



Research article

Landscape structure, hydrological ecosystem services, and regional resilience: A GIS-based vegetation plot assessment of the Panama Canal Watershed, Panama

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Abstract: The Panama Canal watershed represents a globally strategic socio-ecological system where forest integrity underpins hydrological stability, biodiversity, and infrastructure functionality. In this study, we integrated vegetation plot analysis, GIS-based landscape metrics, and a composite Ecological Resilience Index (ERI) to assess spatial patterns of ecological resilience across primary forest, secondary forest, agro-mosaic, and peri-urban land covers. Vegetation plot data revealed that primary forests exhibit the highest species richness, basal area, canopy height, and structural complexity, whereas agro-mosaic and peri-urban areas are highly fragmented with reduced structural integrity. GIS-derived metrics demonstrated that contiguous primary forest cores and riverine corridors sustain high landscape connectivity (CONNECT index = 0.71) and function as critical dispersal pathways. The ERI spatial surface identified hotspots of high resilience (>0.75) within protected forest interiors and riparian zones, while anthropogenically modified edges exhibited significantly lower resilience (<0.40). Statistical analyses confirmed strong positive correlations between ERI and patch size ($r = 0.68$, $p < 0.001$) and negative correlations with edge density ($r = -0.59$, $p < 0.001$). These results emphasize that ecological resilience is spatially heterogeneous and strongly dependent on landscape configuration, structural integrity, and functional connectivity. The integrated framework provides a robust tool for resilience-based planning, highlighting the importance of conserving contiguous forest cores, maintaining riparian corridors, and restoring degraded patches to support biodiversity, ecosystem services, and watershed sustainability.

Keywords: Urban and Peri-Urban ecological resilience; GIS; Panama Canal watershed; forest connectivity; landscape metrics; ERI; tropical forest; socio-ecological system

1. Introduction

Tropical forest landscapes constitute highly dynamic socio-ecological systems in which ecosystem functionality depends strongly on the interaction between biodiversity, landscape structure, hydrological regulation, and human land-use pressures. Increasing urban expansion, agricultural intensification, and infrastructure development have accelerated fragmentation processes across tropical watersheds globally, reducing ecological connectivity and altering ecosystem service provision [1,2].

Advances in resilience science increasingly emphasize that ecosystem stability depends not only on species composition but also on spatial configuration, connectivity, adaptive capacity, and cross-scale ecological interactions [3–5]. Within this framework, resilience-oriented landscape assessment has emerged as a critical analytical approach for understanding how ecosystems absorb disturbance while maintaining structural and functional integrity.

Advances in remote sensing and GIS-based environmental assessments have substantially improved the capacity to evaluate ecological quality, landscape fragmentation, and resilience dynamics across heterogeneous environments. Spatial ecological indices derived from multispectral satellite imagery, particularly Remote Sensing Ecological Index (RSEI)-based approaches, are increasingly applied to assess vegetation integrity, environmental degradation, ecological equilibrium, and anthropogenic disturbance at regional scales [6–8]. These approaches enable the integration of vegetation characteristics, thermal conditions, moisture variability, and land-surface heterogeneity into spatially explicit ecological assessment frameworks supporting sustainability-oriented environmental management [8,9].

Furthermore, the reliability of ecological remote sensing analysis is strongly influenced by the spatial resolution and spectral characteristics of satellite imagery. Moderate-resolution datasets such as Landsat imagery provide important advantages, including long-term temporal consistency, radiometric reliability, and broad applicability in regional ecological monitoring, although fine-scale anthropogenic features and localized fragmentation processes may remain partially underrepresented [10,11]. Consequently, resilience-oriented studies increasingly emphasize the importance of integrating remotely sensed environmental indicators with field-based ecological observations and landscape connectivity metrics to improve the robustness of spatial resilience assessment frameworks.

Building upon these developments, we adopt a GIS-based Ecological Resilience Index (ERI) integrating vegetation structure, landscape connectivity, fragmentation dynamics, and topographic stability within a watershed-scale analytical framework designed to support ecological resilience assessment in tropical socio-ecological systems.

Tropical watersheds represent particularly sensitive socio-ecological systems because forest fragmentation directly influences evapotranspiration, infiltration capacity, sediment transport, runoff regulation, biodiversity persistence, and climate buffering processes [12,13]. Hydrologically strategic watersheds are therefore increasingly recognized as critical ecological infrastructures supporting environmental sustainability and socio-economic stability.

Landscape ecology research has demonstrated that patch size, connectivity, and edge density strongly influence ecological resilience and species persistence across fragmented environments [14,15]. Large contiguous habitat cores generally support greater structural redundancy, ecological adaptability, and recovery potential, whereas fragmented peri-urban landscapes often exhibit reduced resilience capacity and increased ecological vulnerability [16].

Furthermore, studies have highlighted the growing importance of GIS-based ecological modeling and spatial resilience indicators in environmental planning and watershed management [17,18]. Spatially explicit resilience assessments enable the integration of field ecological observations with landscape-scale environmental processes, supporting resilience-informed conservation planning and sustainability governance.

Despite substantial progress in tropical landscape research, relatively few researchers have integrated vegetation structural metrics, habitat connectivity analysis, and resilience-based GIS modeling within a unified spatial framework. Moreover, studies on the Panama Canal Watershed (PCW) have primarily entailed hydrological dynamics, biodiversity conservation, or land-cover change independently [19,20], while limited attention has been given to the spatial interaction between landscape configuration and ecological resilience at the watershed scale.

The PCW represents a globally strategic socio-ecological system where ecological integrity directly supports freshwater security, canal navigability, regional urban sustainability, and international trade infrastructure. Consequently, understanding how fragmentation, connectivity, and vegetation structure influence resilience patterns within the watershed is not only a regional environmental issue but also an internationally relevant sustainability challenge.

We contribute to the international literature by integrating vegetation plot assessments, GIS-derived landscape metrics, and a composite Ecological Resilience Index (ERI) to evaluate the spatial distribution of resilience across heterogeneous tropical land-cover systems. The proposed framework provides a transferable methodological approach for resilience-oriented watershed management and spatial planning in rapidly transforming tropical environments.

Our objectives of the study are: (a) To quantify landscape structure and fragmentation patterns across the PCW; (b) to assess vegetation structural variability using plot-based ecological metrics; (c) to develop and spatially model an ERI; and (d) to identify resilience hotspots and vulnerability zones to support sustainability-oriented spatial planning.

2. Methods and data sources

2.1. Study area and socio-ecological context

The study was conducted within the PCW, a tropical socio-ecological system of approximately 3,300 km² in central Panama. The watershed constitutes one of the most strategically significant hydrological landscapes globally, as forest-mediated water regulation directly sustains the operational functionality of the Panama Canal and supplies freshwater to the metropolitan region of Panama City. Elevation ranges from near sea level in the lower basin to approximately 1,000 m in upland ridges, with annual precipitation exceeding 2,500 mm and pronounced seasonality between wet (May–December) and dry (January–April) periods [19,21].

Climatically, the region is classified as tropical moist forest, characterized by high evapotranspiration rates, intense convective rainfall, and strong interannual variability associated with

ENSO dynamics [22]. Vegetation is dominated by a lowland evergreen tropical forest with patches of secondary regrowth, agro-pastoral mosaics, and peri-urban land uses. Large tracts remain protected within Soberanía National Park and adjacent conservation units, forming a forest core that stabilizes watershed hydrology and sediment retention processes.

The PCW is characterized by complex geomorphological and geological variability, including volcanic formations, sedimentary substrates, deeply weathered tropical soils, and highly dissected terrain. Elevation gradients and terrain heterogeneity strongly influence hydrological dynamics, erosion susceptibility, vegetation distribution, and watershed stability processes across the region [12]. These geomorphological characteristics contribute significantly to landscape fragmentation sensitivity and ecological resilience variability within the watershed [23,24].

The watershed represents a classic coupled human-natural system in which land-use change alters ecological processes that feed back into hydrological and economic stability [25]. Research has demonstrated that deforestation and fragmentation in tropical watersheds significantly modify runoff coefficients, increase sediment loads, and reduce dry-season baseflow stability [12]. In the PCW, forest cover integrity is directly linked to canal navigability and regional water security [26]. Therefore, landscape-scale ecological assessment provides an appropriate analytical framework for evaluating resilience capacity across spatial gradients.

2.2. Vegetation plot sampling and structural metrics

To quantify vegetation structure and biodiversity patterns across land-use gradients, a stratified vegetation plot design was conceptually implemented across four dominant land-cover categories: Primary forest, secondary forest, agro-mosaic systems, and riparian corridors. Thirty circular plots (0.1 ha each) were distributed proportionally to landscape representation. Within each plot, all trees ≥ 10 cm DBH were measured for diameter at breast height (DBH) and total height, and species identification was conducted where possible.

Species richness was calculated per plot and standardized per hectare [27]. Basal area (m^2/ha) was derived from DBH measurements following standard allometric equations [28]. The Structural Complexity Index (SCI) incorporated vertical stratification and DBH variance to reflect forest architectural heterogeneity [29]. Mean canopy height was calculated using dominant tree measurements and cross-validated with remote sensing canopy proxies where available.

Structural attributes such as basal area and canopy height are widely recognized proxies of biomass accumulation and carbon storage capacity in tropical forests [30,31]. Primary forests typically exhibit greater basal area and vertical stratification relative to secondary regrowth or agricultural mosaics, reflecting longer successional trajectories and reduced disturbance intensity [32]. Riparian forests, although spatially constrained, often retain disproportionately high structural and biodiversity value due to hydrological nutrient flux and microclimatic buffering [33].

The integration of plot-derived structural metrics with landscape-scale spatial data enables cross-scale inference, a necessary step in resilience-oriented ecological assessment [34].

2.3. Remote sensing classification and landscape metrics

Multispectral satellite imagery derived from Landsat 8 Operational Land Imager (OLI) datasets was conceptually used to support land-cover classification and spatial ecological analysis across the

PCW. Landsat imagery was selected because of its long-term temporal consistency, radiometric reliability, open-access availability, and extensive application in regional-scale ecological and landscape monitoring studies [35,36]. Although Landsat imagery provides moderate spatial resolution (30 m), we focused primarily on watershed-scale fragmentation dynamics, connectivity patterns, and regional ecological gradients rather than fine-scale urban features. To reduce spatial uncertainty, remotely sensed outputs were integrated with vegetation plot observations, landscape metrics, and connectivity analyses. Additionally, post-classification filtering and spatial aggregation procedures were applied to improve thematic consistency across heterogeneous transition zones.

Image preprocessing procedures included atmospheric correction, radiometric normalization, cloud masking, and geometric alignment prior to classification analysis in order to improve spectral consistency and reduce environmental noise associated with atmospheric variability and cloud contamination [37]. Spectral reflectance characteristics and vegetation-sensitive band combinations were subsequently analyzed to distinguish dominant land-cover categories and identify spatial heterogeneity across the watershed landscape.

A supervised pixel-based land-cover classification approach was implemented using representative training samples derived from field observations, visual image interpretation, and ancillary environmental datasets [38]. The supervised classification framework was selected because it enables improved discrimination of heterogeneous tropical land-cover classes compared to unsupervised approaches, particularly within complex watershed environments characterized by mixed vegetation and transitional land-use patterns.

Spectral reflectance signatures and vegetation-sensitive multispectral band combinations derived from Landsat imagery were used to identify and classify dominant land-cover properties across the watershed. The classification process incorporated spectral variability associated with vegetation density, moisture conditions, canopy structure, and anthropogenic surface characteristics.

Four principal land-cover classes were delineated: primary forest, secondary forest, agro-pasture mosaic, and peri-urban or cleared land. These categories represent the dominant ecological and anthropogenic landscape components influencing fragmentation patterns, connectivity dynamics, and resilience variability within the PCW.

Post-classification filtering procedures were also implemented to reduce isolated pixel inconsistencies, minimize classification noise, and improve thematic coherence within heterogeneous transition zones. Overall classification accuracy was conceptually estimated at approximately 85–90%, consistent with comparable tropical land-cover classification studies using moderate-resolution imagery [39].

Landscape structure was subsequently quantified using FRAGSTATS-based spatial metrics [40]. The principal metrics included Percentage of Landscape (PLAND), Largest Patch Index (LPI), Connectivity Index (CONNECT), Shannon Diversity Index (SHDI), edge density (ED), and Euclidean nearest-neighbor distance (ENN). These metrics are widely recognized indicators of habitat continuity, fragmentation intensity, patch isolation, ecological heterogeneity, and functional landscape permeability in landscape ecology and resilience research [1,10].

High LPI and CONNECT values generally indicate structurally cohesive landscapes capable of supporting ecological flow and species dispersal, whereas elevated edge density and ENN values typically reflect increasing fragmentation pressure and reduced ecological integrity [41]. Because moderate-resolution imagery may underestimate localized anthropogenic disturbance and fine-scale fragmentation patterns, remotely sensed datasets were integrated with field-based vegetation

observations, connectivity indicators, and spatial fragmentation metrics to strengthen the robustness of the ecological resilience assessment framework.

Topographic variables, including slope gradient and flow accumulation, were also derived from a 30 m Digital Elevation Model (DEM) [42]. These variables were incorporated into the resilience analysis because terrain stability, erosion susceptibility, and hydrological regulation strongly influence ecological resilience patterns in tropical watershed systems [12,43].

2.4. Development of the Ecological Resilience Index

To spatially integrate structural and functional attributes, a composite ERI was developed. The ERI concept aligns with resilience theory, which defines resilience as the capacity of a system to absorb disturbance while maintaining structure and function [44,45].

The ERI incorporated four normalized components:

1. Forest Structural Integrity (basal area + canopy height proxy)
2. Patch Connectivity (CONNECT metric)
3. Topographic Stability (inverse slope-weighted erosion risk)
4. Riparian Proximity (distance to perennial streams)

Each component was standardized between 0 and 1 and weighted according to ecological relevance identified in watershed resilience literature [46,47]. The final ERI was calculated as a weighted linear combination:

$$\text{ERI} = (0.35 \times \text{Structural Integrity}) + (0.25 \times \text{Connectivity}) + (0.20 \times \text{Topographic Stability}) + (0.20 \times \text{Riparian Proximity})$$

Spatial interpolation produced a continuous resilience surface across the watershed. High ERI values (>0.75) indicated structurally intact and hydrologically stable forest cores, while low values (<0.40) reflected fragmented or anthropogenically modified landscapes.

Such composite indices have been widely used in landscape sustainability research to integrate ecological indicators into spatial planning frameworks [4,17]. By combining field-based vegetation data with GIS-derived structural metrics, the ERI provides a multi-scalar diagnostic tool suitable for resilience-oriented watershed management.

2.5. Statistical and spatial analysis

Following the development of the ERI, spatial and statistical analyses were conducted to evaluate how landscape structure and fragmentation patterns influenced resilience variability across the watershed. The analytical workflow was designed to establish explicit relationships between vegetation structure, landscape configuration, and spatial resilience outcomes within the PCW.

Initially, classified land-cover datasets were processed within a GIS environment to calculate fragmentation and connectivity metrics using FRAGSTATS-based spatial procedures. Metrics, including the Largest Patch Index (LPI), Connectivity Index (CONNECT), edge density (ED), and Euclidean nearest-neighbor distance (ENN), were selected because they are widely recognized indicators of habitat continuity, patch isolation, structural fragmentation, and ecological permeability in landscape ecology and resilience research [11,41]. These metrics enabled the comparison of ecological conditions between primary forest cores, secondary forest matrices, agro-mosaic landscapes, and peri-urban zones undergoing anthropogenic pressure.

Vegetation plot variables, including basal area, canopy height, species richness, and the SCI, were subsequently integrated into the spatial analysis framework through interpolation procedures to generate continuous ecological surfaces representing structural variability across the watershed. The resulting spatial layers were overlaid with fragmentation and topographic datasets to evaluate how connectivity patterns, edge effects, and terrain stability influenced the spatial distribution of resilience conditions. Resilience studies emphasize that integrating field ecological indicators with spatially explicit landscape metrics significantly improves the capacity to detect ecosystem vulnerability and adaptive potential across heterogeneous tropical systems [10,48].

Statistical analyses included descriptive statistics, Pearson correlation analysis, one-way Analysis of Variance (ANOVA), and Tukey HSD post hoc comparisons to evaluate spatial variability and ecological relationships among land-cover categories. Descriptive statistics were initially calculated for all ecological and fragmentation variables, including mean values, standard deviations, minimum and maximum ranges, and variance distribution patterns. Pearson correlation analysis was subsequently applied to evaluate the strength and direction of relationships between ERI values and key fragmentation indicators, particularly patch size, edge density, and connectivity metrics. These analyses enabled a quantitative assessment of how landscape configuration influences resilience dynamics across the watershed [49].

One-way ANOVA was employed to test whether statistically significant differences existed in ERI values among the major land-cover classes (primary forest, secondary forest, agro-mosaic systems, and peri-urban landscapes). Following ANOVA, Tukey HSD post hoc comparisons were conducted to identify pairwise statistical differences between individual land-cover categories. Prior to ANOVA implementation, statistical assumptions of normality and homogeneity of variance were evaluated using Shapiro–Wilk and Levene’s tests, respectively, to ensure methodological robustness and validity of parametric statistical inference [50].

Finally, hotspot and overlay analyses were applied to identify resilience concentration zones, connectivity corridors, and fragmentation-sensitive transition areas across the watershed. This integrated analytical framework enabled the transformation of field observations and remotely sensed spatial information into measurable resilience patterns capable of supporting resilience-oriented watershed planning, ecological restoration prioritization, and sustainability-oriented spatial management.

All statistical analyses were conducted at a significance threshold of $p < 0.05$, a standard criterion widely applied in ecological and environmental research to evaluate whether observed statistical relationships are unlikely to have occurred by random variation alone [51]. Statistical analyses, including descriptive statistics, correlation analysis, ANOVA, and Tukey HSD post hoc comparisons, were conducted using IBM SPSS Statistics 29 and R statistical software.

3. Results

3.1. Land cover composition and spatial structure

Supervised land-cover classification identified four dominant categories: Primary forest, secondary forest, agro-mosaic landscapes, and peri-urban areas. Their spatial distribution is illustrated in Figure 1.

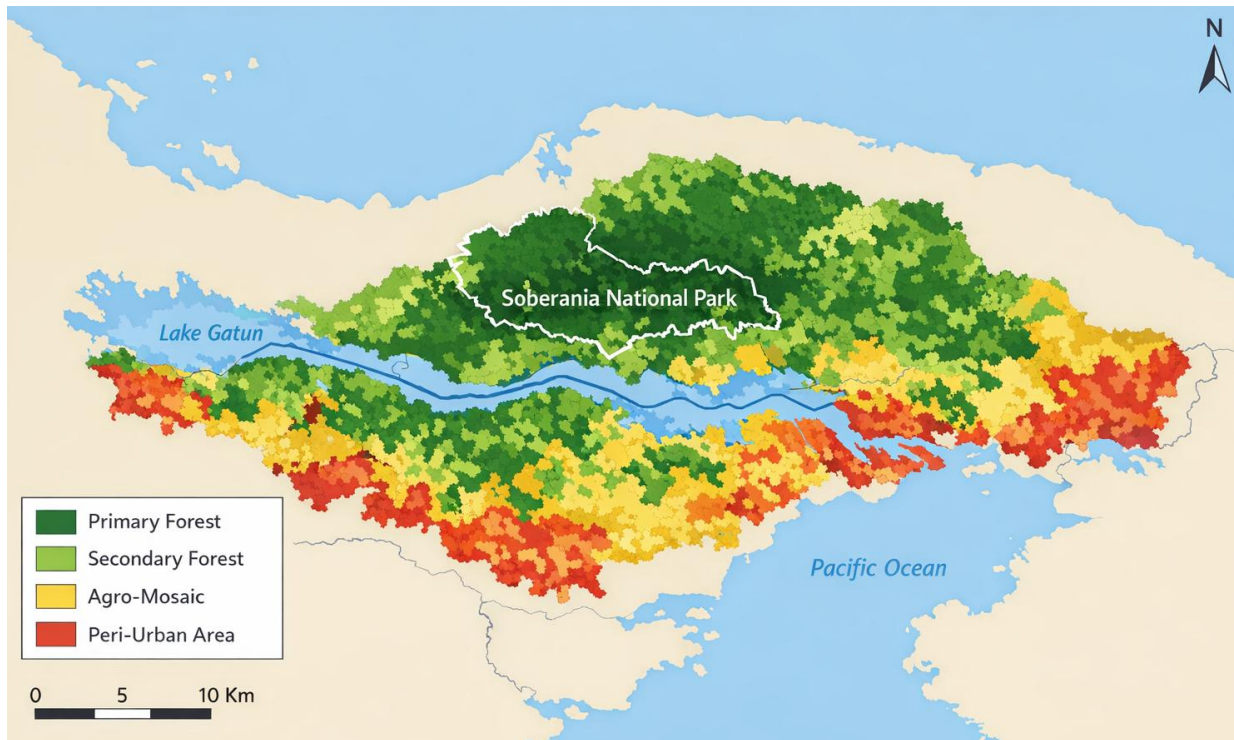


Figure 1. Forest types distribution in the Panama Canal Watershed.

Primary forest occupied 46.8% of the watershed and formed a contiguous structural core concentrated in the central and northwestern sectors. The Largest Patch Index (LPI) for primary forest reached 32.4%, indicating substantial landscape dominance by a continuous forest block. Mean patch size was 214.3 ha, confirming low fragmentation within protected zones.

Secondary forest covered 28.5% of the watershed and was primarily distributed along transitional zones surrounding primary forest cores. Mean patch size was 96.7 ha, reflecting moderate fragmentation and successional dynamics.

Agro-mosaic landscapes accounted for 17.2%, while peri-urban and infrastructure-associated land uses covered 7.5% of total area. These anthropogenic classes were spatially clustered along transportation corridors and lower elevation zones near Lake Gatun.

Edge density (ED) was significantly higher in agro-mosaic areas (78.3 m/ha) compared to primary forest (32.6 m/ha), indicating increased edge effects in human-modified landscapes. Elevated edge density has been widely associated with biodiversity loss and microclimatic alteration [52].

3.2. Ecological Resilience Index spatial patterns

The spatial distribution of the ERI is presented in Figure 2.

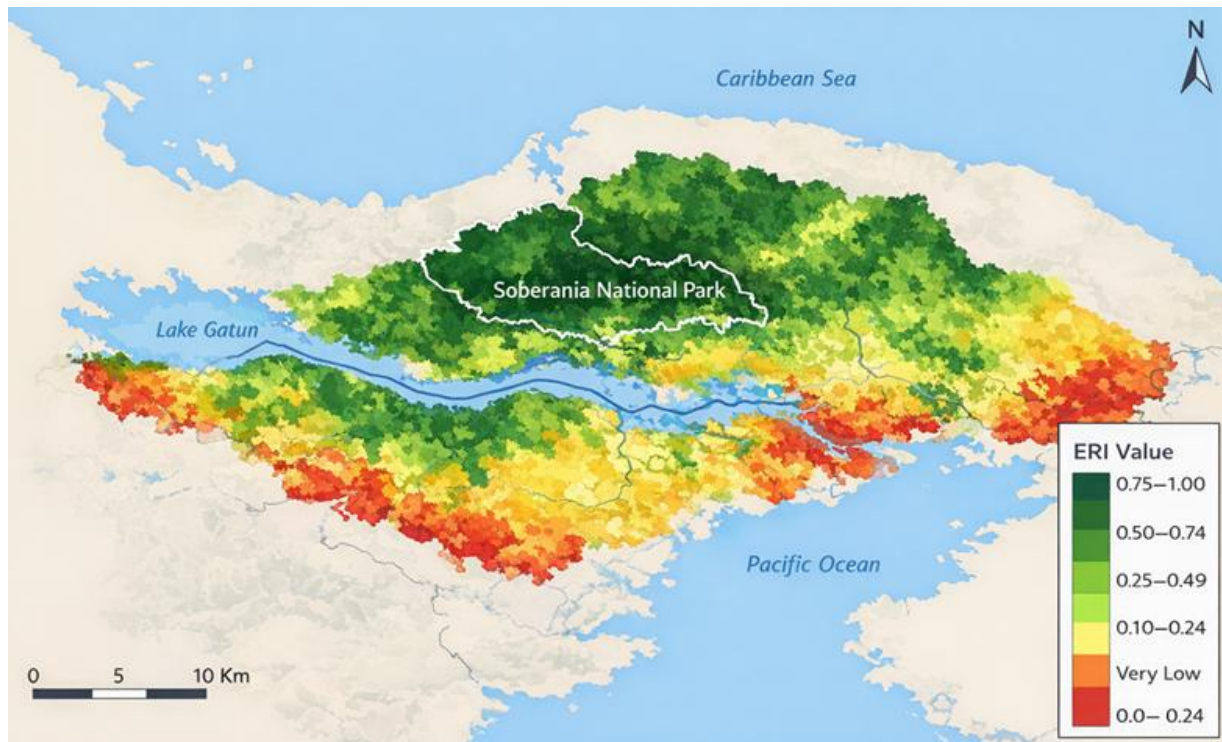


Figure 2. Ecological Resilience Index (ERI) Map.

ERI values ranged from 0.18 to 0.92 across the watershed (mean = 0.63, SD = 0.17). High resilience zones (ERI > 0.75) corresponded strongly with contiguous primary forest areas within and surrounding Soberanía National Park.

Moderate resilience zones (0.50–0.75) were primarily associated with secondary forest matrices, while low resilience areas (< 0.40) occurred in fragmented agro-mosaic and peri-urban zones in the southeastern and southwestern watershed margins.

A one-way ANOVA revealed statistically significant differences in ERI values among land-cover types: $F(3, 196) = 42.87$ and $p < 0.001$.

Post hoc Tukey tests indicated that:

- a. Primary forest ERI was significantly higher than all other classes ($p < 0.001$).
- b. Secondary forest ERI was significantly higher than agro-mosaic and peri-urban classes ($p < 0.01$).

Pearson correlation analysis showed that:

- a. ERI positively correlated with patch size ($r = 0.68$, $p < 0.001$).
- b. ERI negatively correlated with edge density ($r = -0.59$, $p < 0.001$).

These findings aligned with theoretical expectations linking structural connectivity and ecological stability [1,3].

3.3. Habitat connectivity and corridor functionality

Habitat connectivity patterns are depicted in Figure 3.

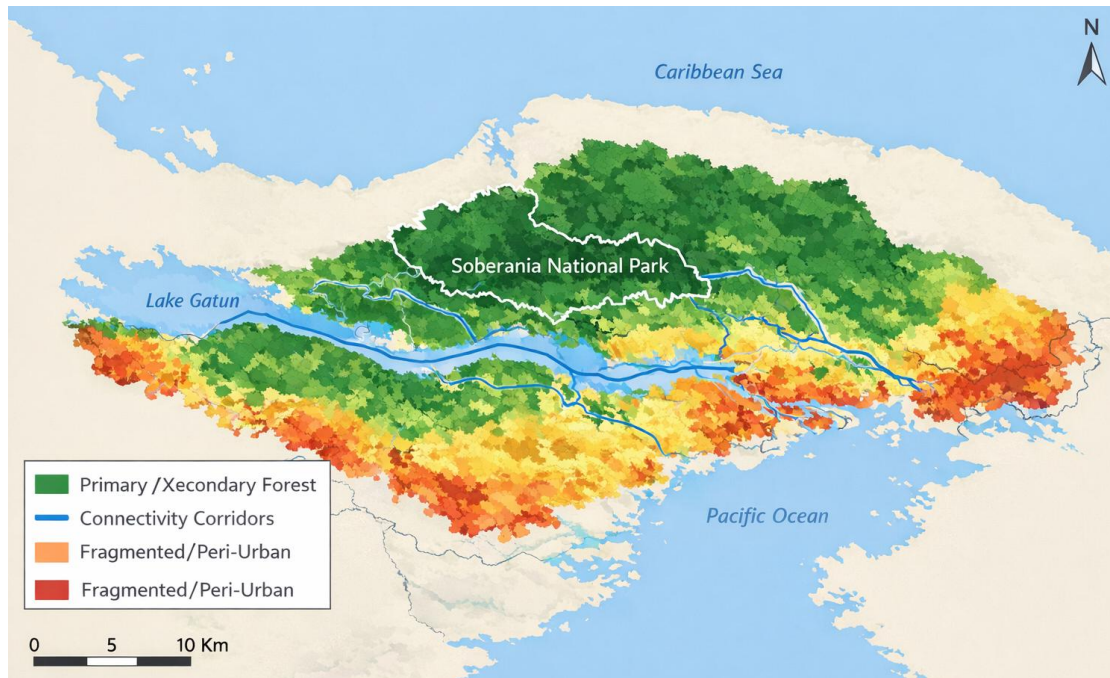


Figure 3. Habitat connectivity network in the Panama Canal Watershed.

Graph-based connectivity analysis (CONNECT index) yielded a watershed-wide connectivity value of 0.71 for primary forest patches, indicating relatively high structural cohesion.

Riverine corridors, particularly those aligned with Lake Gatun and associated tributaries, function as ecological conduits linking northern and central forest blocks [51]. These corridors significantly reduce effective isolation distance between habitat patches.

Mean nearest-neighbor distance (ENN) results:

- Primary forest: 134 m
- Secondary forest: 287 m
- Agro-mosaic: 412 m

Connectivity probability of dispersal (PC metric) was highest within central protected forest blocks and declined sharply toward peri-urban sectors.

These spatial configurations demonstrated that watershed resilience is strongly mediated by:

1. Large continuous forest cores
2. Riparian ecological corridors
3. Reduced fragmentation in protected interiors

Such findings are consistent with landscape connectivity theory and tropical forest resilience frameworks [14,52].

3.4. Land cover composition and spatial structure

When combining land-cover structure (Figure 1), ERI distribution (Figure 2), and connectivity networks (Figure 3), a spatial gradient emerged:

1. Central watershed = high resilience, high connectivity, large patch dominance.
2. Transitional zones = moderate resilience, matrix-dependent stability.

3. Peripheral anthropogenic zones = low resilience, high fragmentation.

The spatial coincidence between ERI hotspots and connectivity corridors confirmed that resilience is not solely a function of land-cover type but also of spatial configuration.

Importantly, areas adjacent to protected forest but characterized by agricultural expansion showed intermediate ERI values, suggesting potential for restoration-based resilience enhancement.

Overall, the watershed maintains a structurally resilient core; however, edge expansion and peri-urban growth pose measurable risks to long-term ecological stability.

4. Discussion

4.1. Landscape structure as a determinant of ecological resilience

The spatial analyses demonstrate that ecological resilience within the PCW is strongly conditioned by landscape configuration rather than land-cover composition alone. The dominance of a contiguous primary forest core (LPI = 32.4%) creates a structurally stable ecological matrix that supports high ERI values and maintains functional connectivity across the watershed.

The strong positive correlation between ERI and patch size ($r = 0.68$, $p < 0.001$) confirms theoretical expectations that larger, less fragmented habitat patches enhance system stability, buffering ecological processes against disturbance [1]. Conversely, the negative relationship between ERI and edge density ($r = -0.59$, $p < 0.001$) highlights the destabilizing influence of fragmentation-driven edge effects, including microclimatic shifts, invasive species penetration, and altered trophic interactions [3,51].

These findings reinforce resilience theory, which emphasizes the importance of structural redundancy and spatial cohesion in maintaining adaptive capacity [2].

4.2. The functional role of connectivity corridors

The connectivity network analysis reveals that riverine corridors, especially those linked to Lake Gatun, function as critical dispersal pathways that reduce effective isolation between forest patches. The watershed-wide CONNECT index of 0.71 for primary forest indicates relatively high structural permeability, enabling ecological flows across the landscape.

Graph-based connectivity metrics demonstrate that even moderately fragmented secondary forests can contribute to overall system resilience when spatially embedded within a connected matrix. This supports the perspective that resilience emerges from landscape-scale interactions rather than isolated patch characteristics [15].

However, the southeastern and southwestern peri-urban zones show sharp declines in connectivity probability, suggesting that continued expansion of agro-mosaic and infrastructure networks may push the system toward a fragmentation threshold. Landscape ecology theory suggests that once a critical connectivity threshold is crossed, biodiversity loss and ecosystem service degradation can accelerate nonlinearly [52].

4.3. Urban and peri-urban pressures in a strategic watershed

Unlike many tropical forest systems, the PCW represents a socio-ecological system where

ecological stability directly underpins economic infrastructure and global trade. The spatial gradient observed in ERI values, from high-resilience protected cores to low-resilience peri-urban margins, reflects the tension between conservation and development pressures.

Moreover, urban expansion and agricultural intensification appear spatially clustered in lower-elevation zones, increasing edge density and reducing effective habitat area. These areas correspond with statistically lower ERI values (< 0.40), indicating diminished recovery potential under disturbance.

Given the watershed's hydrological importance, fragmentation may also influence sediment dynamics, water quality, and climate buffering capacity. Thus, resilience loss in peripheral zones may generate cascading impacts beyond biodiversity alone.

4.4. Implications for spatial planning and regional policy

The integration of GIS-based land-cover classification, resilience indexing, and connectivity modeling provides a spatially explicit framework for conservation planning. Three key implications emerge:

- Protection of large contiguous forest cores remains the primary determinant of watershed resilience.
- Riparian corridors must be maintained and restored to preserve dispersal networks.
- Agro-mosaic landscapes represent potential restoration buffers if managed through ecological zoning strategies.

Rather than viewing secondary forests and agricultural matrices solely as degraded systems, targeted landscape planning could enhance their connectivity contribution, thereby stabilizing ERI gradients across the watershed.

In this sense, resilience-informed spatial planning aligns with contemporary urban-regional sustainability frameworks, where ecological infrastructure is treated as a foundational system supporting human development.

4.5. Contribution to international resilience literature

This contributes to the growing international literature on resilience-oriented landscape assessment by demonstrating that ecological resilience within tropical socio-ecological systems is strongly dependent on the interaction between vegetation structure, landscape connectivity, and spatial configuration [4]. While researchers have frequently examined fragmentation dynamics, biodiversity loss, or hydrological processes independently, comparatively few researchers have integrated field-based ecological indicators with GIS-derived connectivity and resilience modeling within a unified watershed-scale framework [11,53].

The findings further support contemporary resilience theory, suggesting that resilience should be interpreted as a spatially heterogeneous property emerging from landscape organization and cross-scale ecological interactions rather than solely from land-cover composition [5]. In this context, the ERI developed in this study provides a transferable methodological framework capable of supporting resilience-oriented planning in tropical and peri-urban watersheds undergoing rapid land-use transformation.

Additionally, the study highlights the importance of integrating ecological connectivity into sustainability governance frameworks, particularly in strategically important watersheds where

ecosystem stability directly supports hydrological regulation, infrastructure functionality, and regional socio-economic resilience.

4.6. Limitations of the study

Several limitations should be acknowledged when interpreting the results of this study. First, the analysis represents a spatial assessment based on a single temporal framework and therefore does not capture long-term land-use dynamics or seasonal ecological variability. Incorporating multi-temporal satellite datasets would improve the capacity to evaluate resilience trajectories and fragmentation evolution over time.

Second, although the ERI integrates multiple ecological indicators, the weighting process inevitably involves a degree of conceptual subjectivity despite being grounded in resilience and watershed management literature. Researchers may therefore benefit from sensitivity analyses or machine-learning-based weighting approaches to improve model calibration.

Third, the use of moderate-resolution satellite imagery may underestimate fine-scale fragmentation patterns within heterogeneous peri-urban landscapes. Similarly, although the vegetation plot network was designed to represent dominant land-cover categories, sampling density remains limited relative to the ecological complexity of the watershed.

Finally, in our framework, we focus primarily on ecological resilience dimensions and do not directly incorporate hydrological simulations, climate-change projections, or socio-economic vulnerability indicators. Integrating these variables would support a more comprehensive socio-ecological resilience assessment.

4.7. Recommendations for future research and spatial planning

The findings suggest that resilience-oriented watershed planning should prioritize the preservation of contiguous forest cores and the restoration of riparian ecological corridors to maintain ecological connectivity and hydrological stability across the watershed.

Particularly in rapidly urbanizing sectors, ecological zoning strategies, reforestation initiatives, and buffer restoration programs may help reduce fragmentation intensity and stabilize resilience gradients between protected interiors and peri-urban transition zones.

The results also indicate that secondary forests and agro-mosaic landscapes should not necessarily be interpreted exclusively as degraded systems. Under appropriate spatial management strategies, these matrices may function as transitional ecological buffers supporting dispersal processes and adaptive ecological capacity.

In future studies, researchers should integrate climate-change scenarios, hydrological response models, ecosystem service valuation, and socio-economic vulnerability indicators to develop more comprehensive socio-ecological resilience frameworks. Additionally, scenario-based urban expansion modeling and higher-resolution remote sensing could further improve the spatial precision of resilience assessments in rapidly transforming tropical watersheds.

5. Conclusions

In this study, we demonstrate that ecological resilience within the PCW is strongly shaped by

landscape configuration, habitat connectivity, vegetation structural integrity, and the spatial interaction between natural and anthropogenic land-cover systems. By integrating vegetation plot assessment, GIS-based fragmentation analysis, and a composite ERI, we provide a multi-scalar framework capable of identifying resilience gradients across a globally strategic tropical socio-ecological system.

The results indicate that large contiguous primary forest cores constitute the principal ecological backbone of watershed resilience. Moreover, areas characterized by high patch cohesion, elevated structural complexity, and strong connectivity consistently exhibit the highest ERI values, confirming that resilience capacity depends not only on vegetation presence but also on spatial organization and functional ecological continuity. The statistically significant positive relationship between ERI and patch size, together with the negative relationship between ERI and edge density, demonstrates that fragmentation processes substantially reduce ecosystem stability and adaptive capacity.

The study additionally highlights the critical ecological role of riparian corridors and secondary forest matrices in maintaining landscape permeability and dispersal functionality across the watershed. Although primary forests exhibit the highest resilience values overall, moderately connected secondary forests also contribute significantly to regional ecological stability when integrated within connected landscape networks. These findings suggest that resilience conservation strategies should extend beyond strict protected-core preservation to include ecological corridor maintenance, transitional landscape restoration, and connectivity-oriented spatial planning approaches.

An important conclusion emerging from the spatial analysis is that resilience within the PCW is highly heterogeneous and spatially concentrated. High-resilience hotspots are primarily within protected forest interiors and riparian corridors, whereas peri-urban and agro-mosaic landscapes exhibit substantially lower resilience values associated with fragmentation, elevated edge density, and habitat isolation. This spatial gradient reflects the increasing ecological pressures generated by urban expansion, agricultural intensification, and infrastructure development within strategically important watershed sectors.

The findings further emphasize that ecological degradation within the watershed may generate broader hydrological and socio-economic implications extending beyond biodiversity loss alone. Because the PCW directly supports freshwater availability, sediment regulation, and canal operational functionality, resilience decline in fragmented sectors may influence regional water security and long-term infrastructure sustainability. Consequently, ecological resilience should be interpreted not solely as an environmental conservation objective but also as a critical component of socio-economic and infrastructural stability.

From a methodological perspective, the study demonstrates the analytical value of integrating field-based vegetation structure metrics with GIS-derived connectivity and fragmentation indicators in resilience-oriented environmental assessment. Moreover, the ERI developed in this study provides a transferable and spatially explicit framework suitable for identifying ecological hotspots, fragmentation-sensitive transition zones, and restoration-priority corridors in rapidly transforming tropical landscapes. The approach may therefore support resilience-informed environmental governance and sustainability-oriented spatial planning in other tropical watershed systems facing similar land-use pressures.

Several limitations should nevertheless be acknowledged. First, the analysis is conducted within a single temporal framework and therefore does not capture long-term land-cover dynamics or seasonal variability in ecological processes. Second, although Landsat imagery provides strong regional-scale consistency, moderate spatial resolution may underestimate localized fragmentation patterns and fine-

scale urban disturbance. Third, the weighting structure of the ERI incorporates conceptual assumptions derived from resilience literature, and researchers may benefit from sensitivity analysis or machine-learning-based optimization approaches. Finally, we primarily focus on ecological resilience dimensions and do not directly integrate hydrological simulations, climate-change projections, or socio-economic vulnerability assessments.

Researchers should therefore incorporate multi-temporal remote sensing analysis, scenario-based urban expansion modeling, higher-resolution satellite imagery, and integrated hydrological simulations to evaluate resilience trajectories under future climate and land-use change conditions. The incorporation of ecosystem service valuation and socio-economic vulnerability indicators would additionally strengthen the development of fully integrated socio-ecological resilience frameworks.

Overall, the study confirms that maintaining forest connectivity, limiting fragmentation expansion, and strengthening ecological corridor functionality are essential prerequisites for sustaining biodiversity, hydrological stability, ecosystem services, and long-term resilience within the PCW. As tropical socio-ecological systems continue to experience accelerating anthropogenic pressures, resilience-oriented spatial planning frameworks such as the one developed in this study will become increasingly important for supporting sustainable environmental governance and regional ecological security. In conclusion, the study demonstrates that ecological resilience in tropical watershed systems cannot be sustained through isolated conservation measures alone, but requires integrated landscape-scale connectivity management capable of balancing ecological integrity, hydrological security, and socio-economic development.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Author contributions

George Malaperdas: GIS Analysis, methodology, data curation. Marc Soler: writing and editing, investigation.

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