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Top of page

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Review

A Sustainable Spatial Decision Support System (S-SDSS): A Systematic Review and Conceptual Integration of Ecological Network Optimization Frameworks

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Abstract

Rapid urbanization and increasing landscape fragmentation pose significant threats to ecological connectivity, creating a need for integrative decision support approaches in sustainable spatial planning. This study presents a systematic review of ecological network optimization studies published between 2005 and 2025, following the PRISMA protocol. A total of 78 peer-reviewed studies were analyzed to identify methodological trends, recurring limitations, and research gaps in the assessment of structural and functional connectivity. Based on the gaps identified through the systematic review, this study proposes a conceptual Sustainable Spatial Decision Support System (S-SDSS) framework that integrates Morphological Spatial Pattern Analysis (MSPA), Multi-Criteria Evaluation (MCE/AHP), Minimum Cumulative Resistance (MCR), Least-Cost Path (LCP), and Gravity Modeling (GM) within a unified analytical structure. The review findings reveal a clear shift from single-method applications toward integrated multi-model approaches that better represent ecological processes and improve corridor prioritization. The proposed framework synthesizes the complementary strengths of these established methods to support evidence-based ecological network planning. The framework operates as a hybrid structure that combines a sequential analytical workflow with a unified typological classification system, generating Hybrid Ecological Typologies (T1–T5) as planning-oriented outputs that cannot be produced by any individual method alone. The proposed S-SDSS offers a transferable and policy-relevant conceptual basis for ecological network optimization, supporting green infrastructure planning, biodiversity conservation, and long-term landscape resilience across multiple spatial scales.

Keywords: ecological networks; spatial decision support system; MSPA; landscape connectivity; minimum cumulative resistance; green infrastructure; sustainable spatial planning

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1. Introduction

The escalating global pressure of urbanization and rapid land-use transformations are inducing significant spatial fragmentation of natural ecosystems, leading to the critical loss of ecological functions. Habitat fragmentation weakens ecosystem continuity, thereby restricting species mobility and genetic flow [1,2]. Forested areas, serving as vital carbon sinks and biodiversity reservoirs under global climate pressures, are among the habitat types most severely affected by this fragmentation process [3,4]. Within this context, the sustainability of forest landscapes depends not only on the preservation of existing habitat patches but also on maintaining their morphological and functional connectivity [2].

Ecological networks play a critical role in maintaining ecological and biological continuity by facilitating species movement, sustaining gene flow, and enhancing adaptation to climate change [5–10]. By preserving connections among habitat patches, these networks support the long-term resilience of ecosystem services such as carbon sequestration, water regulation, and erosion control. From a landscape planning perspective, ecological networks provide the spatial foundation for green infrastructure development, help reduce edge effects around core habitats, and support the prioritization of conservation and restoration actions under limited resources [5,11].

As summarized in Table 1, ecological networks contribute to biodiversity conservation and ecosystem resilience while simultaneously providing a strategic spatial framework for green infrastructure planning and conservation prioritization [6,12,13]. These multiple functions underscore the need for analytical approaches capable of integrating ecological structure, functional connectivity, and planning relevance within a unified decision support framework.

Table 1. Ecological functions and planning implications of ecological networks.

Functional Dimension	Ecological Significance	Planning Implications	References
Species movement and gene flow	Maintains genetic diversity and reduces local extinction risk by enabling dispersal among habitat patches.	Supports identification of critical habitat corridors and stepping stones.	[1,2]
Climate change adaptation	Facilitates species range shifts toward climatically suitable habitats.	Guides long-term ecological adaptation strategies.	[3,4]
Ecosystem service resilience	Sustains carbon sequestration, hydrological regulation, and erosion control through connected landscapes.	Strengthens ecosystem-based planning and nature-based solutions.	[4,5]
Morphological integrity and edge-effect reduction	Preserves core habitats and reduces fragmentation and edge effects.	Supports delineation of buffer zones and ecological restoration priorities.	[1,14]
Green infrastructure integration	Provides the spatial basis for linking natural areas across urban and rural landscapes.	Informs sustainable land-use planning and infrastructure design.	[5]
Spatial prioritization	Enables ranking of areas for conservation and restoration under limited resources.	Supports transparent and evidence-based decision making.	[2,8]

In landscape ecology, connectivity is commonly addressed through two complementary dimensions: structural and functional connectivity [6,9,12,13]. Structural connectivity refers to the spatial arrangement and physical continuity of habitat patches, whereas functional connectivity reflects the degree to which landscape characteristics facilitate or impede ecological flows and species movement. Although these concepts are well established, the landscape planning literature still lacks a consistent analytical framework that clearly defines how different ecological network modeling approaches should be sequenced, parameterized, and integrated.

Previous studies have applied a wide range of analytical techniques to ecological network design, including Morphological Spatial Pattern Analysis (MSPA), habitat suitability modeling, Multi-Criteria Evaluation (MCE/AHP), Minimum Cumulative Resistance (MCR), Least-Cost Path (LCP), and Gravity Modeling (GM). Each method addresses a specific aspect of ecological connectivity. For example, MSPA identifies the structural components of habitat networks [14], habitat suitability and MCE/AHP support the delineation of ecologically valuable areas [15,16], resistance-based models such as MCR and LCP simulate species movement across heterogeneous landscapes [7,17], and Gravity Models quantify the interaction strength between habitat patches [8,18]. However, when these

methods are used independently, they provide only a partial representation of ecological connectivity and may limit the robustness and applicability of planning outcomes [19–22].

This methodological fragmentation highlights the need for integrative approaches capable of combining structural connectivity, resistance-based functional connectivity, and spatial prioritization within a unified decision support framework [8,19,20]. Such integration is particularly important for translating ecological theory into operational planning tools that can simultaneously account for ecosystem services, anthropogenic pressures, and biodiversity conservation objectives [2,4].

This study comprises two complementary components. First, a PRISMA-based systematic literature review was conducted to synthesize ecological network optimization studies published between 2005 and 2025 and to identify methodological trends, recurring limitations, and research gaps [23,24]. Second, based on the gaps identified through this review, a conceptual Sustainable Spatial Decision Support System (S-SDSS) framework is proposed. The framework integrates habitat suitability analysis [15,16], Morphological Spatial Pattern Analysis (MSPA) [14], Minimum Cumulative Resistance (MCR) [7], Least-Cost Path (LCP) [17], and Gravity Modeling (GM) [18] within a coherent analytical structure designed to support ecological network optimization.

Rather than introducing a new stand-alone algorithm, the proposed S-SDSS represents a review-derived conceptual synthesis that combines established and complementary analytical approaches into a scalable decision support architecture. Rather than functioning as a simple sequential pipeline, the framework integrates these methods within a unified typological classification system in which each analytical stage directly conditions the subsequent one, generating Hybrid Ecological Typologies (T1–T5) as planning-relevant outputs that reflect the integrated contribution of all components rather than the sum of independent results. By linking systematic evidence synthesis with methodological integration, the study aims to bridge the gap between theoretical advances in landscape ecology [20,25] and the practical requirements of sustainable spatial planning, green infrastructure development [5,26], biodiversity conservation [1,4], and long-term ecological resilience [2,6].

2. Methodology

This study adopts a two-stage methodological design consisting of complementary review and conceptual synthesis components. In the first stage, a PRISMA-based (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) systematic literature review [23,24] was conducted to synthesize evidence from 78 peer-reviewed publications, identifying methodological trends, commonly applied analytical approaches, and recurring research gaps in ecological network optimization studies published between 2005 and 2025. In the second stage, the findings of this review were synthesized to develop a conceptual Sustainable Spatial Decision Support System (S-SDSS) framework designed to provide planners with a concrete and transferable decision support structure.

Within this framework, the Hybrid Ecological Typology Development model constitutes the classification and integration component that combines habitat suitability [15], structural connectivity assessed through MSPA [14], resistance-based functional connectivity via MCR [7,17], and OpenStreetMap (OSM)-based transportation barrier data into a unified hierarchical structure for classifying the ecological potential of urban vacant lands (urban voids) [26].

Accordingly, the Hybrid Ecological Typology should be interpreted as an internal component of the broader S-SDSS framework rather than as a separate methodological contribution.

2.1. Research Design

The primary objective of this study is to systematically examine the frequency of use, integration patterns, and parameterization approaches of Morphological Spatial Pat-

tern Analysis (MSPA) [14], Minimum Cumulative Resistance (MCR) [7], Least-Cost Path (LCP) [17], and Gravity Model (GM) [18] methods within ecological network optimization studies. In addition, the study aims to evaluate how these analytical approaches have been conceptually integrated into ecological connectivity and spatial planning frameworks in the literature [6,11]. To ensure a transparent, reproducible, and evidence-based synthesis, the research was designed as a PRISMA-based systematic literature review [23].

2.2. Databases and Search Strategy

The search process encompasses peer-reviewed articles published between January 2005 and December 2025, retrieved from the Web of Science (WoS), Scopus and Google Scholar databases. The core search string utilized during the data collection phase is as follows: ("ecological network" OR "landscape connectivity") AND ("MSPA" OR "minimum cumulative resistance" OR "MCR" OR "least cost path" OR "LCP" OR "gravity model") AND ("green infrastructure"). By employing Boolean operators (AND/OR), this query ensured an interdisciplinary and comprehensive capture of the relevant literature.

2.3. Inclusion and Exclusion Criteria

The following criteria were rigorously applied in the selection of the articles evaluated within the scope of this study:

Inclusion criteria: Studies containing original spatial modeling on ecological networks or connectivity analysis; utilization of at least one of the MSPA, MCR, LCP or GM methods; and publication in a peer-reviewed international journal [15,20].

Exclusion criteria: Articles limited to conceptual discussions; studies performing species-based biological analysis without presenting a spatial model; mono-disciplinary analyses lacking methodological integration; and gray literature (theses, reports), book chapters, and non-peer-reviewed conference proceedings [11,23].

2.4. PRISMA Protocol and Literature Selection Process

The review followed the PRISMA protocol to ensure transparency and reproducibility [23,24]. Mendeley Desktop software (Version 1.19.8) was utilized for literature management and the removal of duplicate records.

The selection process was conducted in four distinct stages:

1. **Identification:** A total of 214 records were identified across databases. After removing 38 duplicate records, 176 studies were transitioned to the screening phase.
2. **Screening:** Following an evaluation of titles and abstracts, 64 irrelevant publications were excluded, leaving 112 articles eligible for full-text review.
3. **Eligibility:** During the full-text assessment, 34 studies were excluded for reasons such as failing to generate a resistance surface or lacking methodological integration (e.g., the combination of MSPA-MCR).
4. **Included:** Upon completion of the screening processes, 78 original studies were included in the analytical synthesis and methodological classification (Table 2).

Table 2. PRISMA flow summary of the systematic literature review process (2005–2025).

Stage	Number of Records (n)	Number of Records (n)
1. Identification	Total records identified through database searching.	214
	Removal of duplicate records.	38
	Total records screened after deduplication	176

Table 2. *Cont.*

Stage	Number of Records (n)	Number of Records (n)
2. Screening	Records excluded after title and abstract screening.	64
	Articles retained for full-text eligibility assessment.	**112**
3. Eligibility	Full-text articles excluded based on exclusion criteria.	34
	Lack of resistance surface modeling.	18
	No integrated methodological framework.	10
	Lack of spatial decision support focus.	6
4. Included	**Final studies included in qualitative and analytical synthesis.**	**78**

The four-stage literature selection process conducted in accordance with the PRISMA protocol is illustrated in Figure 1.

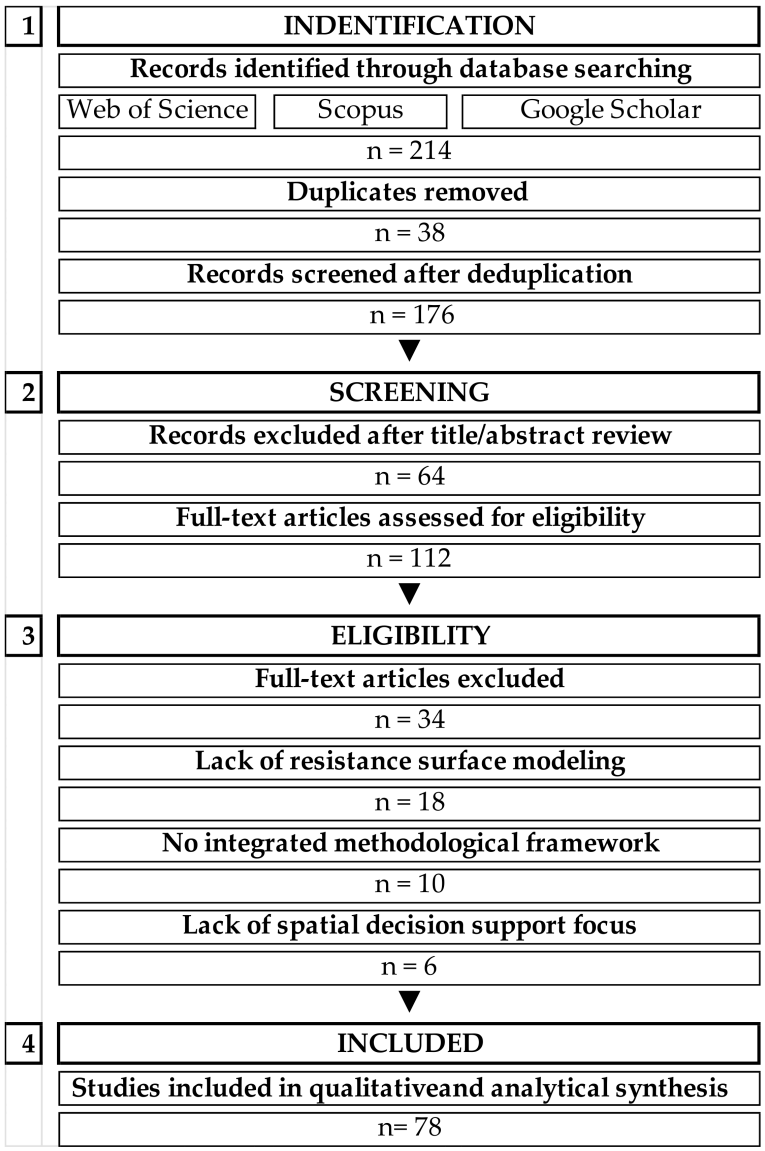

Figure 1. PRISMA flow diagram of the systematic literature review process (2005–2025).

2.5. Analytical Coding Framework

Each of the 78 included studies was transferred to a structured coding matrix in MS Excel. The analytical coding process was conducted across five primary parametric axes:

Analytical components: MSPA [14], MCR [7], LCP [17] and GM [18].

Resistance parameterization approaches: Expert judgment, AHP [16], MCE/MCDM, TOPSIS or empirical calibration methods [15].

Integration level: Single model application, hybrid (dual/triple) integration, or full hierarchical (S-SDSS) integration [19,20].

Validation and analytical procedures: Scenario analysis, sensitivity analysis [26,27], and the use of species-based field data (e.g., radio-tracking) [28].

Planning relevance and transferability: Green infrastructure standards [5], land-use policies, and the capacity to provide strategic planning recommendations [11].

3. Results: Analytical Synthesis and Methodological Rationale of S-SDSS

Rather than serving as a passive historical review, the systematic synthesis of the literature (2005–2025) acts as an empirical baseline to justify the architectural necessity of the proposed Sustainable Spatial Decision Support System (S-SDSS). The statistical and categorical patterns extracted from the 78 reviewed studies explicitly expose critical methodological "gaps" that the S-SDSS framework is designed to bridge.

3.1. Methodological Evolution and the Integration Gap

The ecological network modeling literature has undergone a substantial methodological evolution over the last two decades, which can be categorized into five major methodological periods. As synthesized in Table 3, studies published after 2015 show a marked increase in the application of Morphological Spatial Pattern Analysis (MSPA) for identifying structural habitat components [29,30]. Concurrently, the integration of Gravity Models (GM) [31] and Circuit Theory (CT) [32,33] contributed to more advanced approaches for network prioritization and ecological connectivity assessment [18,26,33,34]. Despite these methodological developments, the review indicates that limitations related to resistance parameterization, scale sensitivity, uncertainty analysis, and planning transferability continue to represent recurring challenges within the literature.

Table 3. Methodological evolution matrix and S-SDSS design rationale.

Period	Core Frameworks	Methodological Gaps & Limitations	Identified Evidences	S-SDSS Architectural Response
2005–2009	Stand-alone LCP/MCR	Subjective resistance values; total disregard of structural morphology.	[13,17,31,32,35]	Replaces expert bias with systematic MCE and probabilistic surfaces.
2010–2014	MSPA + LCP	Heavy scale sensitivity; loss of narrow corridors in low resolutions.	[29,30]	Implements high-resolution (10 m) morphological filtering.
2015–2018	MSPA + MCR + LCP	Static connection pipelines; lack of dynamic sensitivity analysis.	[36,37]	Integrates spatial uncertainty analysis within decision thresholds.
2019–2022	MSPA + MCR + LCP + CT/GM	Computational bottlenecks; results are too abstract for statutory plans.	[7,8,32–34]	Translates "pinch-points" into spatially explicit planning categories.
2023–2025	Integrated MCE Models	Lack of localized validation and species-specific parameter synchronization.	[38–41]	Embeds automated sensitivity validation (AHP-MCE-Uncertainty loop).

During Period 1 (2005–2009), early research focused on corridor identification using stand-alone LCP or MCR approaches, where resistance values were predominantly derived from subjective expert opinions [13,17,35], and the foundational theory of circuit-based connectivity emerged [32]. This focus shifted toward morphological analysis during Period 2 (2010–2014), where MSPA-based core area identification became a standardized practice for evaluating habitat structure alongside corridor connectivity [14]. Subsequently, Period 3 (2015–2018) marked the integration of structural (MSPA) and functional (MCR) connectivity, making frameworks more robust through the joint application of diverse connectivity metrics [40]. As research moved toward advanced flow analysis and network prioritization during Period 4 (2019–2022), the integration of Circuit Theory (CT) gained prominence for modeling probabilistic movement patterns [32], while Gravity Models (GM) were systematically embedded into the MSPA–MCR–LCP pipeline to establish functional hierarchies and identify critical "pinch-points" within the ecological network [8,19,31]. Finally, the current era, Period 5 (2023–2025), is defined by the rise of Integrated MCE Models, where MCE/AHP-supported dynamic resistance surfaces and systematic literature synthesis protocols, such as PRISMA, ensure maximum methodological rigor [23,24,38].

Despite this multi-staged progression, a critical methodological gap remains: existing frameworks treat these components as a sequential pipeline rather than a unified, dynamic system [19,20]. Models typically feed structural components into functional friction layers without an algorithmic feedback loop, often resulting in abstract outputs that restrict their transferability to statutory land-use planning hierarchies [11,42].

Within this evolutionary context, the proposed S-SDSS architecture deliberately adopts an integrated pipeline oriented toward graph theory [43] and structural morphology (MSPA-MCR-LCP). While Circuit Theory (CT) specializes in analyzing distributed movement patterns based on random walk theory [32], its non-deterministic outputs can complicate formal boundary definitions. By bridging spatial pattern recognition with deterministic corridor modeling, the S-SDSS directly translates complex ecological flows into stable, planning-relevant spatial planning categories, ensuring a seamless integration into statutory planning frameworks [26,44].

3.2. Resistance Surface Parameterization and Uncertainty Diagnostics

The resistance surface is the fundamental determinant of functional connectivity [15]. However, the systematic analysis of the 78 reviewed studies highlights core methodological challenges that persist in the current literature. Rather than generic limitations, these challenges serve as the direct empirical motivation for the S-SDSS architecture:

- **The Subjectivity and Resolution Gap:** The inherent subjectivity in Analytic Hierarchy Process (AHP) weightings often limits the reproducibility of resistance surfaces, making models highly dependent on expert bias [16,45]. Furthermore, at low resolutions, pixel size distorts morphological reality, causing a critical "corridor vanishing" effect where narrow linear elements—often misidentified as "urban voids" or idle lands—are completely excluded from macro-scale models [29,30].
- **The Policy-Validation and Safety Gap:** In highly urbanized landscapes under intensive development pressure, the "least-cost path" does not always equate to the safest path due to intense anthropogenic noise and barrier effects [36,37]. A significant lack of species-specific field validation or empirical ground-truthing persists, which limits the biological accuracy of modeled corridors [28]. Concurrently, the scarcity of robust sensitivity analyses remains a persistent barrier to model validation, rendering the resulting corridors highly unstable under minor parameter fluctuations [27].

- **The Static Fallacy:** Conventional frameworks treat highly dynamic anthropogenic pressures (e.g., road density, urban sprawl) as static constraints, generating "dead lines" that target species avoid in real life [1,46].
- **The S-SDSS Resolution:** To eliminate these systematic constraints, the proposed S-SDSS architecture replaces arbitrary, static scoring with a mathematically audited parameter matrix linked to explicit spatial sensitivity analysis [27]. It mandates a high-resolution (10–25 m) baseline at the local planning scale to preserve narrow morphological pathways [29]. Influenced by the statistical breakthroughs in the reviewed literature, the S-SDSS models anthropogenic inputs with a 40% dominant weight and topography with a 25% sensitivity deviation. By embedding species-oriented habitat suitability derived from objective predictive software like MaxEnt (Version 3.4.4) [47] alongside statistical validation metrics—such as ROC/AUC values [48] and Jackknife tests [49]—the S-SDSS isolates the exact thresholds where human encroachment breaks the network, transitioning ecological corridors from theoretical predictions into evidence-based and spatially explicit planning structure.

3.3. From Structural–Functional Dichotomy to Methodological Depth

A central challenge in ecological network planning lies in the discrepancy between structural connectivity, which describes the spatial configuration and continuity of habitat patches [9,12], and functional connectivity, which reflects species movement across heterogeneous landscapes [15]. Analyses based solely on structural geometry may overlook ecological barriers and movement constraints [14], whereas functional models without structural context may fail to represent the spatial organization of habitat systems [17].

To address this challenge, graph-theoretical metrics are widely used to evaluate network performance and connectivity efficiency [43]. Common indices include alpha (α), beta (β), and gamma (γ), which quantify network redundancy, complexity, and the proportion of realized connections, respectively [50]. In addition, metrics such as Betweenness Centrality and the Probability of Connectivity (dPC) help identify habitat patches and corridors that play a critical role in maintaining overall network integrity [8,21,22,51,52].

The systematic review indicates that methodological depth in ecological network modeling has evolved from isolated single-model applications toward fully integrated multi-component frameworks [19,20]. Based on the reviewed studies, four methodological depth levels were identified (Table 4), ranging from simple structural analyses to advanced decision support systems that combine structural connectivity, functional resistance modeling, and hierarchical prioritization.

Table 4. Methodological depth taxonomy and planning integration levels.

Depth Level	Core Modeling Architecture	Validation Mechanisms	Primary Reference Anchors	Planning Integration Level
Type A (Isolated)	Single Model (MSPA or LCP)	None	[29,30]	**Low:** Structural geometry mapped; functional flow ignored.
Type B (Spliced)	MSPA + MCR	Limited Expert Review	[7,8,36,37]	**Medium:** Disconnection points identified without hierarchical order.
Type C (Integrated)	MSPA + MCR + LCP	Scenario Analysis Matrices	[40,41]	**Medium-High:** Least-cost pathways drawn but highly vulnerable to parameter shifts.
Type D (S-SDSS Framework)	**MSPA + MCR + LCP + GM + MCE/AHP**	**Sensitivity and Spatial Uncertainty Analysis**	[22,33,34,38,52]	**High:** Establishes highly resilient, spatially explicit planning boundaries based on optimized thresholds.

The proposed S-SDSS corresponds to the highest level of methodological integration (Type D). It combines habitat suitability analysis [15], MSPA [14], MCR [7], LCP [17], Gravity Modeling [31], and sensitivity analysis [27] within a unified conceptual framework.

This integrated structure supports the translation of ecological connectivity assessments into planning-relevant outputs that can inform conservation prioritization [8,19], ecological restoration [20], and spatial planning decisions [11].

4. Discussion

4.1. Methodological Gaps Revealed by the Systematic Review

The systematic review reveals a persistent methodological fragmentation in ecological network modeling, where structural and functional connectivity approaches are frequently applied independently. Morphological Spatial Pattern Analysis (MSPA) has become a widely used technique for identifying habitat cores and spatial structures [14,53]; however, when used alone, it cannot account for species movement dynamics or landscape resistance [29,30]. Conversely, functional approaches such as Minimum Cumulative Resistance (MCR) and Least-Cost Path (LCP) provide valuable insights into movement processes, yet their results are highly sensitive to resistance parameterization and often assume a single optimal movement route [21,52].

The review of 78 studies indicates a gradual shift from isolated applications toward more integrated modeling strategies, particularly after 2015 [40,54]. Despite this methodological evolution, no consistently applied framework was identified that systematically combines habitat suitability analysis, structural connectivity assessment, resistance-based modeling, and quantitative prioritization within a single decision support architecture. This gap limits the reproducibility, comparability, and operational applicability of ecological network models in spatial planning and policy-making processes [21,22].

4.2. Conceptual Contribution and Novelty of the S-SDSS Framework

In response to the methodological gaps identified in the literature, this study proposes a conceptual Sustainable Spatial Decision Support System (S-SDSS) that integrates habitat suitability analysis [15], Morphological Spatial Pattern Analysis (MSPA) [14], Minimum Cumulative Resistance (MCR) [7], Least-Cost Path (LCP) [17], and Gravity Modeling (GM) [31] within a unified analytical framework.

The principal contribution of the framework lies not in introducing a new standalone algorithm, but in providing a structured and hierarchical synthesis of complementary methods that are typically applied separately [19,20]. Within this architecture, habitat suitability analysis defines ecologically favorable areas [15], MSPA identifies structural network components [14], MCR and LCP model resistance-based movement pathways [7,17], and the Gravity Model prioritizes ecological corridors based on interaction strength between habitat patches [18].

By explicitly incorporating ecosystem services [55] and anthropogenic pressures [1,46] into the analytical workflow, the proposed framework improves the relevance of ecological network modeling for sustainable spatial planning [11]. In this way, the S-SDSS translates methodological advances in landscape ecology [25] into a coherent and transferable decision support structure that can support green infrastructure planning [5], biodiversity conservation [1], and ecological resilience [2].

The proposed S-SDSS is designed as a hybrid structure that combines a sequential decision support workflow with a unified analytical architecture. While the individual methods are applied in a defined sequence—progressing from habitat suitability assessment and structural pattern recognition through resistance-based movement simulation to network prioritization—their outputs are not treated as independent results. Instead, each analytical stage directly conditions and constrains the subsequent one, and all outputs are systematically integrated within a common typological classification system (T1–T5).

The distinct analytical value that emerges from this integration lies in the generation of Hybrid Ecological Typologies, which cannot be produced by any individual method alone. Specifically, the framework produces spatially explicit planning categories that simultaneously reflect structural habitat geometry (MSPA), landscape resistance and movement potential (MCR-LCP), and corridor interaction strength and hierarchical priority (GM). This multi-dimensional synthesis enables planners to move beyond isolated connectivity assessments toward an integrated, evidence-based spatial decision structure that is directly applicable to statutory land-use planning processes [19,20,39,40].

The resulting Hybrid Ecological Typologies (T1–T5) thus provide a direct interface between ecological analysis and statutory planning decisions [11,42].

4.3. Limitations and Future Research Directions

Several limitations should be acknowledged. First, the proposed S-SDSS is a conceptual framework derived from a systematic synthesis of the literature and has not yet been empirically validated through case-study implementation [56]. Future applications should test the framework under different ecological and planning contexts to assess its practical performance and transferability. Second, many ecological connectivity models remain dependent on expert-based weighting methods such as the Analytic Hierarchy Process (AHP) [16], which may introduce subjectivity into resistance surface construction [15]. Future studies may explore data-driven and machine learning approaches to improve objectivity and reproducibility [38]. Third, the review confirms that sensitivity analysis [27] and field-based validation remain limited in the literature [28]. Incorporating uncertainty assessment, species-specific movement data, and temporal dynamics will be essential for strengthening the ecological realism of future applications [57]. Despite these limitations, the proposed S-SDSS offers a structured conceptual foundation for integrating structural and functional connectivity analyses within a planning-oriented decision support framework [6,11].

5. Proposed Conceptual Framework: Ecological Network-Based Sustainable Spatial Decision Support System (S-SDSS)

The principal methodological contribution of the proposed Sustainable Spatial Decision Support System (S-SDSS) lies in its ability to transform multiple analytical outputs into a unified typological classification system that directly supports planning and zoning decisions [11,42]. Building upon the methodological gaps identified through the systematic literature review and analytical synthesis presented in the preceding sections, this section presents the S-SDSS as a review-derived conceptual framework for integrating structural and functional ecological connectivity [10,12] within a unified decision support architecture [11,42].

The framework consists of a sequence of complementary analytical stages culminating in the development of Hybrid Ecological Typologies, which integrate habitat suitability [15], structural connectivity [14], resistance-based functional connectivity [7,17], and network prioritization [31] into a common planning-oriented classification system [39,40]. While the analytical stages follow a defined sequence, each stage directly conditions and constrains the subsequent one, ensuring that the final typological outputs reflect the integrated contribution of all components rather than the sum of independent results.

Figure 2 presents the step-by-step operational protocol and processing hierarchy of the proposed framework, while the integrated analytical components and methodological sequence are illustrated in Figure 3.

	INPUT DATA				
	Optical	Sentinel-2, Landsat-8	CORINE/CLC	Land Cover classification	NDVI / Transportation classification
	Resolution	5x5 m or 10x10 m	High-resolution data precision for urban scale		
	Vector	OpenStreetMap-OSM	Transportation	Green Infrastructure	Built Environment
	Topographic	SRTM/ASTER DEM	Generating Roughness	Slope and Aspect	TPI Indeks TWI Indeks
	Theoretical	Systematic Literature Review		Weighting	Criteria Identification
	OUTPUT	Data Harvesting: The creation of a unified, high-precision spatial database.			
1	**STRUCTURAL ANALYSIS (MSPA)**				
	Software	GuidosToolbox (MSPA Engine)		QGIS/ArcGIS (Pre-processing)	RTB (Raster Toolbox)
	MSPA Thresholds	MSPA and Habitat Parameters		Structural Form	Morphological strength of green spaces
		Pixel Scale	**10m x10m**	High-resolution data precision	
		Edge Effect	**30- 90 m**	Critical depth where habitat degradation begins	
		Minimum Core Area	**>2 - 5 ha**	Biodiversity hosting lower limit	
		Neighborhood Analysis	**8-Pixel Connectivity**	The most sensitive threshold for capturing diagonal connections.	
	OUTPUT	MSPA Map	Breakpoints	Core, Edge, Perforated, Bridge, Loop, Islet, Branch	
2	**RESISTANCE MODELLING (AHP/MCE)**				
	Software	QGIS / ArcGIS	Weighting by Expert Opinion (AHP) and Overlapping Resistance Surfaces (MCE)		
	AHP / MCE Thresholds	Weighting Coefficient (wi)	**CR< 0.10**	Consistency Ratio (CR)	Cumulative resistance and friction level
		Resistance Scale (R)	**1-1000**	Natural/Permeable: 1	Artificial/Barrier: 1000
		Slope Threshold	**> %25**	Sudden increase point in physical resistance	Cost-increasing obstacle
		Road / Urbanization	**50 m - 100 m**	Distance to road networks	Buffer zone weight
		Resistance Surface	**80-100**	High Resistance	Scoring thresholds for roads
		Mapping (MCE)	**1-10**	Low Resistance	Natural vegetation scoring thresholds
		Anthropogenic Pressure	**Expert Opinion**	AHP-Weighting	Resistance surface generation
	OUTPUT	Resistance Modelling	AHP / MCE	Resistance surface generation	MCE Map
3	**CONNECTIVITY SYNTHESIS AND FUNCTIONAL CORRIDOR SIMULATION (MCR/LCP)**				
	Software	Connectivity Synthesis	Linkage Mapper (MCR/LCP) & Circuitscape (Current Density)		
		Barrier Analysis	QuickOSM (OSM data extraction) & ArcGIS Pro/QGIS		
		Network Hierarchy	Graphab/Conefor/Network Analysis (for dPC and Gravity Model calculations)		
A	**MCR Thresholds**	Dispersal Distance	**500 m**	1000 m Medium mobility	1000- 2500 m Maximum dispersal
		Corridor Geometry	**Min. 30 m**	30-150 m	Lines free from edge effects
	OUTPUT	Minimum corridor standards		Maximum movement threshold of target species within the landscape	
B	**LCP Thresholds**	Barrier Effect	Motorways, secondary roads based on OpenStreetMap (OSM) data.		
			Weighted overlay of LULC, slope, and anthropogenic pressure		
	OUTPUT	MCR Map	LCP Map	Buffer zones	Optimum Ecological Corridors
4	**HYBRID ECOLOGICAL TYPOLOGY DEVELOPMENT (MSPA +MCE + MCR+ LCP Synthesis)**				
A	**MSPA +MCE + MCR+ LCP Thresholds**	Synthesis Weighting	**%50 Structural (MSPA) + %50 Functional (MCR and LCP) Overlay**		
		Typology Matrix	**T1-T5**		
		Urban Void Score	**The "strategic gap" value of the void on the corridor**		
	OUTPUT	Overlapping of Structural (MSPA) and Functional (MCR / LCP) Data and Ecological Strategic Zoning			
	T1 Protection Area	**T2** Restoration Area	**T3** Ecological Corridors	**T4** Sustainable Use Area	**T5** Buffer Zone
	OUTPUT	Decision Matrix		Ecological Characterization	
5	**GRAVITY MODEL (GM) & VALIDATION (Network Hierarchy)**				
	Software	Graphab	Conefor	Network Analysis	
A	**Gravity Model Thresholds**	GM	**G: > 1.0**	Interaction Strength	Strategic path priority
		Connectivity Index (dPC)	**>%5 Critic**	Risk of network collapse if the area is removed from the system	
B	**Software**	SPSS	R	GIS	QGIS
	Validation	Sensitivity Threshold	**AUC:0.70 Acceptance**	0.85: High Precision	Statistical sensitivity
	OUTPUT	Model Verification	Strategic planning map	Ecological network backbone with hierarchical priority	
6	**PLANNING OUTPUT AND DECISION SUPPORT (Sustainable Spatial Decision Support System S-SDSS)**				
	Strategic Focus	Restoration of urban voids & ecological corridor design			
	OUTPUT	Sustainable planning and policy recommendations		Regional, Master, and Implementation Scale Planning Guide	

Figure 2. Operational protocol and processing hierarchy of the proposed S-SDSS framework (synthesized by the author based on the systematic review).

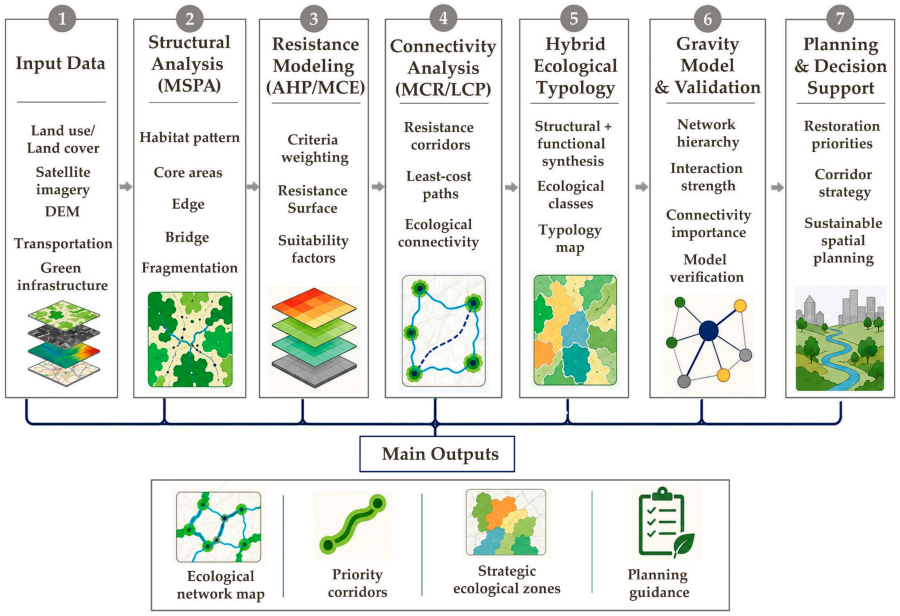

Figure 3. Methodological sequence and analytical components of the proposed S-SDSS framework.

5.1. Methodological Framework and Data Input

The proposed Sustainable Spatial Decision Support System (S-SDSS) is founded on a standardized data input structure designed to integrate ecological, spatial, and planning-related datasets within a common analytical framework [14,58].

Figure 4 presents the overall conceptual structure of the Hybrid Ecological Typology Development process and illustrates how habitat suitability analysis [15], the Analytic Hierarchy Process (AHP) [16,45], Morphological Spatial Pattern Analysis (MSPA) [14], Minimum Cumulative Resistance (MCR) [7], Least-Cost Path (LCP) [17], and Gravity Modeling (GM) [31] are integrated within the proposed framework.

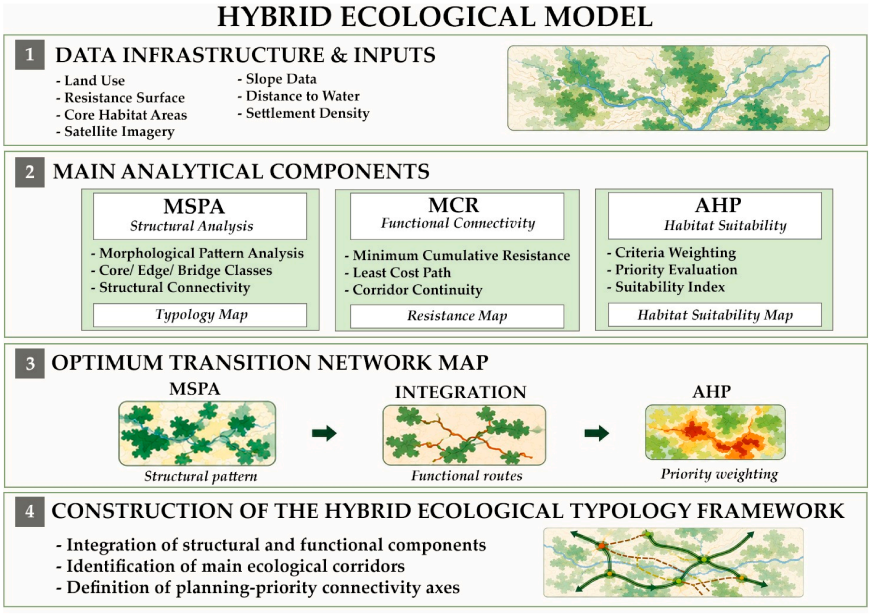

Figure 4. Hybrid Ecological Typology development.

To enhance methodological transparency, Figures 4–9 provide schematic representations of the principal analytical components, developed based on the systematic literature review [23,24]. Figure 5 illustrates the MSPA-based structural connectivity analysis [14,29,30].

Figure 6 presents the MCR-based resistance modeling process [7,15]. Figure 7 depicts the LCP-based corridor delineation workflow [17,36]. Figure 8 shows the AHP decision hierarchy for habitat suitability modeling [16,45]. Figure 9 illustrates the Gravity Model-based network hierarchy and validation procedure [31,51].

The synthesis of these complementary analytical components is presented in Figure 3, which illustrates the integrated hybrid ecological modeling workflow and the generation of planning-oriented outputs within the S-SDSS framework.

The framework is structured around four fundamental principles:

1. **Standardization of connectivity metrics:** The effectiveness of ecological network analyses depends on aligning connectivity metrics with the relevant planning scale (e.g., basin, regional, or urban) [6,43]. By incorporating a flexible set of indicators associated with ecosystem services [55], the S-SDSS supports a goal-oriented evaluation structure rather than a uniform analytical procedure [16,45,58,59].
2. **Climate change adaptation compatibility (CMIP6):** The proposed framework is designed as a forward-looking decision support system rather than a static landscape analysis. In this context, CMIP6 climate scenarios [3] provide a conceptual data layer to ensure that planning outputs remain robust under future climatic conditions, including temperature shifts and hydrological changes [3,4,57,60].
3. **Structural and functional hybrid approach:** To overcome the limitations of purely morphological or solely species-based analyses [14,15,61], the S-SDSS integrates structural and functional connectivity within a unified decision framework [40,41]. This hybrid approach simultaneously evaluates landscape configuration and species movement potential [28].
4. **UN 2030 agenda and strategic alignment:** The framework is designed to translate technical outputs into planning-relevant policy guidance. By aligning with the United Nations Sustainable Development Goals (SDGs 11, 13, and 15) [60], the S-SDSS connects local planning decisions to broader sustainability objectives [1,2,4,11,62,63].

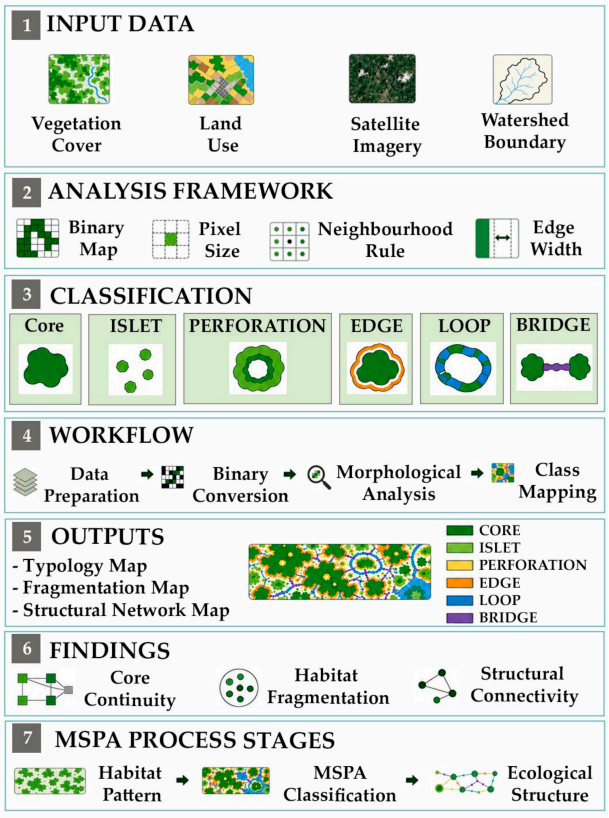

Figure 5. Morphological Spatial Pattern Analysis (MSPA).

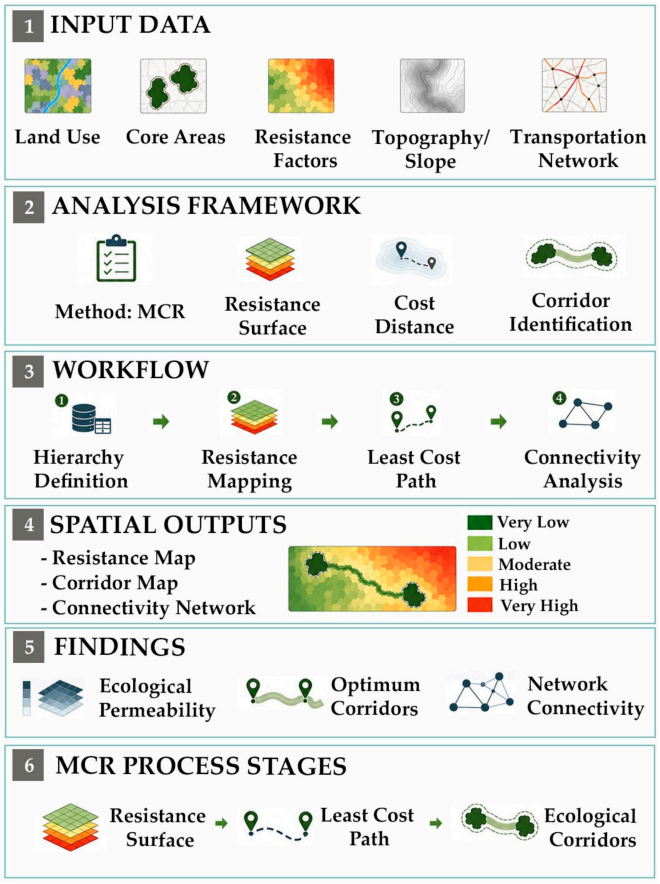

Figure 6. Minimum Cumulative Resistance Analysis (MCR).

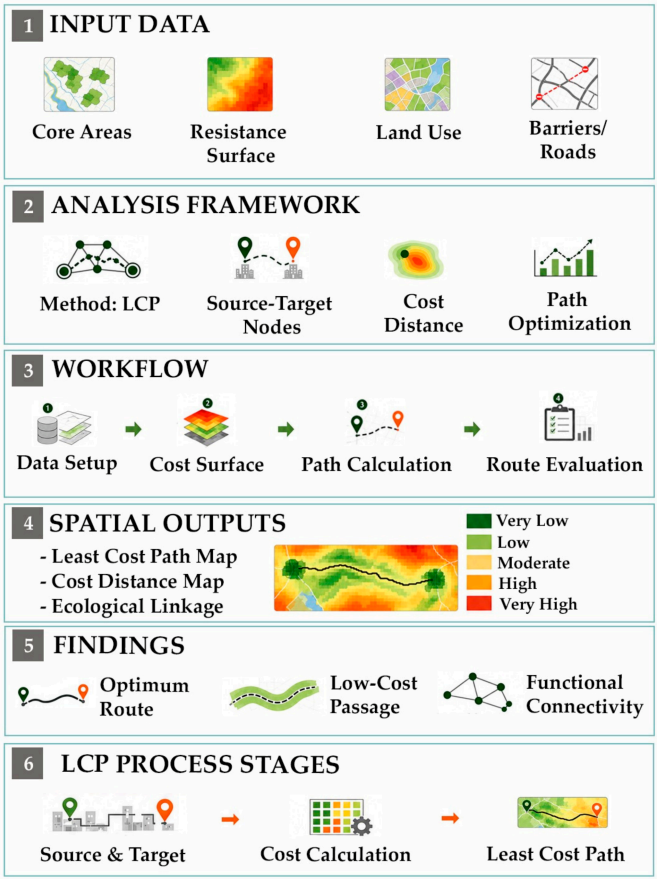

Figure 7. Least-Cost Path Analysis (LCP).

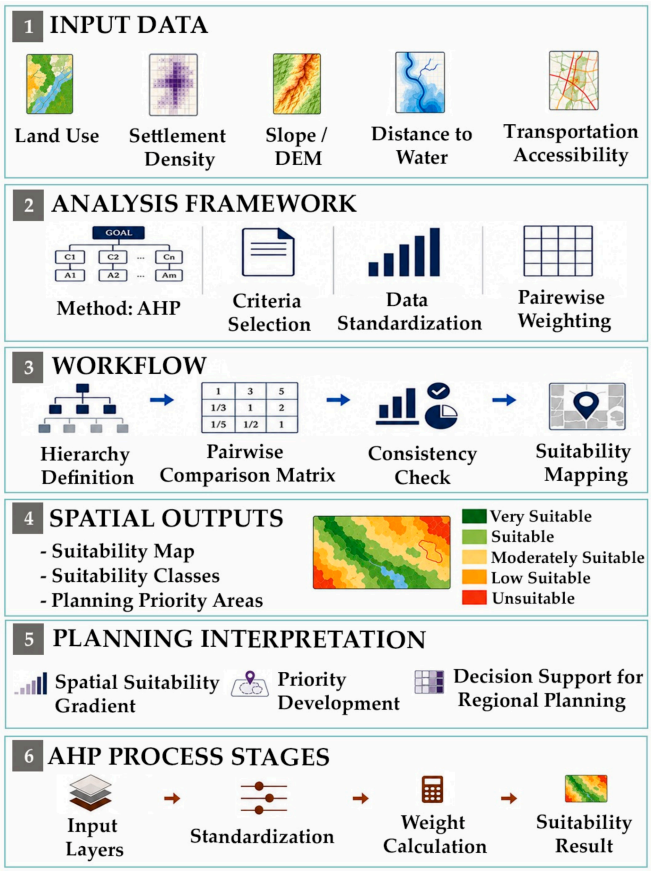

Figure 8. Analytic Hierarchy Process (AHP) modeling.

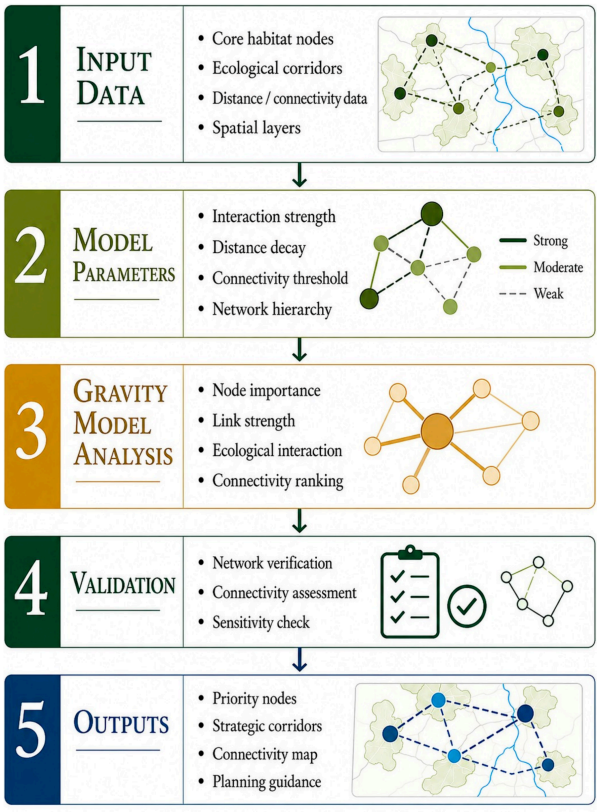

Figure 9. Gravity Model (GM) and validation (network hierarchy).

Table 5 synthesizes the operational blocks of the proposed S-SDSS framework, including the associated analytical methods, software environments, and key literature sources that support each component.

Table 5. Operational blocks of the proposed S-SDSS framework: methodological components, analytical tools, and literature synthesis.

Operational Blocks	Method/Software Utilized	Literature Synthesis and References
Input Data	**Data harvesting and validation:** Satellite imagery procurement.	Selection of high-resolution datasets for urban-regional alignment and classification accuracy. Establishing the spatial baseline for national ecological security [4,11,30,53,58,64–67].
Structural Analysis (MSPA)	**MSPA segmentation:** Detection of core, edge, and bridge elements via mathematical morphology.	Identification of structural connectivity elements based on pixel-based segmentation and landscape geometry [14,29,30,53,61,62].
Resistance Modeling	**AHP and MCE execution:** Weighting of resistance factors and anthropogenic pressures.	Resolving multi-criteria decision conflicts through hierarchical consistency and landscape permeability studies [15–17,33,39,41,45,68].
Least-Cost Path (LCP)	**Cost-surface simulation:** Modeling of cumulative resistance and potential movement paths.	Modeling of cost surfaces to determine the ease of ecological movement across modified urban landscapes [17,19,32,43,68,69].
Connectivity Synthesis	**Functional simulation (MCR/LCP and CT):** Probabilistic current density and dispersal route analysis.	Simulation of functional corridors and "paths of least resistance" for regional biodiversity continuity [1,7,10,12,13,19,20,25,32,40,41,70].
Gravity Model (GM)	**Interaction strength ranking:** Prioritization of ecological hubs and network backbones.	Quantification of interaction strength between strategic hubs and numerical proof of node importance [8,18,20,31,51,71].
Model Validation	**Performance verification:** Sensitivity testing and predictive power via AUC-ROC.	Minimizing uncertainty through statistical validation, ROC performance, and parametric stability tests [27,33,34,38,47–49,62,72–74].
Planning Output	**S-SDSS implementation:** Translation of analytical maps into actionable urban planning policies; decision support. Hybrid Typology (T1–T5).	Aligning analytical outputs with sustainable spatial future guidelines and UN Sustainable Development Goals [1,2,4,8,20,25,38,60,75–79].

5.2. Operational Workflow of the S-SDSS Framework

The proposed S-SDSS framework is operationalized through five fundamental analytical layers that process standardized ecological and spatial data through a hierarchical workflow to generate planning-oriented decision outputs:

Layer 1: Structural analysis (MSPA): Numerically identifies the geometric capacity of the landscape [14,30,80].

Layer 2: Resistance modeling (MCE-AHP): A surface representing anthropogenic pressure and topographic resistance, weighted through expert opinion [15,16,45].

Layer 3: Functional connectivity (MCR-LCP): Utilizes LCP algorithms to simulate movement potential and identify optimal ecological routes [17,36,43,81].

Layer 4: Network hierarchy (Gravity Model): Calculates the interaction strength between nodes to prioritize corridors within the overall network [20,31,51,76].

Layer 5: Model validation and policy integration: Validates the framework's sensitivity via AUC/ROC and translates findings into spatially explicit planning boundaries and zoning recommendations [11,20,27,38,48].

The final output of the S-SDSS framework is the generation of a Spatial Intervention Matrix, which categorizes the landscape into five distinct ecological typologies (T1–T5) (Table 6). This classification system goes beyond traditional zoning by aligning technical connectivity metrics with specific planning priorities such as biodiversity conservation [1,82], connectivity enhancement [40,83], and urban resilience [84,85]. Each typology serves as a decision-making filter for determining the intensity and nature of spatial interventions, ranging from absolute conservation in core habitats to Low Impact Development (LID) in urban buffer zones.

Table 6. Ecological typologies and planning priorities (T1–T5).

Code	Typology Name	Definition/Sensitive Areas	Planning Priority	Intervention Strategy
T1	**Absolute Conservation Area**	Core forests, wetlands, endemic habitats.	Biodiversity conservation.	**Zero intervention:** Construction ban; buffer control [1,20,77,86].
T2	**Restoration Area**	Fragmented habitats, degraded riverbeds, urban voids.	Ecosystem services recovery.	**Active improvement:** Native afforestation; habitat repair [1,77,86].
T3	**Ecological Corridors**	River networks, bridge, and stepping stone links.	Connectivity, genetic flow and species mobility.	**Connectivity:** Ecological bridges; linear green protection [17,40,63,83].
T4	**Sustainable Use Area**	Agricultural lands, pastures, rural fringes.	Human–nature balance.	**Controlled:** Regenerative agriculture; ecotourism [2,87,88].
T5	**Buffer Zone**	Urban boundaries, development pressure zones.	Limiting urban sprawl.	**Low Impact Development (LID):** Green buildings; permeable surfaces [2,26,84,85,88].

The proposed S-SDSS framework enables the development of spatial strategies aligned with the United Nations Sustainable Development Goals (SDG 11 and SDG 15) [11,60]. By focusing on the continuity of ecological flow rather than static conservation areas, the S-SDSS framework makes the resilience of urban ecosystems against temporal changes numerically trackable [20,42,77]. The sensitivity of the framework has been cross-referenced with similar basin studies in the literature and validated through AUC analyses to confirm its methodological validity [38,47–49].

The S-SDSS framework operationalizes the transition from regional ecological security to site-specific urban design through a structured integration protocol (Table 7). This multi-scalar approach ensures that macro-corridors identified at the regional level [42,89] are preserved as functional greenways at the implementation scale [26,90], while micro-scale interventions such as barrier mitigation are guided by technical connectivity parameters [17,91,92]. This integration process occurs at three fundamental levels:

- **Prioritization:** Utilizing numerical data from the Gravity Model, corridors are identified as strategic lines requiring absolute protection [31,51,71].
- **Transfer to planning hierarchy:** The model facilitates a multi-scalar integration by defining ecological cores as "Areas to be Protected for Natural Character" at the macro scale (1/100,000). At the micro scale (1/1000), these findings are directly incorporated into zoning plans as parks, greenways, or "Ecological Transition Zones"—strictly

prohibited from construction—thereby ensuring the legal preservation of connectivity nodes [11,44].

- **Policy recommendations:** The analysis results provide a concrete technical basis for local authorities regarding land acquisition strategies, restoration projects, and the determination of sustainable urban growth boundaries [11,56,81,86].

Table 7. Integration protocol of the S-SDSS framework into the planning hierarchy.

Planning Scale	Related Plan Type	Core Contribution of the Model	Strategic Intervention Focal Point
Macro Scale (Regional)	Regional Plan, Environmental Layout Plan	Hierarchical identification of macro-corridors and core areas.	Continuity of the green infrastructure backbone and establishment of ecological security [20,42].
Meso Scale (Master)	1/5000 Master Development Plan	Analysis of ecological thresholds and optimization of construction boundaries.	Time-dependent landscape changes and environmental risk projections [11,93–96].
Micro Scale	1/1000 Implementation Development Plan	Protection of critical connectivity nodes and bottlenecks.	Management of urban development pressure and corridor continuity [26,44,90].
Site/Project Scale	Urban Design and Landscape Projects	Standards for corridor width and buffer zone design.	Mitigation of barrier effects at the micro-scale and biotope improvement [17,81,86,91].

5.3. Typological Proposals and Strategic Inferences

The analytical synthesis of the literature and the operational structure of the proposed S-SDSS framework indicate that the success of ecological networks is strongly dependent on spatial context and scale [6,11]. In this regard, the model translates technical outputs into spatially explicit planning strategies through a typology-based approach [39,40].

5.3.1. Technical Synthesis and Framework Requirements

The transition from analytical modeling to spatial implementation requires the alignment of three fundamental technical components:

- **Resolution precision:** In fragmented urban landscapes, spatial resolution between 10 and 25 m is essential to accurately detect critical elements such as bridges and islets, which often represent the last remaining connectivity components [14,29,30].
- **Functional weighting:** Resistance surfaces should incorporate species-oriented and dynamic parameters rather than relying solely on static expert-based scoring [15,16]. This ensures that identified corridors reflect actual ecological movement potential.
- **Hierarchical continuity:** The prioritization of ecological components must be based not only on size but also on their functional role within the network structure [31,51], ensuring continuity across multiple spatial scales [42,89,92].

5.3.2. Integration of S-SDSS Outputs into Urban Planning Typologies

The S-SDSS framework operationalizes ecological network outputs through five spatial typologies (T1–T5), each corresponding to specific planning priorities and intervention strategies as detailed in Table 6.

These typologies range from absolute conservation areas (T1) and ecological restoration zones (T2) to functional corridors (T3), sustainable use areas (T4), and urban buffer zones (T5). Together, they provide a spatially explicit and planning-oriented classification system that translates complex analytical outputs into actionable land-use decisions.

5.3.3. Strategic Inferences for Spatial Planning

The typology-based structure of the S-SDSS framework provides a direct interface between ecological analysis and planning decision-making. Based on this framework, the following strategic inferences can be derived:

- **Protection of ecological continuity:** Core areas and corridors should be formally integrated into upper-scale spatial plans as ecological security zones to ensure long-term continuity [11,42,97].
- **Re-evaluation of urban voids:** Vacant and underutilized urban areas should be considered as potential ecological stepping stones rather than development reserves, contributing to network integrity [26,77].
- **Multi-scalar planning integration:** Ecological network outputs must be systematically transferred from regional-scale strategies to local implementation plans, ensuring consistency across planning hierarchies [44,89,93].
- **Resilience-oriented spatial strategies:** Planning approaches should incorporate adaptive mechanisms to respond to environmental changes, ensuring the long-term functionality of ecological networks [2,4,79,84].

6. Conclusions and Recommendations

This study demonstrates a clear methodological transition in ecological network modeling, shifting from fragmented, single-method approaches toward integrated, multi-component frameworks [20,25,34]. By systematically synthesizing the literature and addressing key operational gaps, the proposed Sustainable Spatial Decision Support System (S-SDSS) establishes a structured and scalable conceptual framework for supporting spatial planning decisions [11,42,70]. The proposed hybrid typologies (T1–T5) provide a direct interface between complex ecological data and statutory planning processes, ensuring that biodiversity conservation is not merely an environmental goal but a legal and spatial constraint in urban development [76,78,85,97].

6.1. Methodological Contributions

The primary contribution of this research lies in the development of a unified analytical framework that integrates structural and functional connectivity within a single decision support system [9,12,17]. By combining Morphological Spatial Pattern Analysis (MSPA) [14], resistance-based modeling (MCR/LCP) [7,17], and network prioritization through the Gravity Model [31], the proposed approach overcomes the limitations of isolated methodologies [19,20,92]. The framework operates as a hybrid analytical structure in which a sequential processing workflow and a unified output generation system are combined. Each analytical stage directly conditions the subsequent one, and all outputs converge within a common typological classification system that produces Hybrid Ecological Typologies (T1–T5) as its principal added value—planning-oriented categories that simultaneously reflect structural habitat geometry, landscape resistance, movement potential, and corridor prioritization, and that cannot be generated through any individual method alone.

In conclusion, in an era where habitat fragmentation has become a global crisis [1,46], the proposed S-SDSS framework suggests that ecological networks not only protect biodiversity but also constitute the fundamental infrastructure of resilient cities [60,79]. This study has demonstrated that the ecological potential of urban voids has been merged into a single framework, combining the geometric precision offered by MSPA [61] with the ecological reality provided by experts [40,77]. This synthesis represents a holistic planning revolution that transforms urban void spaces into strategic and functional components of the ecological network [14,33]. In light of the synthesized findings, five core ecological typologies (T1–T5)

are proposed within the context of sustainability (Table 7). Based on each identified typology, the current natural structure of the basin and anthropogenic pressures can be evaluated through numerical values, areal sizes, and spatial distributions [46,75]. In this framework, the hierarchical ranking derived from the Gravity Model serves as a strategic prioritization manual for metropolitan green infrastructure investments, guiding local authorities in resource allocation [31,51,71]. The methodological differences and the ecological added value provided by the proposed connectivity-oriented S-SDSS framework compared to traditional area-oriented approaches are presented comparatively in Table 8.

Table 8. Comparison between the traditional approach and the proposed S-SDSS framework.

Analysis Criterion	Traditional Approach (Area-Oriented)	Proposed S-SDSS Framework (Connectivity-Oriented)	Ecological Output/ Contribution
Prioritization	Size-dependency; large patches only [1,25,46].	Parametric Weighting + Expert Opinion (Area + Location + Quality) [15,16,45].	Strategic discovery of small/key areas [77].
Decision Basis	Static, single-scenario [19,46].	Multi-Threshold and Boolean Logic [16,45].	Legally grounded, realistic planning base [15,26].
Connectivity Metric	Static Euclidean distance [12,13].	Dynamic Resistance (MCR-LCP) [15,17,36,69].	Identification of functional routes [7,36,83].
Network Hierarchy	Ignored interactions [43].	Graph Theory (Node interactions) [18,32,43,51].	Numerical proof of network backbone [8,31,38–40,71].
Landscape Pattern	Isolated reserves [68].	Network Theory (MSPA integration) [14,40].	Survival in fragmented textures (AUC > 0.90) [38,48,49,53].

6.2. Methodological Synthesis and Addressing Literature Gaps

Findings obtained from the literature review indicate a distinct methodological divergence between structural and functional connectivity in ecological network modeling. It has been identified that a large portion of existing publications focus either solely on morphological (MSPA) or solely on resistance-based (MCR) analyses [7,14,21], which fails to fully reflect the dynamic structure of the ecosystem. To bridge this gap, this article presents a conceptual framework that synthesizes the approaches of Vogt et al. [14] and Knaapen et al. [13]. Uncertainties in resistance parameterization are frequently criticized due to the subjectivity of expert opinion and dependence on single scenarios [15,27].

The multi-scenario sensitivity analysis offered by the proposed model aims to increase methodological reliability and species-based calibration precision by minimizing the margin of error in parameter assignments. At this point, the originality of the framework lies in linking the success of technical algorithms (MSPA/LCP/MCR) not just to automated data, but to a calibration process refined through "Expert Opinion" and "Parametric Weighting" [16,27,45]. Unlike static frameworks in the literature, S-SDSS transforms expert experience from a random input into a scientific filter, ensuring that the technical analysis aligns with ecological reality.

The findings further indicate that ecological network analyses are evolving from static area-based calculations toward dynamic network hierarchies. Integrating structural patterns (MSPA) with functional processes (MCR–LCP) ensures that ecological networks are defined not only as formal spatial entities but also as dynamic and functional systems. Moreover, increasing levels of methodological integration significantly enhance the transferability of analytical outputs into spatial planning and policy frameworks [9–11,42].

6.3. Integration into the Planning Hierarchy and Policy

A key outcome of the S-SDSS framework is its capacity to translate analytical results into spatial planning practices across multiple scales [11,44,93]. The framework facilitates the transfer of ecological network components from regional strategies into local implementation tools, ensuring continuity between macro-level planning and site-specific interventions [42,96].

By embedding ecological connectivity into planning hierarchies, the framework supports the development of green infrastructure systems that are both spatially coherent and policy-relevant [5,44,75]. This approach contributes to the alignment of planning decisions with sustainability objectives, particularly in relation to ecosystem continuity, urban resilience, and controlled spatial development [2,60,79].

6.4. Framework Limitations

Despite its comprehensive structure, the proposed framework is subject to several limitations. The reliance on expert-based weighting methods in resistance modeling introduces a degree of subjectivity, which may influence model outputs depending on the selected criteria and evaluation process [15,16,45].

In addition, the accuracy of the framework is highly dependent on data resolution and quality [29,30]. High-resolution spatial datasets are essential for identifying critical connectivity elements, particularly in fragmented urban environments where small-scale features play a significant role.

Furthermore, the limited availability of empirical validation data, such as species movement observations, remains a constraint for fully verifying model outputs [28,56]. Addressing these limitations requires the integration of more robust validation techniques and data sources in future applications [27,38].

6.5. Future Research and Strategic Outlook

Future research should focus on enhancing the objectivity and adaptability of ecological network models. The integration of data-driven approaches, including machine learning techniques, offers significant potential for reducing subjectivity in resistance parameterization and improving predictive accuracy [38].

In parallel, the development of dynamic monitoring systems based on real-time data sources, such as remote sensing technologies and environmental sensors [61,65], can transform ecological network modeling into a continuous decision support process. This transition would enable planners to respond more effectively to changing environmental conditions and urban dynamics.

From a strategic perspective, advancing the integration of ecological connectivity into legal and institutional planning frameworks remains a critical priority. Ensuring that analytical outputs are directly embedded into regulatory tools will strengthen the practical impact of ecological network models and support the long-term sustainability of spatial systems as conceptualized in the dynamic monitoring framework.

Beyond the theoretical framework offered by the S-SDSS model, the establishment of a "Dynamic Ecological Network Monitoring and Audit System" is proposed as a strategic necessity for the system's sustainability. When successful global applications are examined the habitat fragmentation tracking carried out by the European Union via the Copernicus Land Monitoring Service (CLMS) and China's 24/7 satellite surveillance via the Big Data-supported Ecological Redline Policy have achieved high success in minimizing anthropogenic pressures [65,66].

To translate this global success into local action, the S-SDSS framework offers specific policy recommendations. It is suggested that municipalities integrate these hybrid typolo-

gies (T1–T5) into statutory land-use plans as legal "Ecological Protection Zones" [11,26,94]. Furthermore, local authorities should implement green infrastructure incentives, such as density bonuses, to preserve critical stepping stones identified by the framework [5,77].

In this context, testing the developed framework in different biogeographic regions and climate scenarios within the scope of CMIP6 projections will strengthen the system's adaptation capability. It is of critical importance for future studies to manage the conflict between ecological resilience and urban growth pressure through IoT and remote sensing-based real-time data flows.

Specifically, collecting this data within a National GIS Network will transform the system from a static analysis into a live monitoring mechanism. Through this integration, threats such as illegal construction or uncontrolled sprawl in ecological corridors can be monitored instantaneously via a centralized national network, and the impact of local governments' zoning decisions on network continuity can be verified at a central level [64].

To operationalize this vision, four strategic directions are proposed:

- **Ecological digital twins:** Establishing "Digital Twin" systems that simulate the impact of urban interventions on connectivity metrics before physical implementation. This allows harmful projects to be blocked before they reach the implementation phase [64].
- **Centralized and continuous satellite surveillance (24/7):** As seen in the Copernicus (EU) examples, instantaneous monitoring of anthropogenic pressures on the "Ecological Redline" through the integration of satellite data and Artificial Intelligence.
- **Climate-sensitive adaptive management:** Establishing a flexible management cycle based on the "Plan–Implement–Monitor–Learn" principle, where corridor routes are dynamically updated according to future climate scenarios via CMIP6 projections [3].
- **National GIS and legislative integration:** Adding a centralized "Ecological Security Approval" mechanism to legal legislation to audit the impact of local zoning decisions on national ecological network continuity.

This cycle, which is the operationalized version of the analytical S-SDSS framework detailed in Section 5, symbolizes the construction of a live Ecological Security Network that adapts instantaneously to landscape dynamics through satellites and sensors (Figure 10).

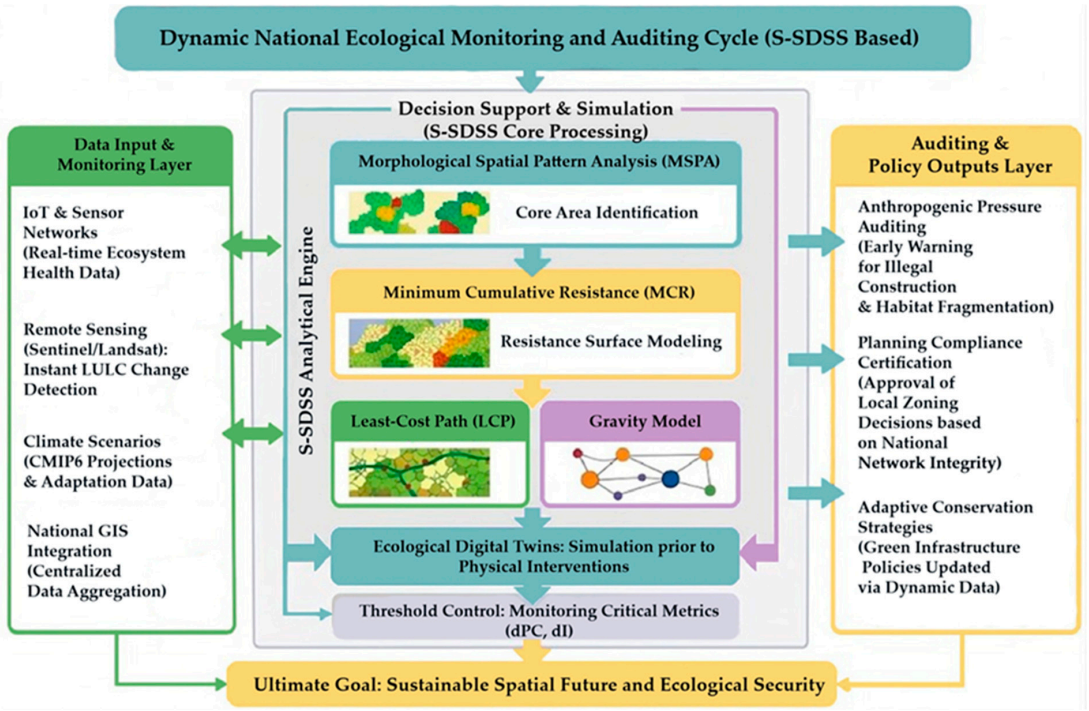

Figure 10. Operational cycle of the S-SDSS-based dynamic ecological monitoring system.

In conclusion, the S-SDSS framework introduces a connectivity-oriented paradigm that prioritizes ecological interactions over static spatial configurations. The framework demonstrates that small but strategically located stepping stones are as critical as large habitat patches for ensuring biodiversity continuity. By bridging the gap between analytical precision and planning implementability, S-SDSS provides a robust and transferable conceptual roadmap for spatial planning. The transition from static mapping to a continuously monitored ecological management system represents a necessary advancement for safeguarding basin ecosystems under increasing climate and urbanization pressures.

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