourism Crowding; Resident Behavior, Resource Balance, System Design, Nudge Theory, Multi-Criteria Decision Analysis (MCDA)

I. INTRODUCTION

The rapid global growth of tourism has pushed many destinations into the emerging reality of "overtourism." While rising visitor numbers can bring clear economic benefits, they also intensify pressures on local ecosystems and socio-cultural life, often amplifying resident dissatisfaction and triggering approach/avoidance responses toward tourism development [1]. Under urgent climate change and decarbonization constraints, destination governance is further required to move beyond short-term crowd-control fixes and adopt proactive, system-oriented management strategies that remain feasible for local capacities [2].

Against this backdrop, this study asks: how can an Ecological Sensitivity Design Framework be created to systematically connect ecological conservation, resident behavior, and resource management? Recent research suggests that integrating environmental sensitivity into tourism spatial/network identification provides a practicable pathway for linking ecological constraints with tourism supply–demand structures [3]. Building on this direction, we take a design-oriented approach to proactively shape resident practices and dynamically allocate limited resources using low-barrier, reproducible data and methods — deliberately moving away from reactive management logic.

To fill these gaps, we develop and validate a lightweight, reproducible Ecological Sensitivity Design Framework. Rather than relying on single-point fixes, the framework adopts a systems-design strategy that links ecological sensitivity assessment, quasi-experimental behavioral evaluation, and Multi-Criteria Decision Analysis (MCDA) into a continuous management cycle. Importantly, it avoids dependence on expensive or high-tech data sources (e.g., mobile signaling or large-scale sensing infrastructures), enabling replication across diverse tourism settings with limited technical capacity.

II. LITERATURE REVIEW

This section reviews core theories and recent advances relevant to the proposed ecological sensitivity design framework, providing the theoretical basis for an integrated analytical model. The discussion is organized into four themes: (1) ecological sensitivity and sustainable tourism, (2) tourism crowding and governance challenges, (3) resident behavior and behavior-optimization strategies, and (4) resource-balancing mechanisms.

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A. Ecological Sensitivity and Sustainable Tourism Development

Ecological sensitivity describes the degree to which an ecosystem can tolerate external disturbances. Beyond purely ecological diagnostics, sustainable tourism development increasingly emphasizes translating sensitivity constraints into spatial planning and design practices. For example, guidance on eco-conscious destination development stresses the need to embed ecological considerations into destination design decisions and visitor-use planning in ways that are actionable for practitioners [4].

At the operational level, ecological sensitivity and vulnerability assessments are often implemented through indicator-based approaches that combine natural and human-activity variables. Empirical work on ecological vulnerability identification demonstrates how multi-factor indicator systems can reveal key drivers and spatial heterogeneity, providing methodological references for constructing streamlined sensitivity assessment indicators with accessible data inputs [5]. Similarly, recent sensitivity and landscape-pattern assessments in disturbed or degraded land systems show how sensitivity evaluation can be conducted with interpretable indicators rather than relying exclusively on technically intensive sensing pipelines [6].

Meanwhile, remote-sensing-based ecological quality monitoring (e.g., time-series indices) can support dynamic observation of environmental conditions, but may require higher technical thresholds and data-processing capacity, which limits adoption in many small destinations [7]. Accordingly, this study aligns with a "lightweight" direction: it prioritizes publicly available land-use information and field-friendly measurements to support reproducible ecological sensitivity identification in destination contexts.

B. Tourism Crowding and Governance Challenges

Tourism crowding and overtourism governance are ultimately socio-ecological management problems in which resident perceptions and behaviors matter. Evidence shows that tourism crowding can shape residents' approach/avoidance reactions, and these responses are closely tied to sustainability outcomes and pro-environmental orientations [1]. This suggests that managing crowding cannot rely solely on reactive restrictions; it also requires governance mechanisms that influence behaviors and strengthen local support.

From a behavioral governance perspective, research on eco-tourism nudging highlights that tourists' psychological mechanisms can be leveraged to steer behavior toward lower-impact choices, providing a complementary route to purely capacity-based management approaches [8]. In this study, we treat such behavioral levers as a practical component of "low-barrier" destination management, particularly when high-tech sensing and real-time control infrastructures are unavailable.

C. Resident Behavior and Optimization Strategies

Residents' attitudes and behaviors are central to sustainable destination outcomes, not only because they experience tourism impacts directly, but also because they participate in everyday practices that shape local environmental quality. Beyond crowding-driven reactions [1], contemporary tourism dynamics also include new drivers such as social-media-induced travel behaviors, which can alter visitor flows and create additional management pressures; research in this area discusses behavioral intervention approaches relevant to both tourists and local contexts [9].

Nudge-based approaches have gained attention in sustainable tourism, but recent scholarship argues that effective nudging requires moving beyond simplistic "choice architecture" assumptions to better understand when, why, and for whom nudges work in tourism settings [10]. Therefore, our study designs a combined information–economic–environmental nudge package aimed specifically at residents and evaluates its effects via a quasi-experimental design, focusing on feasibility and reproducibility in real destinations.

In addition, resident behavioral responses may extend beyond direct participation (e.g., compliance or conservation practices) to communication and social influence processes such as word-of-mouth (WOM). Modeling work on residents' WOM behavior indicates that psychological and social mechanisms can systematically shape how residents support or resist tourism narratives, offering additional insight into how behavioral interventions might diffuse through communities [11].

D. Resource Balancing Mechanisms and Decision Support

Sustainable destination management requires balancing competing objectives (ecological protection, resident well-being, and tourism viability). While complex optimization algorithms can be powerful, they are often difficult for local managers to interpret and replicate. Multi-Criteria Decision Analysis (MCDA) provides a transparent and low-barrier decision-support approach for comparing policy or resource-allocation scenarios. For example, MCDA has been applied to assist sustainable tourism planning in intermunicipal governance contexts, demonstrating its utility for structured trade-off evaluation and stakeholder-aligned decision processes [12].

Relatedly, MCDA methods such as PROMETHEE-GAIA have been used to evaluate tourism competitiveness in rural settings, illustrating how multi-indicator evaluation frameworks can be operationalized to support comparative assessments and strategy selection [13]. Building on this evidence, our framework adopts MCDA as a reproducible mechanism for prioritizing intervention areas and allocating limited resources under multiple constraints.

III. Methodology

A combined Systematic Design and Mixed-Methods Research strategy was used to build and validate a dynamic, multi-level Ecological Sensitivity Design Framework. The methodology links theoretical modeling with empirical case-study work to ensure scientific rigor, operational feasibility, and practical value. The research followed a clear sequence—theory construction → low-barrier validation → framework refinement—and included five core components: (1) research strategy, (2) ecological sensitivity assessment, (3) data collection, (4) quasi-experimental nudge validation, and (5) MCDA-based resource balancing. The overall structure is shown in Figure 1.

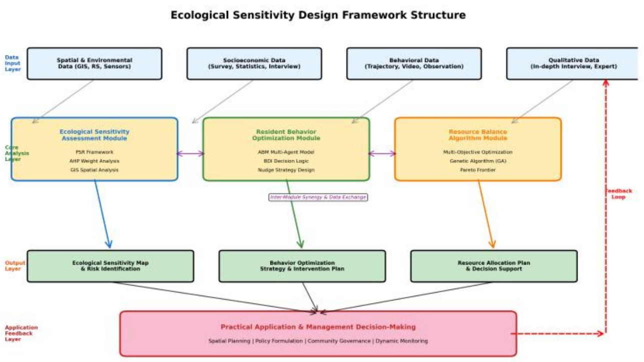

Fig. 1. Ecological Sensitivity Design Framework Structure

A. Ecological Sensitivity Assessment (ESA)

We developed a multi-tier assessment model based on the Pressure – State – Response (PSR) framework. A defining feature of this adaptation is that all indicators rely only on low-barrier data sources.

Pressure indicators include: tourist density (estimated from public ticket/entry records and supplemented by manual counts), the density of tourism-related facilities, and the intensity of wastewater and exhaust emissions (from published government reports).

State indicators include: vegetation coverage (from official green-space statistics), water quality (measured using portable test kits or obtained from public monitoring bulletins), soil erosion risk (assessed through field evaluation), and a biodiversity index (derived from structured on-site observations or expert scoring).

Response indicators include: the proportion of financial investment devoted to environmental protection, the share of area under ecological restoration, and the rate of resident participation in sustainability initiatives.

The composite Ecological Sensitivity Index (ESI) for each spatial grid unit is computed using the following formula:

$$ESI = \sum_{i=1}^{n} (W_{pi} \cdot P_i) + \sum_{j=1}^{m} (W_{sj} \cdot S_j) + \sum_{k=1}^{l} (W_{rk} \cdot R_k) \quad (1)$$

Where W represents the weight of each indicator, and P, S, R represent the normalized values of each indicator.

B. Quasi-Experimental Nudge Validation (Replacing ABM/BDI)

To test the effectiveness of the proposed interventions, we implemented a quasi-experimental design using resident survey data (N=120) and on-site behavioral records. This approach replaces complex computational simulations (e.g., Agent-Based Modeling, ABM), ensuring results remain statistically testable and methodologically reproducible without advanced modeling infrastructure.

The study compared adoption rates of sustainable practices — such as proper waste disposal and off-peak business operation — across four conditions: (1) a control group with no intervention; (2) an information-only nudge group; (3) an economic-only nudge group; and (4) a combined nudge group receiving the full intervention package. Analyses used t-tests, Mann – Whitney U tests, and regression models (with relevant control variables) to evaluate differences over time (pre vs. post) and across space (intervention vs. control areas). This design produces a clear, accessible chain of statistical evidence.

C. Multi-Criteria Decision Analysis (MCDA) (Replacing Genetic Algorithm)

For resource balancing, we adopted Multi-Criteria Decision Analysis (MCDA) instead of computationally intensive optimization methods such as genetic algorithms. MCDA provides a transparent, reproducible way to compare alternative resource-allocation strategies.

We applied the Analytic Hierarchy Process (AHP) to derive weights for three objectives: tourism revenue, ecological impact, and resident satisfaction. We then assessed three representative policy scenarios — economy-oriented, ecology-oriented, and a balanced approach — by scoring each scenario against the weighted criteria. The full procedure is explicit and easy for destination managers to replicate, effectively producing a practical decision "menu."

IV. Experimental Design and Evidence

This section explains how the methodology was implemented in practice using low-barrier procedures, highlighting concrete adjustments to data collection and analytical complexity.

A. Implementation of Low-Barrier Data Collection

High-barrier data sources were systematically replaced with accessible substitutes:

Mobile signaling / Wi-Fi probe data were replaced by public visitor registration or ticket-sales records, supplemented with fixed-interval manual counts (e.g., every 15 minutes) to estimate flows and crowding.

Automated video analytics were replaced by researcher-led observation protocols, using standardized sheets to record crowding levels, conflict incidents, and waste-disposal behavior at regular intervals.

Remote sensing / NDVI data were replaced by publicly available government land-use and green-space statistics, supplemented with field-based sensitivity scoring and photo documentation.

Permanent sensor networks were replaced by portable, one-time spot measurements (e.g., noise meters, water-quality test strips) or by using official public monitoring reports.

B. Sample Size and Survey Design

Primary data collection was intentionally kept at a manageable but methodologically robust scale to support reproducibility:

Structured questionnaire survey: The sample was capped at 120 valid responses, using stratified sampling across key dimensions (core vs. non-core areas; merchants vs. non-merchant residents).Informed consent was obtained from all subjects involved in the study.

In-depth interviews: Semi-structured interviews were conducted with 10 key informants, including destination managers, resident representatives, and local merchants.

Reporting standards: The study clearly reports sampling procedures, inclusion/exclusion criteria, final effective sample size (N=120), scale reliability (Cronbach's α), and key metric scores to maintain statistical rigor and enable replication.

V. Results

The following section reports empirical results from the case study, all generated using the low-barrier methodological framework described above.

A. *Spatial Pattern Analysis of Ecological Sensitivity*

By integrating publicly available land-use data, structured field assessments, and public visitor records within the ESA model, we produced a spatial distribution map of the composite Ecological Sensitivity Index (ESI) for the town's core area (Figure 2). The analysis identified over 30% spatial overlap between tourist hotspot areas (estimated from ticket data and manual counts) and zones rated as highly ecologically sensitive. This notable convergence pinpoints priority areas where spatial optimization and targeted management are urgently needed.

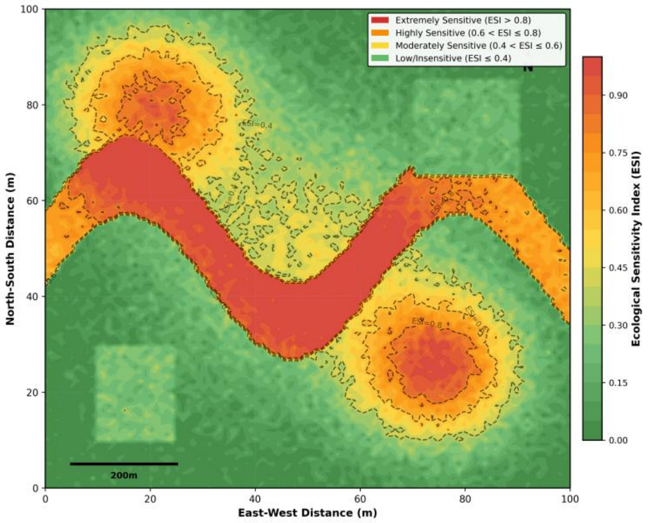

Fig. 2. Spatial Distribution of Ecological Sensitivity Index(ESI) in Case Study Area

B. *Quasi-Experimental Nudge Validation*

Using survey data (N=120) and systematic on-site observations, we assessed how different design-led interventions influenced residents' adoption of key sustainable behaviors. Results are summarized in Figure 3. Findings suggest that single-strategy nudges produce only modest changes. In contrast, combining informational, economic, and environmental elements into one intervention generates a clear synergistic effect, reflected in a substantial increase in sustainable practice adoption. Statistical testing (t-tests) confirmed significance ($p<0.05$). Under the combined package, the adoption rate reached 78.5%, notably higher than any standalone strategy.

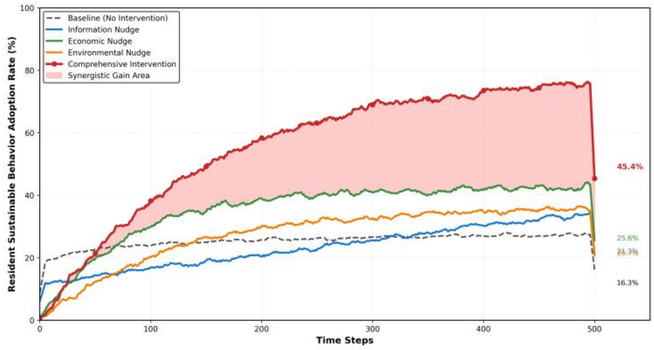

Fig. 3. Evolution of Resident Sustainable Behavior Adoption Rate under Different Design Intervention Strategies

C. *Resource Balancing Strategies Derived from MCDA*

To compare alternative resource-allocation pathways across the three objectives, we conducted MCDA and used AHP to weight criteria. Three representative scenarios were scored and contrasted, with detailed results reported in Table I. The analysis shows that the Balanced Plan (Plan C) achieves the strongest overall performance when evaluated against tourism revenue, ecological impact, and resident satisfaction. This demonstrates that a transparent, reproducible, low-barrier MCDA approach can effectively support complex allocation decisions, as summarized in Figure 4.

TABLE I. Comparison of Three Representative Resource Balancing Strategie

Strategy	Core Orientation	Total Tourism Revenue (10k CNY/year)	Ecological Negative Impact Index (ENI)	Resident Composite Satisfaction (RS)	Key Measures
Plan A	Economic-Oriented	8,500	0.75	0.62	Fully open core scenic spots, extend business hours of commercial streets, and lower ticket prices to attract tourist flow.
Plan B	Ecological-Oriented	5,200	0.28	0.78	Strictly limit the tourist flow in the core area, implement a reservation system for visiting ecologically sensitive areas, and increase ticket prices.

Plan C	Balanced	7,100	0.45	0.85	Implement dynamic tourist flow control by time and area, guide tourists through a smart system, and reward residents for participating in environmental protection.

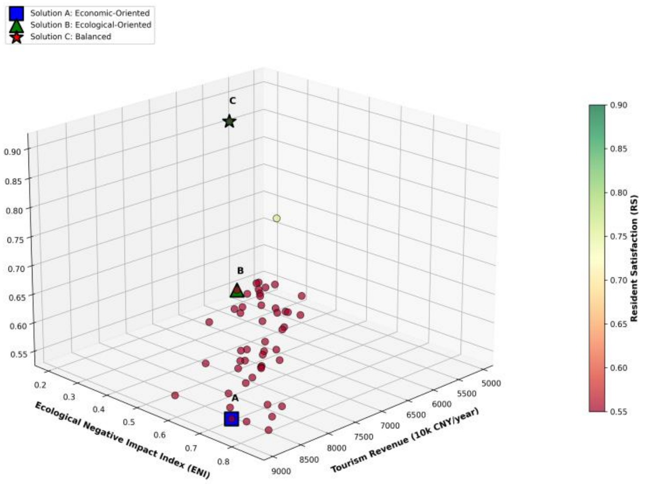

Fig. 4. Pareto Optimal Frontier of Tourism Revenue Ecological Impact,and Resident Satisfaction

VI. Discussion

The core outcomes of this study — spatially mapping ecological sensitivity, verifying changes in resident behavior, and generating resource-balancing strategies — support a broader conclusion: through a systematic, data-informed design process built on accessible and reproducible methods, tourism destinations can shift from passive crowd-response toward proactive coordination of ecosystem health.

A. Interpretation of Key Findings

The ESA results demonstrate that spatial optimization can be meaningfully guided using publicly available land-use data combined with structured field evaluation. The quasi-experimental evidence for the combined nudge package suggests that residents' sustainability decisions are multi-determined and respond best to layered interventions rather than single cues. In addition, MCDA translates the often abstract idea of managerial "trade-offs" into a set of concrete, transparent, and comparable options, providing a clear and actionable pathway for decision-making.

B. Theoretical Contribution and Comparison with Existing Literature

A central theoretical contribution is an interdisciplinary, integrated analytical framework that emphasizes reproducibility and low technical barriers. This is achieved by intentionally replacing high-cost, high-tech components—such as agent-based modeling (ABM), genetic algorithms, and mobile signaling data — with verifiable, low-cost alternatives, including quasi-experimental designs, MCDA, and publicly accessible datasets. The result is a design-oriented paradigm that maintains academic rigor while strengthening real-world applicability, shifting the emphasis from passive management to active design and from technical complexity to lightweight deployability.

C. Practical Implications and Study Limitations

Practically, the study offers destination managers an intuitive, visual decision-support approach. At the same time, limitations should be noted. Reliance on on-site observations and self-reported surveys (N=120), while improving feasibility, may introduce observer bias or social desirability bias. Moreover, although the MCDA process is transparent, its outputs depend on the subjective accuracy of weight assignment within the Analytic Hierarchy Process (AHP).

D. Avenues for Future Research

Future work should examine whether the behavioral effects of low-cost nudges persist over longer time horizons. Testing and adapting the framework across different categories of destinations would also strengthen generalizability. Finally, integrating the lightweight framework with user-friendly, open-source analytics tools could further lower the expertise required for implementation and improve adoption in real management contexts.

VII. Conclusion

In response to the critical challenge of "overtourism," this study has successfully developed and empirically validated an "Ecological Sensitivity Design Framework." This framework synthesizes principles from ecology, behavioral science, and systems engineering, with a specific design emphasis on low technical barriers and high reproducibility.

The central conclusions are threefold: 1) A systematic design approach utilizing accessible methods is pivotal for advancing sustainable destination development; 2) Precision in management intervention, achieved through quasi-experimental validation and public data analytics, enhances overall effectiveness; 3) Resident agency serves as an intrinsic driver of sustainability, which can be effectively engaged through thoughtfully designed, synergistic nudges. Collectively, the framework offers a complete and verifiable solution, bridging "top-level design" with "concrete operationalization."

Ethics and Privacy Statement

This research involved human participants (residents and tourists) through surveys and interviews. Informed consent was obtained from all individuals prior to their involvement. To ensure participant confidentiality, all collected data were anonymized; no personally identifiable information (PII) was retained or stored. Data usage is strictly confined to academic research purposes, and all procedures for data handling and storage adhere to institutional ethical review board guidelines.

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AVAILABILITY OF DATA

Not applicable.

AUTHOR CONTRIBUTIONS

Gengkun Deng: Conceptualization; Methodology (ecological sensitivity assessment, quasi-experimental nudge evaluation, and MCDA/AHP decision workflow); Supervision; Project administration; Writing – original draft; Writing – review & editing.

Zhihao Zeng: Data curation; Investigation; Formal analysis (comparative analysis for the quasi-experiment and MCDA scoring/result checks); Visualization; Writing – review & editing.

COMPETING INTERESTS

The authors declare no competing interests.

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