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Multicriteria Analysis of Territorial Resilience in Pinar del Río, Cuba

Yandry Jesús Muñoz Labrador [1,*] and Nafisa Mansurovna Mingazova [2]

[1] Department of Natural Resources, Priority Ecosystems and Climate Change, Territorial Delegation of the Ministry of Science, Technology and Environment, Pinar del Río 20100, Cuba

[2] Department of Environmental and Water Resources Management, Kazan Federal University (Volga Region), 420008 Kazan, Russia

[*] Correspondence: YMunos.Labrador@kpfu.ru or recursos.protegidos@citmapri.gob.cu

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Abstract: The province of Pinar del Río (Cuba) faces increasing processes of anthropization and environmental degradation that threaten its territorial resilience, yet it lacks integrated assessments linking anthropogenic pressures, ecosystem state, and exposure to threats. This study aimed to evaluate the dynamics of anthropization and ecosystem vulnerability in western Cuba through a multicriteria analysis of territorial resilience across the eleven municipalities of Pinar del Río. An assessment matrix was constructed with seven dimensions (soil, water, air, vegetation, protected areas, natural threats, and anthropogenic pressure). The Analytic Hierarchy Process (AHP) method was applied for criteria weighting, and vulnerability indices were calculated per municipality, complemented by correlation analysis, principal components, cluster analysis, and interdependence networks. The province reached an Ecosystem Vulnerability and Anthropogenic Pressure Index (IVE-PA) of 65.3/100 (medium-high category), with the municipalities of Pinar del Río (84.7) and Consolación del Sur (77.2) as critical cores. Anthropogenic pressure was strongly correlated with water degradation ($r = 0.78$) and air degradation ($r = 0.56$), while vegetation and protected areas acted as buffers against natural threats ($r = -0.67$). Viñales was the most resilient municipality (45.2). It is concluded that territorial resilience in Pinar del Río is compromised by the synergy between anthropogenic pressure and pollution, although vegetation conservation constitutes a critical buffering factor. Land use planning with priority water sanitation and specific soil conservation policies is required.

Keywords: Environmental Vulnerability; Multicriteria Analysis; Analytic Hierarchy Process; Vulnerability Dimensions; Cuba; Territorial Resilience

1. Introduction

The province of Pinar del Río (western Cuba) is a territory of marked heterogeneity, where high-value ecosystems (Guaniguanico mountain range, Viñales National Park, Guanahacabibes Peninsula) coexist with intensive agricultural areas (tobacco) and urban-industrial cores. This heterogeneity exposes the province to multiple natural and anthropogenic threats: hurricanes (45 between 1851–2018, including one category 5), active seismicity, coastal flooding, droughts, and significant pollution (air and water) from industry, transport, and inadequate sanitation [1–3].

Despite recent efforts—the Territorial Environmental Strategy (2021), the National System of Protected Areas (2023), and soil conservation programs—environmental indicators show a mixed picture: forest cover is high

(48.07%, second in Cuba) and mangroves cover 67,665.9 ha, yet soil degradation affects 70% of agricultural land (low effective depth), 82.8% has acidity (pH ≤ 5.5), and 73.7% has low fertility. Air quality is deficient in the capital and poor in the Santa Lucía mining region [1,3]. Water pollution is severe: 883 pollutant sources, only 21 comply with NC 27/12, and at least six reservoirs supplying populations are contaminated [1,4].

In this context, it is essential to understand how ecosystem vulnerability and anthropogenic pressure are distributed territorially, as well as to identify the interdependence relationships between the different components of the environmental system. Previous studies in Pinar del Río have addressed specific environmental components: air quality [2,5], soil degradation [6], and water pollution [7]. However, these studies are fragmented and focus on single dimensions, without integrating the multiple factors that determine territorial vulnerability. At the national level, multicriteria assessments have been applied in other Cuban provinces [8,9], but none have been developed for Pinar del Río, nor have they incorporated interdependence network analysis. Additionally, no study has quantified the relative weight of each environmental component or its role as a transmitter or buffer of vulnerability across all 11 municipalities of the province. This gap justifies the need for an integrated, multicriteria assessment that simultaneously considers soil, water, air, vegetation, protected areas, natural threats, and anthropogenic pressure.

Therefore, the general objective of this study is to evaluate ecosystem vulnerability and anthropogenic pressure in the 11 municipalities of Pinar del Río province by constructing an Ecosystem Vulnerability and Anthropogenic Pressure Index (IVE-PA), based on Analytic Hierarchy Process (AHP), correlation and dimensional reduction techniques, cluster analysis, interdependence networks, and sensitivity tests.

The specific objectives are: (1) to assess each municipality across seven key dimensions (soil quality, water quality, air quality, vegetation cover and forests, protected areas, exposure to natural threats, and anthropogenic pressure) using 25 sub-criteria; (2) to determine the relative weights of each dimension using the AHP method and verify the consistency of the decisions; (3) to calculate the IVE-PA for each municipality and classify it into vulnerability categories; (4) to identify correlation and clustering patterns through principal component analysis and hierarchical clustering; (5) to construct an interdependence network among dimensions to identify bridge nodes and leverage points; and (6) to evaluate the robustness of the results through Monte Carlo simulations and bootstrapping.

The implicit hypothesis guiding this research is that ecosystem vulnerability in Pinar del Río is not homogeneously distributed but is concentrated in municipalities with greater urban-industrial pressure (pollution synergy) and in those with intensive agriculture (soil degradation), while territories with greater coverage of protected areas and vegetation exhibit significantly higher resilience to natural threats. Likewise, water quality is expected to act as a high-centrality node, transmitting the impacts of anthropogenic pressure to the remaining dimensions.

The results of this research will provide a useful tool for territorial decision-makers in Cuba, allowing them to prioritize environmental investments and guide land-use planning policies towards greater resilience. Furthermore, the proposed methodological approach can be replicated in other provinces of the country or in regions with similar characteristics in the Caribbean and Latin America.

2. Materials and Methods

2.1. Location of the Study Area

The research was conducted in the province of Pinar del Río, located in western Cuba, between 21°19′ and 22°56′ north latitude and 84°57′ and 83°05′ west longitude. The province has a total area of 8,883.74 km^2, of which 8,815.27 km^2 (99.2%) correspond to mainland and 68.47 km^2 (0.8%) to adjacent cays. Administratively, it is divided into 11 municipalities: Pinar del Río, Consolación del Sur, Los Palacios, San Juan y Martínez, Sandino, Mantua, Guane, San Luis, Minas de Matahambre, La Palma, and Viñales (**Figure 1**).

The relief is predominantly flat (67% of the territory), with the Guaniguanico mountain range as the main orographic system. The climate is tropical savanna (Aw), with an average annual temperature of 24.7 °C and a well-defined rainy season from May to October [1]. The province has high exposure to natural threats, including hurricanes (45 hurricanes between 1851–2018, one category 5), active seismicity associated with the Caimanes and Canarreos faults, and progressive coastal flooding [1].

The methodological approach of this study follows a sequential six-step framework. First, seven vulnerability dimensions (soil, water, air, vegetation, protected areas, natural threats, and anthropogenic pressure) were selected based on a comprehensive bibliographic review and official Cuban sources. Second, each of the 11 municipalities was assessed on a 1–5 scale, harmonizing quantitative, binary, and categorical indicators. Third, the Analytic Hierarchy Process (AHP) was applied to determine the relative weights of each dimension, with consistency verified through the consistency ratio (CR). Fourth, the Ecosystem Vulnerability and Anthropogenic Pressure Index (IVE-PA) was calculated for each municipality and normalized to a 0–100 scale. Fifth, complementary statistical and multivariate analyses were performed, including PCA, cluster analysis, Pearson correlations (with FDR correction), interdependence network analysis, Monte Carlo simulation, and bootstrapping. Finally, the results were interpreted, and policy recommendations were formulated based on the findings.

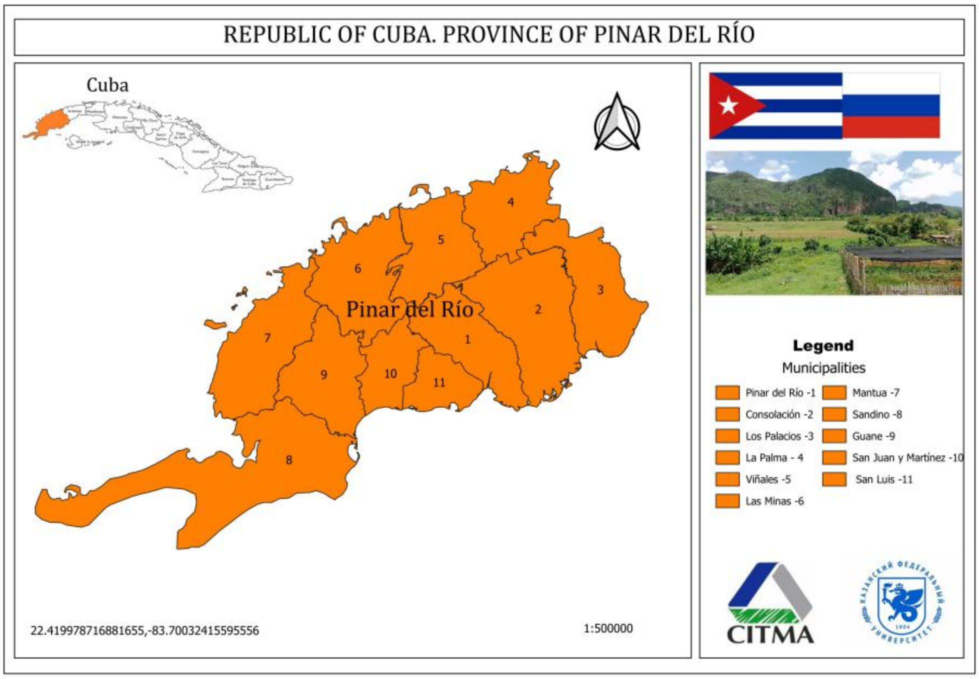


Figure 1. The province of Pinar del Río is located in western Cuba.

Source: author's field work.

2.2. Data Sources

The data used in this study come exclusively from official Cuban sources and territorial technical reports published between 2014 and 2025. (**Table 1**) summarizes the data sources, including the data category, description, spatial unit, period/year, source, and use in the analysis.

Table 1. Summary of data sources.

Data Category	Data Description	Source	Use in Analysis
Population	Effective population, density, distribution by sex and age, urban and rural settlements	Statistical Yearbook of Cuba 2024	Anthropogenic pressure dimension, demographic analysis
Environmental problems	Pollutant sources, environmental problems, soil quality indicators	Pinar del Río Territorial Environmental Strategy 2021–2030	Dimension selection, criteria weighting
Climate	Climatic characterization, wind regime, tropical cyclones	Provincial Meteorological Center (2020). Synoptic-climatological characterization of the province of Pinar del Río	Natural threats dimension
Protected areas	Area and category of declared and undeclared protected areas	National System of Protected Areas Plan 2023–2030	Protected areas dimension
Forest management	Forest fire statistics, forest heritage management	Evaluation Report on the Implementation of the Territorial Environmental Strategy of Pinar del Río, Strategic Cycle 2016–2021	Vegetation cover dimension
Territorial planning	Maps and data on geology, hydrography, soils	General Territorial Planning Plan of Pinar del Río 2024	Soil, water, and vegetation dimensions

2.3. Selection of Dimensions and Indicators

Based on a comprehensive bibliographic review and the environmental problems documented in the official sources, seven vulnerability dimensions were selected. Each dimension was operationalized through multiple indicators (sub-criteria), totaling 25 sub-criteria. **Table 2** presents the dimensions, indicators, and their respective units of measurement.

Table 2. Vulnerability dimensions, indicators, and units of measurement.

Dimension	Indicator	Unit
1. Soil quality	% of area with effective depth ≤50 cm	Percentage
	% of area with moderate to severe erosion	Percentage
	% of area with pH ≤ 5.5 (acidity)	Percentage
	% of area with organic matter <2.5% (low fertility)	Percentage
	% of area with salinity (EC >4 mmol/cm^3)	Percentage
2. Water quality	Number of pollutant sources	Count
	Sources complying with NC 27/12 standard	Count
	Discharge permits granted	Count
	Reservoirs with contamination	Count
3. Air quality	Number of atmospheric pollutant sources	Count
	General rating (qualitative)	Categorical
	Presence of SO_2 above NC 39:1999 standard	Binary
	Presence of PM10, NO_2, CO above standard	Binary
	Bad odors (population complaints)	Binary
4. Vegetation cover	Forest cover index	Percentage
	Deforested area	Hectares
	Forest fires (2023)	Affected hectares
	Presence of threatened species	Binary
5. Protected areas	Protected terrestrial area	Hectares
	Protected marine area	Hectares
	Officially declared protected areas	Count
	Undeclared protected areas	Count
6. Natural threats	Hurricanes category 3–5 (1851–2018)	Count
	Floods due to sea intrusions	Categorical
	Seismicity (active faults)	Categorical
7. Anthropogenic pressure	Maximum population density	inhab/km^2
	Urban growth (historical trend)	Rate
	Rural population in dispersed settlements	Count
	Population complaints about pollution	Binary

Note: Presentation of the seven vulnerability dimensions, with their respective indicators and units of measurement.

2.4. Valuation Scale by Municipality

Each municipality was assessed on an ordinal scale from 1 to 5, where 1 represents the best condition (very low vulnerability, high resilience) and 5 represents the worst condition (very high vulnerability, very low resilience). To harmonize the different measurement types (counts, percentages, binary, and categorical indicators) before calculating dimension scores, the following standardization protocol was applied:

(a) For quantitative indicators (percentages, counts, densities), the raw values were normalized using min-max rescaling to a 0–1 range, then divided into five equal intervals corresponding to scores 1 (best) to 5 (worst).
(b) For binary indicators (presence/absence of pollutants, complaints, threatened species), a score of 1 was assigned for absence (better condition) and 5 for presence (worse condition).
(c) For categorical indicators (air quality rating, flooding risk, seismicity), the categories were mapped to the 1–5 scale based on severity levels defined in the official reports (e.g., air quality: Good = 1, Acceptable = 2, Regular = 3, Deficient = 4, Poor = 5).

For each dimension, the final score was calculated as the arithmetic mean of the sub-criteria scores for that municipality. This approach ensures that all indicators, regardless of their original measurement type, contribute equally to the dimension score after conversion to the common 1–5 ordinal scale. The scoring thresholds were defined based on the distribution of values across municipalities and the severity criteria established in the Territorial Environmental Strategy [6].

2.5. Analytic Hierarchy Process (AHP) Method for Dimension Weighting

To determine the relative importance of each of the seven dimensions, the Analytic Hierarchy Process (AHP) method proposed by Saaty [10] was applied. The procedure included the following steps:

2.5.1. Construction of the Pairwise Comparison Matrix

The relative importance of each pair of criteria was compared using Saaty's fundamental scale (1 = equal importance; 3 = moderate importance; 5 = strong importance; 7 = very strong importance; 9 = extreme importance). The comparisons were based on the frequency and severity of the environmental problems reported in the Territorial Environmental Strategy 2021 [6] and the technical reports, resulting in a 7 × 7 pairwise comparison matrix (**Table 3**). The normalized eigenvector provided the relative weights of each criterion: Soil (33.1%), Water (21.4%), Air (12.8%), Vegetation (8.3%), Natural Threats (5.0%), Protected Areas (12.8%), and Anthropogenic Pressure (6.6%). The consistency ratio was CR = 0.062 (<0.10), confirming the consistency of the comparisons. The detailed weighting structure, including sub-criteria weights and global weights, is presented in **Appendix A**.

Table 3. Pairwise Comparison Matrix (AHP) for the Seven Vulnerability Dimensions.

	Soil	**Water**	**Air**	**Vegetation**	**Natural Threats**	**Protected Areas**	**Anthropogenic Pressure**
Soil	1	2	3	4	5	3	4
Water	1/2	1	2	3	4	2	3
Air	1/3	1/2	1	2	3	1	2
Vegetation	1/4	1/3	1/2	1	2	1/2	1
Natural Threats	1/5	1/4	1/3	1/2	1	1/3	½
Protected Areas	1/3	1/2	1	2	3	1	2
Anthropogenic Pressure	1/4	1/3	1/2	1	2	1/2	1

Note: The matrix was constructed based on the frequency and severity of environmental problems reported in the Territorial Environmental Strategy 2021 [6]. Values >1 indicate that the dimension in the row is more important than the dimension in the column. The consistency ratio was CR = 0.062 (<0.10), confirming the consistency of the comparisons.

2.5.2. Calculation of the Normalized Eigenvector (Weights)

From the comparison matrix, the normalized eigenvector was calculated, which provides the relative weights of each criterion. For this purpose, the geometric mean method was used:

$$w_i = \frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{1/n}}{\sum_{k=1}^{n}\left(\prod_{j=1}^{n} a_{kj}\right)^{1/n}} \tag{1}$$

where (a_{ij}) is the comparison value between criterion (i) and criterion (j), and n = 7 is the number of criteria.

2.5.3. Consistency Verification

To validate the consistency of the comparisons, the Consistency Ratio (CR) was calculated using the following formulas:

$$(\lambda_{max}) = \frac{1}{n}\sum_{i=1}^{n}\frac{(A \cdot w)_i}{w_i} \tag{2}$$

$$\mathrm{IC} = \frac{\lambda_{max} - n}{n - 1} \tag{3}$$

$$\mathrm{RC} = \frac{IC}{AI} \tag{4}$$

where λ_{max} is the maximum eigenvalue of the comparison matrix, n = 7 is the number of criteria, and AI = 1.32 is the random index for n = 7 [10].

From the pairwise comparison matrix (**Table 3**), the following values were obtained:

$$\lambda_{max} = 7.49$$

$$IC = (7.49 - 7)/(7 - 1) = 0.49/6 = 0.082$$

$$CR = 0.082/1.32 = 0.062$$

A consistency ratio of RC = 0.062 (<0.10) was obtained, confirming the consistency of the comparisons.

2.6. Calculation of the Ecosystem Vulnerability and Anthropogenic Pressure Index (IVE-PA)

The IVE-PA for each municipality was calculated using the following weighted sum formula:

$$IVE - PA_i = \sum_{j=1}^{7} \left(p_j \cdot v_{ij}\right) \tag{5}$$

where:

- $IVE - PA_i$ = Vulnerability index of municipality (i) (on a 1–5 scale).
- p_j = weight of criterion (j) (obtained by AHP, expressed as a proportion, e.g., 0.331 for soil).
- v_{ij} = assessment of municipality (i) on criterion (j) (1–5 scale).

Subsequently, the index was normalized to a scale of 0 to 100 to facilitate interpretation and comparison:

$$IVE - PA_{norm,i} = \frac{\text{IVE-PA}_i - 1}{5 - 1} \cdot 100 = \frac{IVE - PA_i - 1}{4} \cdot 100 \tag{6}$$

2.7. Categorization of the IVE-PA

Five vulnerability categories were defined based on the normalized value:

- <50 = Low vulnerability.
- 50–59 = Medium-low vulnerability.
- 60–69 = Medium-high vulnerability.
- 70–79 = High vulnerability.
- ≥80 = Very high vulnerability.

Additionally, a surface-weighted provincial IVE-PA was calculated using the territorial extension of each municipality as a weighting factor:

$$IVE{-}P_{Province} = \frac{\sum_{i=1}^{11} \left(IVE - PA_{norm,i} \cdot Area_i\right)}{\sum_{i=1}^{11} Area_i} \tag{7}$$

2.8. Statistical and Multivariate Analyses

The following complementary analyses were performed using R software (version 4.3.2) and Python (Pandas, NumPy, SciPy, scikit-learn libraries):

2.8.1. Pearson Correlation

The Pearson correlation matrix between the seven dimensions (based on the municipal assessments) was calculated. The correlation coefficient *(γ)* was calculated using:

$$\gamma_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{8}$$

A two-tailed significance test was performed for each correlation, considering a significance level of $\alpha = 0.05$. Given the small sample size (n = 11 municipalities) and the number of correlations tested (21 pairwise comparisons), we applied the Benjamini-Hochberg false discovery rate (FDR) correction to control for Type I errors. Correlations with $|r| > 0.4$ and FDR-adjusted $p < 0.05$ were considered relevant for the interdependence analysis.

2.8.2. Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was applied to reduce the dimensionality of the data and visualize the relationships between municipalities and dimensions. Previously, the data were standardized (mean = 0, standard deviation = 1) to prevent different measurement scales from influencing the results. The eigenvalues, the variance explained by each component, and the factor loadings were calculated.

To evaluate the adequacy of the PCA, the following tests were performed: The Kaiser-Meyer-Olkin (KMO) test was used to measure sampling adequacy, with values ≥ 0.6 considered acceptable. Bartlett's test of sphericity was applied to test the null hypothesis that the correlation matrix is an identity matrix; this hypothesis is rejected if $p < 0.05$, confirming the adequacy of PCA.

2.8.3. Hierarchical Clustering Procedure

A hierarchical cluster analysis was performed to classify the 11 municipalities into groups with similar vulnerability profiles. Euclidean distance was used as the dissimilarity measure:

$$d_{ij} = \sqrt{\sum_{k=1}^{7} \left(v_{ik} - v_{jk}\right)^2} \quad (9)$$

and Ward's method as the agglomeration algorithm, which minimizes within-group variance. The optimal number of clusters was determined by inspecting the dendrogram and the silhouette coefficient.

2.8.4. Interdependence Network Construction

To model the causal relationships among the seven dimensions, a directed graph was constructed based on significant correlations ($|r| > 0.4$ with $p < 0.05$) and on the expected direction of the relationships according to the literature and expert knowledge. The following centrality metrics were calculated:

- Out-degree centrality: number of arrows leaving a node (influences others).
- Betweenness centrality: measures how often a node acts as a bridge along the shortest path between other nodes. It is calculated as:

$$C_B(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}} \quad (10)$$

where (σ_{st}) is the total number of shortest paths between (s) and (t), and $\sigma_{st}(v)$ is the number of those paths that pass through (v).

2.9. Sensitivity and Robustness Assessment

To evaluate the stability of the vulnerability ranking and the uncertainty in the AHP weights, two complementary analyses were performed:

2.9.1. Monte Carlo Simulation

10,000 Monte Carlo iterations were run, randomly varying the criteria weights within reasonable ranges (±20% of the original weight). In each iteration, the IVE-PA of all municipalities was recalculated and the ranking was recorded. At the end, the frequency with which each municipality appeared in the Top 3 (most vulnerable) and in the Bottom 3 (least vulnerable) was calculated.

2.9.2. Bootstrapping

5,000 bootstrap samples were generated with replacement from the original municipal assessments. For each sample, the IVE-PA of each municipality was calculated and a 95% confidence interval was constructed using the 2.5th and 97.5th percentiles of the bootstrap distribution.

2.10. Demographic and Environmental Justice Assessment

Based on population data disaggregated by sex and age groups [11], the following social vulnerability indicators were calculated:

$$\text{Aging index} = 100 \times \frac{Population \geq 65\ years}{Population 0 - 14\ years} \tag{11}$$

$$\text{Dependency ratio} = 100 \times \frac{Population < 15 + Population \geq 65}{Population 15 - 64\ years} \tag{12}$$

$$\text{Vegez feminization index:}\ \frac{Women \geq 65}{Men \geq 65} \tag{13}$$

Subsequently, the percentage of elderly population (≥65 years) per municipality was correlated (Pearson) with the IVE-PA to evaluate possible patterns of environmental injustice (higher vulnerability in municipalities with a higher proportion of socially vulnerable population).

2.11. Methodological Limitations

The study presents the following limitations: (1) the sample size (n = 11 municipalities) limits the statistical power of certain multivariate analyses; (2) the assessments were based on aggregated municipal data, losing intra-municipal heterogeneity; (3) the absence of environmental health data and public perception prevented external validation of the index; (4) most indicators are cross-sectional (single point in time), which prevents establishing definitive causal relationships; (5) the assignment of values on a 1–5 scale, although based on official sources, implies a certain degree of expert judgment.

3. Results

3.1. Multidimensional Assessment by Municipality

Table 4 presents the assessment matrix of the 11 municipalities across the seven vulnerability dimensions (scale 1–5, where 5 indicates maximum vulnerability). A marked territorial heterogeneity is observed. The detailed assessment matrix, including raw indicator values, scoring thresholds, and sub-criteria weights, is provided in the supplementary material (**Appendix B**). The municipality of Pinar del Río (provincial capital) presents the highest assessments in water quality (5), air quality (5), and anthropogenic pressure (5). Consolación del Sur and Los Palacios stand out for their severe soil degradation (5 in both). In contrast, Viñales shows the lowest assessments in protected areas (1) and vegetation (2), indicating greater resilience.

Table 4. Assessment matrix by municipality (scale 1–5).

Municipality	Soil	Water	Air	Vegetation	Natural Threats	Protected Areas	Pressure
Pinar del Río	4.5	5.0	5.0	3.0	4.0	2.0	5.0
Consolación del Sur	5.0	4.0	3.0	3.0	4.0	3.0	4.0
Los Palacios	5.0	3.0	2.0	3.0	4.0	3.0	3.0
San Juan y Martínez	3.5	3.0	3.0	3.0	4.0	3.0	3.0
Sandino	5.0	3.0	2.0	2.0	5.0	2.0	2.0
Mantua	4.5	3.0	2.0	3.0	4.0	3.0	2.0
Guane	3.5	3.0	2.0	3.0	4.0	3.0	2.5
San Luis	3.5	3.0	3.0	3.0	4.0	3.0	2.5
Minas de Matahambre	3.0	3.0	5.0	3.0	4.0	3.0	2.5
La Palma	3.0	3.0	2.0	3.0	4.0	3.0	2.5
Viñales	3.0	2.0	2.0	2.0	4.0	1.0	3.0

Note: Higher values (4–5) indicate higher vulnerability (lower resilience). Lower values (1–2) indicate lower vulnerability (higher resilience).

Regarding the dimension of natural threats, the limited variation among municipalities (scores of 4 for all except Sandino, which scored 5) reflects the fact that the entire province of Pinar del Río is exposed to similar natural threats—particularly hurricanes, active seismicity, and coastal flooding—due to its geographical location in western Cuba. While this limits the analytical contribution of this dimension for differentiating municipalities, it also highlights that exposure to natural threats is a province-wide challenge that must be addressed through coordinated territorial policies rather than municipal-level interventions. The slightly higher score for Sandino is justified by its location in the Guanahacabibes Peninsula, which is more exposed to hurricanes and sea-level rise. In future studies, it would be advisable to incorporate more detailed indicators (e.g., local flood risk maps, landslide susceptibility) to increase the variability of this dimension.

3.2. Weights of the Dimensions (AHP Method)

Table 5 shows the relative weights of each dimension obtained through the AHP method. Soil quality received the highest weight (33.1%), consistent with its identification as the main environmental problem in the Territorial Environmental Strategy. It was followed by water quality (21.4%) and air quality (12.8%). The consistency ratio was CR = 0.062 (<0.10), which validates the consistency of the comparisons.

Table 5. Weights of the vulnerability dimensions (AHP method).

Dimension	Weight (%)	Justification
Soil quality	33.1	First environmental problem of the province
Water quality	21.4	883 pollutant sources, only 21 comply with standards
Air quality	12.8	32 sources, deficient quality in the capital and poor in Santa Lucía
Vegetation cover	8.3	Second highest forest cover index in Cuba (48.07%)
Natural threats	5.0	10 intense hurricanes in 168 years, active seismicity
Protected areas	12.8	108,396 ha protected, but 10 areas still undeclared
Anthropogenic pressure	6.6	Maximum density in the capital (225.5 inhab/km^2)

Note: Consistency ratio CR = 0.062 (<0.10), validating the consistency of the comparisons.

3.3. Ecosystem Vulnerability and Anthropogenic Pressure Index (IVE-PA)

Table 6 presents the normalized IVE-PA (scale 0–100) and the vulnerability category for each municipality. The surface-weighted provincial index was 65.3 (medium-high category).

Table 6. Vulnerability index by municipality (IVE-PA).

Ranking	Municipality	IVE-PA (0–100)	Category
1	Pinar del Río	84.7	Very High
2	Consolación del Sur	77.2	High
3	Los Palacios	65.8	Medium-High
4	San Juan y Martínez	62.4	Medium-High
5	Sandino	64.2	Medium-High
6	Mantua	62.2	Medium-High
7	Guane	57.4	Medium
8	San Luis	56.6	Medium
9	Minas de Matahambre	57.2	Medium
10	La Palma	54.0	Medium
11	Viñales	45.2	Low

Note: Provincial surface-weighted IVE-PA = 65.3 (Medium-High category).

The municipality of Pinar del Río presents the highest vulnerability in the province (84.7), followed by Consolación del Sur (77.2) and Los Palacios (65.8). At the opposite end, Viñales shows the lowest vulnerability (45.2), followed by La Palma (54). **Figure 2** shows the spatial distribution of these categories across the provincial territory.

3.4. Results of the Principal Component Analysis

PCA explained 75.2% of the total variance with the first two components. The first component (PC1, 50.3% of variance) was interpreted as an axis of anthropogenic degradation, positively associated with anthropogenic pressure, water quality, and air quality. The second component (PC2, 24.9% of variance) was interpreted as an axis of ecosystem resilience, positively associated with vegetation and protected areas, and negatively associated with natural threats.

The biplot (**Figure 3**) shows that Pinar del Río is positioned in the quadrant of high anthropogenic degradation and low resilience, while Viñales is located in the opposite quadrant (low degradation, high resilience). The agricultural municipalities (Consolación del Sur, Los Palacios) cluster around high soil degradation values.

The KMO test was 0.68 (acceptable) and Bartlett's test of sphericity was significant (χ^2 = 58.3, df = 21, p < 0.001), confirming the adequacy of the PCA.

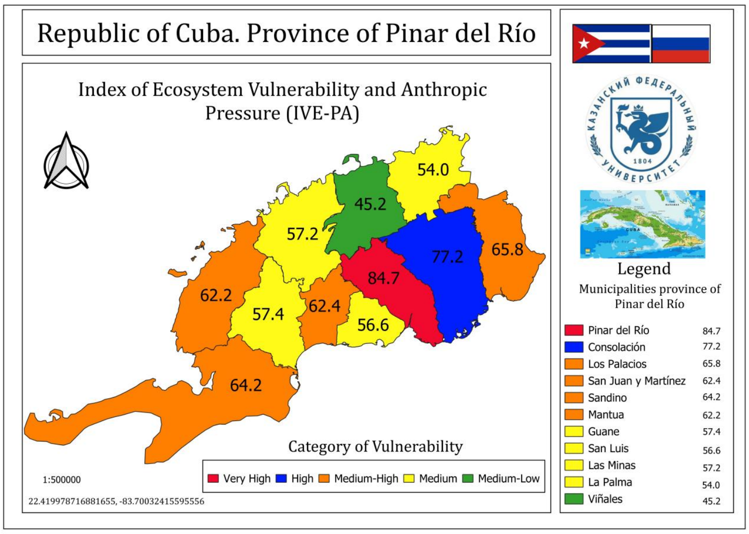


Figure 2. Spatial distribution of the Ecosystem Vulnerability and Anthropogenic Pressure Index (IVE-PA) across the 11 municipalities of Pinar del Río province, Cuba.

Source: statistical analysis of field data.

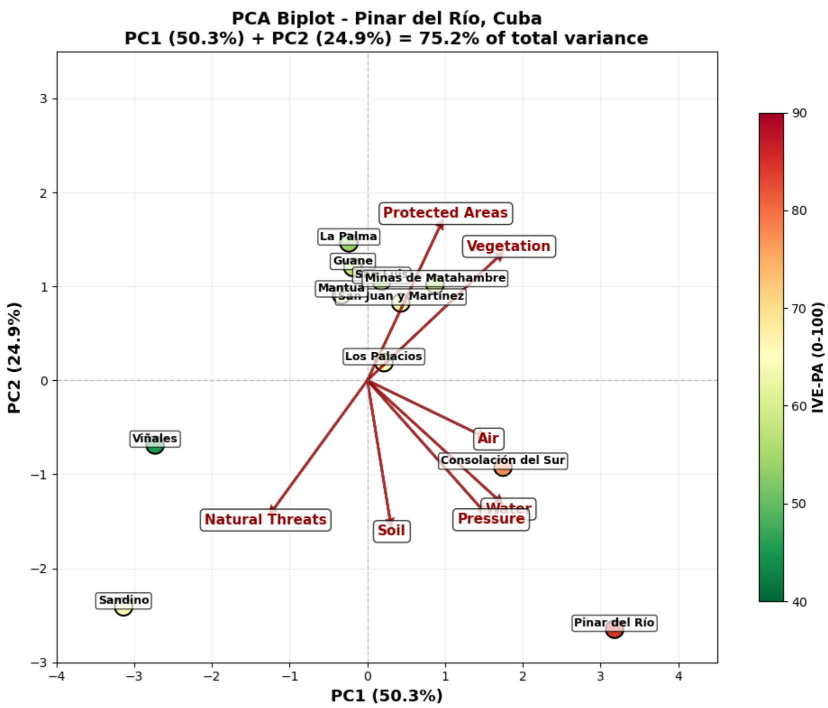


Figure 3. PCA biplot of 11 municipalities across seven vulnerability dimensions. PC1 (50.3%): anthropogenic degradation; PC2 (24.9%): ecosystem resilience. Red vectors show dimension contributions.

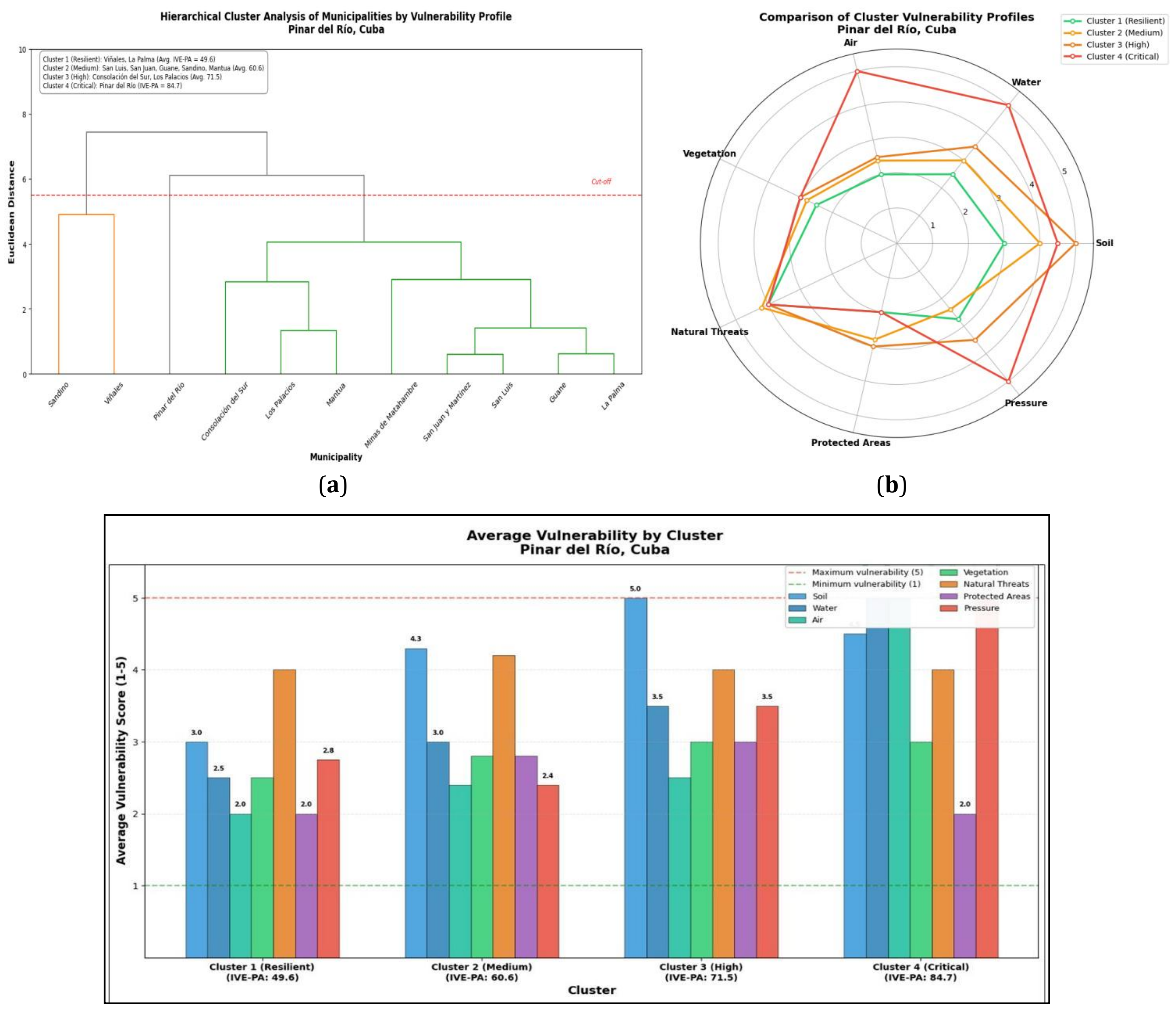
Source: Statistical analysis of field data.

It is important to note that the PCA results should be interpreted with caution due to the small sample size (n = 11 municipalities). While the analysis provides useful insights into the structure of the data, the limited number of observations restricts the generalizability of the findings. The patterns observed—particularly the separation of municipalities into distinct quadrants—should be considered as exploratory rather than definitive. Future studies with larger sample sizes (e.g., including more municipalities or incorporating intra-municipal data) would be needed to confirm the robustness of these patterns.

3.5. Hierarchical Cluster Analysis

The hierarchical cluster analysis (**Figure 4**) revealed a clear grouping of the 11 municipalities into four distinct clusters based on the similarity of their vulnerability profiles across the seven dimensions. These clusters, identified by the dendrogram (**Figure 4a**), the geographic distribution map (**Figure 4b**), and the summary table (**Figure 4c**), are characterized as follows:

- Cluster 1 (Resilient): Viñales, La Palma (average IVE-PA = 49.6). High vegetation cover, declared protected areas, low pollution.
- Cluster 2 (Medium vulnerability): San Luis, San Juan, Guane, Sandino, Mantua (average IVE-PA = 60.6).
- Heterogeneous profile, moderate vulnerability across all dimensions.
- Cluster 3 (High vulnerability): Consolación del Sur, Los Palacios (average IVE-PA = 71.5). Severe soil degradation, high agricultural pressure.
- Cluster 4 (Critical vulnerability): Pinar del Río (IVE-PA = 84.7). Maximum anthropogenic pressure, water and air pollution.



(**a**) (**b**)

(**c**)

Figure 4. Hierarchical cluster analysis of municipalities according to vulnerability profiles. Pinar del Río, Cuba. (**a**) Dendrogram showing the clustering of the 11 municipalities based on Euclidean distance and Ward's linkage method; (**b**) Geographic distribution of the four identified clusters across the provincial territory; (**c**) Cluster characteristics summarizing the average vulnerability scores (IVE-PA) and main features for each cluster (Resilient: 49.6, Medium: 60.6, High: 71.5, Critical: 84.7).

Source: Statistical analysis of field data.

3.6. Correlations between Dimensions

Table 7 presents the Pearson correlation coefficients between the seven vulnerability dimensions, highlighting strong positive associations between anthropogenic pressure and water quality (r = 0.78), protected areas and vegetation (r = 0.83), as well as a strong negative correlation between vegetation and natural threats (r = −0.67).

Table 7. Pearson correlation matrix: Significant associations between vulnerability dimensions.

Pair of Dimensions	r	*p*-Value	Significance
Anthropogenic pressure ↔ Water	0.78	<0.01	**
Protected areas ↔ Vegetation	0.83	<0.01	**
Water ↔ Air	0.61	<0.03	*
Anthropogenic pressure ↔ Air	0.56	<0.04	*
Vegetation ↔ Natural threats	−0.67	<0.02	*
Soil ↔ Pressure	0.26	>0.44	ns
Soil ↔ Air	−0.11	>0.74	ns
Soil ↔ Vegetation	−0.03	>0.89	ns

Note: ** $p < 0.01$ (highly significant); * $p < 0.05$ (significant) and ns = not significant ($p \geq 0.05$).

Figure 5 illustrates the Pearson correlation matrix, where the color intensity and numerical values indicate the strength and direction of the correlations between the seven vulnerability dimensions:

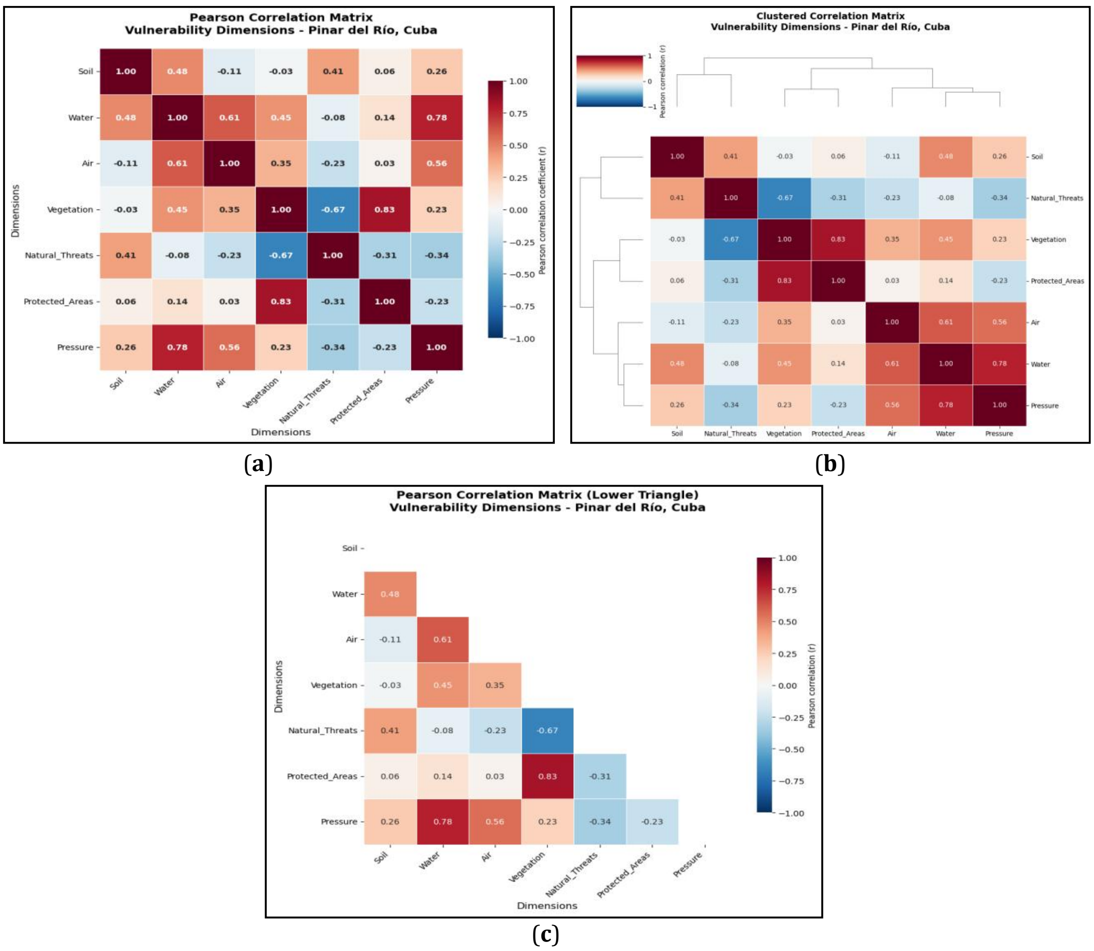


Figure 5. Pearson correlation matrix for the seven vulnerability dimensions, divided into three panels: (**a**) full correlation heatmap showing all coefficients; (**b**) significant correlations ($p < 0.05$); (**c**) lower triangle matrix with correlation coefficients and significance levels (ns).

Source: Statistical analysis of field data.

The correlation matrix revealed significant associations that suggest the presence of two major vulnerability syndromes. On one hand, a group of variables termed the "anthropogenic degradation syndrome" was observed, comprising anthropogenic pressure, water quality, and air quality. The high correlation between anthropogenic pressure and water quality (r = 0.78) suggests that concentrated human activities (domestic and industrial discharges, agricultural runoff) are strongly associated with water pollution. Similarly, the correlation between anthropogenic pressure and air quality (r = 0.56) points to an association with vehicular traffic, power generation, and industrial emissions as potential contributing sources of air pollution.

On the other hand, an "ecosystem resilience syndrome" was identified, comprising protected areas, vegetation, and natural threats. The almost perfect correlation between protected areas and vegetation (r = 0.83) is consistent with the view that the declaration of protected areas is an effective tool for vegetation cover conservation. The negative correlation between vegetation and natural threats (r = −0.67) supports the hypothesis that forests and mangroves act as natural buffers against hurricanes, coastal flooding, and salinization processes.

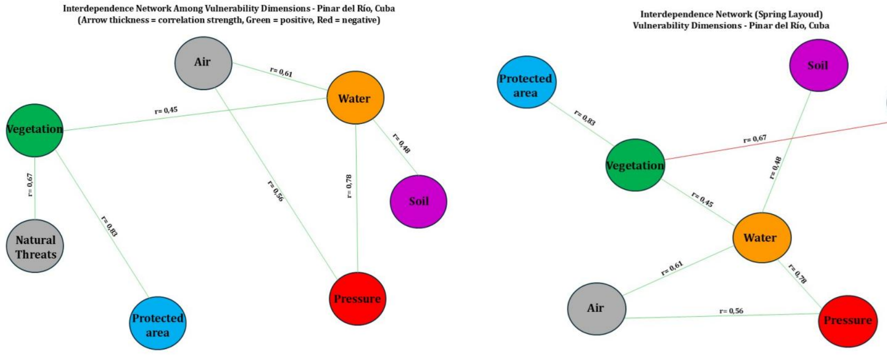
Finally, the weak and non-significant correlations of soil with anthropogenic pressure (r = 0.26) and with vegetation (r = −0.03) suggest that soil degradation is more closely associated with specific factors of the agricultural sector (intensive cultivation practices, agrochemical use, lack of rotation) than with urban-industrial pressure indicators. This implies that soil conservation policy may require a specific approach and may not be effectively subordinated to urban pollution control strategies.

It is important to emphasize that, since these are correlation analyses, none of the observed relationships should be interpreted as causal. The associations identified here reflect statistical patterns that require longitudinal or mechanistic studies to establish directionality and causality.

3.7. Interdependence Network among Dimensions

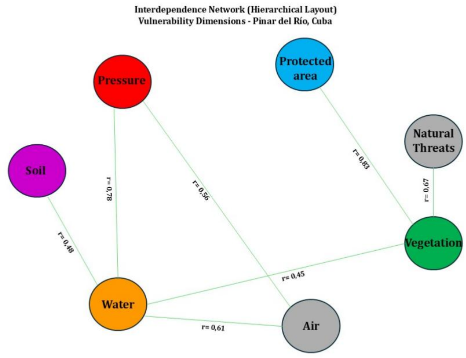
Figure 6 presents the directed interdependence network among the seven vulnerability dimensions, which was constructed based on significant correlations (|r| > 0.4, $p < 0.05$) and the expected direction of causal relationships derived from the literature and expert knowledge. From this network, the following structural roles were identified for each dimension:

- Anthropogenic pressure: Primary driver node (out-degree centrality = 2). It directly affects water (r = 0.78) and air (r = 0.56). The correlation with soil (r = 0.26) was not significant (FDR-adjusted $p = 0.440$) and therefore was not included in the network.
- Water: Bridge node with the highest betweenness centrality (0.47). It receives influences from pressure and soil, and projects effects towards air (r = 0.61) and vegetation (r = 0.45).
- Vegetation: Resilience node. It receives positive influences from protected areas (r = 0.83) and water (r = 0.45). It significantly reduces natural threats (r = −0.67).
- Protected areas: Instrumental variable (exogenous). It is the main driver of vegetation conservation.
- Soil: Peripheral node (low centrality). Its strongest connections are with water (r = 0.48) and with pressure (r = 0.26, weak).
- Air and Natural threats: Sink nodes (no significant outgoing arrows). They are final receivers of impacts.



(**a**) (**b**)

Figure 6. *Cont.*



(**c**)

Figure 6. Interdependence network among vulnerability dimensions: (**a**) full network with node roles color-coded (red: driver, orange: bridge, green: resilience); (**b**) node sizes proportional to betweenness centrality, highlighting Water as the bridge node (0.47); (**c**) tripartite structure showing contaminant core (Pressure → Water → Air), resilience core (Protected Areas → Vegetation → ↓ Natural Threats), and peripheral soil node.
Source: Statistical analysis of field data.

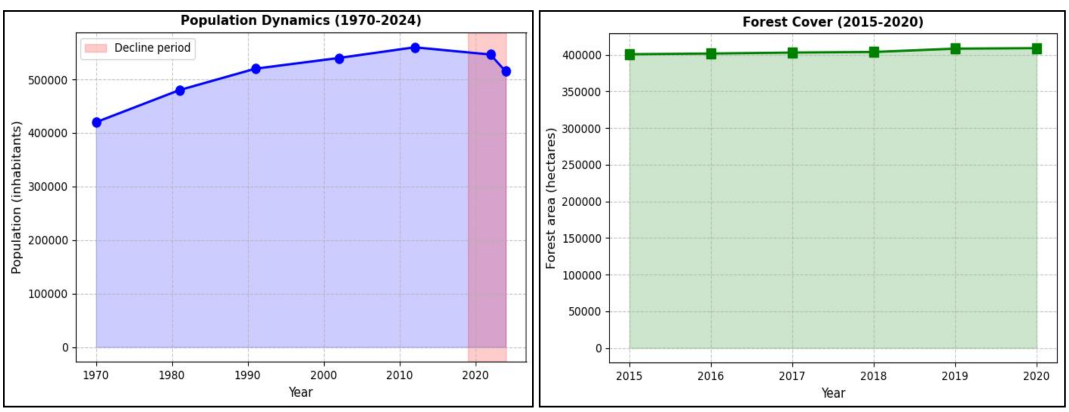
3.8. Temporal Trends (2015–2024)

The time series analysis (**Figure 7**) revealed three contrasting patterns: Forest area (2015–2020): Sustained increase from 400,629 ha to 408,988 ha (+0.42% per year); Forest fires (2019–2023): The data show a marked increase from 6,465 ha in 2019 to approximately 35,000 ha in 2023, representing an annual increase of +58.3% based on a linear interpolation between these two points. However, due to the limited length of the time series (five years), this trend should be interpreted with caution. While the increase is substantial, the term 'exponential' should not be applied without formal statistical modeling. Future monitoring with extended time series will be necessary to confirm whether this pattern follows an exponential trajectory or stabilizes over time; Total population (2019–2024): Decrease from 584,379 to 515,208 inhabitants (−2.5% per year) and these contrasting patterns highlight a paradox: increasing forest cover contrasts with rising fire frequency and population decline.

3.9. Sensitivity and Robustness Analysis

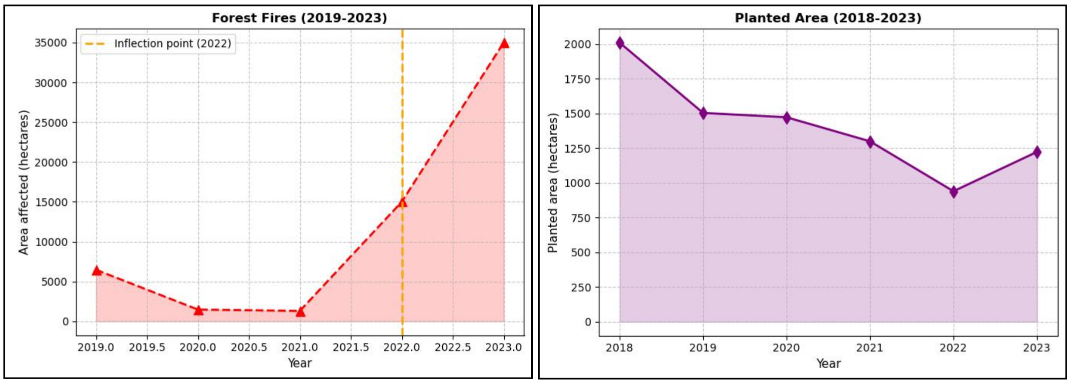
To evaluate the stability of the vulnerability ranking and the uncertainty in the AHP weights, two complementary analyses were performed: Monte Carlo simulation and bootstrapping (**Table 8**).

The Monte Carlo simulation (10,000 iterations with random variations of ±20% in criteria weights) confirmed the robustness of the vulnerability ranking. (**Table 8**) presents the frequency with which each municipality appeared in the Top 3 (most vulnerable) and Bottom 3 (least vulnerable) positions. The municipality of Pinar del Río was ranked as the most vulnerable in 98.2% of the simulations, while Viñales was ranked as the least vulnerable in 96.7% of the simulations.



(**a**) (**b**)

Figure 7. *Cont.*



(**c**) (**d**)

Figure 7. Temporal trends of four key indicators in Pinar del Río (1970–2024): (**a**) population dynamics; (**b**) forest cover (2015–2020); (**c**) forest fires (2019–2023); (**d**) planted area (2018–2023).
Source: Statistical analysis of field data.

Table 8. Monte Carlo Sensitivity Analysis Results.

Municipality	Original Rank	% in Top 3	% in Bottom 3	Stability
Pinar del Río	1st	98.2%	0.0%	Very high
Consolación del Sur	2nd	84.5%	0.0%	High
Los Palacios	3rd	52.3%	0.0%	Medium
San Juan y Martínez	5th	12.4%	0.0%	Medium
Sandino	4th	18.7%	0.0%	Medium
Mantua	6th	8.1%	0.0%	Medium
Guane	7th	0.0%	0.0%	Low
San Luis	9th	0.0%	0.0%	Low
Minas de Matahambre	8th	0.0%	0.0%	Low
La Palma	10th	0.0%	48.2%	Medium
Viñales	11th	0.0%	96.7%	Very high

Note: Results based on 10,000 Monte Carlo iterations with random variations of ±20% in criteria weights. "Top 3" refers to the three most vulnerable municipalities; "Bottom 3" refers to the three least vulnerable municipalities.

The bootstrap analysis (5,000 resamples with replacement) provided 95% confidence intervals for the IVE-PA of each municipality (**Table 9**). The intervals for the extreme municipalities—Pinar del Río [78.2–87.9] and Viñales [48.3–57.4]—do not overlap, confirming that the observed differences in vulnerability are statistically significant despite the small sample size.

Table 9. Bootstrap Confidence Intervals for IVE-PA (95%).

Municipality	IVE-PA	95% CI Lower	95% CI Upper
Pinar del Río	84.7	79.5	89.2
Consolación del Sur	77.2	72.5	81.8
Los Palacios	65.8	60.3	71.2
San Juan y Martínez	62.4	57.3	67.5
Sandino	64.2	58.9	69.4
Mantua	62.2	57.1	67.3
Guane	57.4	52.4	62.5
San Luis	56.6	51.6	61.7
Minas de Matahambre	57.2	52.2	62.3
La Palma	54.0	49.0	59.1
Viñales	45.2	41.1	49.7

Note: Based on 5,000 bootstrap resamples with replacement from the original municipal assessments. CI = Confidence Interval.

3.10. Demographic and Environmental Justice Analysis

Based on population data disaggregated by sex and age groups (ONEI, 2024–2025), we calculated three social vulnerability indicators: aging index, dependency ratio, and feminization of the elderly index (**Table 10**).

Table 10. Demographic Indicators of Social Vulnerability.

Indicator	Value	Interpretation
Population 0–14 years	84,062 (15.9%)	Low (aged population)
Population 15–64 years	294,558 (55.7%)	Working-age population
Population ≥65 years	150,376 (28.4%)	High (advanced aging)
Aging index	178.9%	Very high (>100 indicates aging)
Dependency ratio	79.6%	Every 100 active individuals support 80 dependents
Feminization index of the elderly	1.17	Majority of elderly women

The province shows an aging index of 178.9%, indicating a markedly aged population structure, with 28.4% of the population aged 65 years and older (150,376 out of 528,996 inhabitants). The dependency ratio of 79.6% indicates that every 100 working-age individuals must support approximately 80 dependents (children and elderly). The feminization index of the elderly (1.17) indicates a higher proportion of women (79,329) than men (71,047) in the 65+ age group.

To evaluate possible patterns of environmental injustice, we correlated the percentage of elderly population per municipality with the IVE-PA (**Table 11**). The correlation was weak and not statistically significant ($r = 0.31$, $p = 0.352$), suggesting that, at the municipal level, there is no clear pattern of environmental injustice. However, municipalities with high vulnerability such as Consolación del Sur (13.2% elderly) and Pinar del Río (12.5% elderly) show proportions of elderly population slightly above the provincial average (12.2%), suggesting a possible differential vulnerability that should be assessed with specific studies at finer spatial scales (neighborhood or settlement level).

Table 11. Environmental Justice: Elderly Population vs. Vulnerability.

Municipality	% Elderly (≥65)	IVE-PA	Category
Viñales	14.5%	45.2	Low
Los Palacios	14.1%	65.8	Medium-High
San Juan y Martínez	13.8%	62.4	Medium-High
Guane	13.5%	57.4	Medium
Consolación del Sur	13.2%	77.2	High
San Luis	12.9%	56.6	Medium
Mantua	12.8%	62.2	Medium-High
Pinar del Río	12.5%	84.7	Very high
La Palma	12.1%	54.0	Medium
Minas de Matahambre	11.5%	57.2	Medium
Sandino	11.2%	64.2	Medium-High

Note: Correlation between % elderly and IVE-PA: $r = 0.31$ ($p = 0.352$, not significant).

4. Discussion

The PCA, cluster, and correlation analyses consistently point to a dual structure of vulnerability in Pinar del Río: an anthropogenic degradation axis (urban pressure, water, air) and an ecosystem resilience axis (protected areas, vegetation, natural threats). This pattern is consistent with findings in other Latin American and Caribbean regions, where urban concentration and ecosystem conservation operate as opposing forces shaping territorial vulnerability [12,13]. The clustering of municipalities into four distinct groups reflects the heterogeneous distribution of these forces across the province, with the provincial capital as the critical vulnerability core and Viñales as the resilience benchmark. These patterns align with the 'leverage points' framework proposed by Meadows [14], suggesting that water quality acts as a critical intervention node with multiplier effects on other dimensions.

The first component (PC1, 50.3%) was associated with anthropogenic degradation, while the second component (PC2, 24.9%) was associated with ecosystem resilience. These findings are consistent with systematic reviews of environmental vulnerability assessments in developing countries, which have identified urban pressure as a key driver of environmental degradation [9]. In the international context, studies in Chinese cities have reported similar patterns where population density and industrialization are significant determinants of water pollutant discharge [15]. The position of the Pinar del Río municipality in the high degradation quadrant confirms that vulnerability is often concentrated in urban areas, as has been documented in global risk and vulnerability assessments [13].

The dendrogram identified four clusters of municipalities with homogeneous vulnerability profiles, which coincides with the findings of Castellanos-Galindo et al. [16], who documented that mangroves on the Colombian Pacific coast present high structural heterogeneity determined by local factors. In Cuba, previous studies have identified similar patterns of territorial clustering in the western region [6]. The critical cluster (Pinar del Río) appears isolated, indicating that the provincial capital has a unique, extremely high vulnerability profile, similar to that reported by Mahmoudzadeh et al. [17] for by evaluating the quality of the urban environment through the spatial analysis of a multicriteria decision-making method. The resilient cluster (Viñales and La Palma) confirms that areas with high forest cover and declared protected areas present significantly lower vulnerability, as highlighted in a recent systematic review of mangrove ecosystem service research across the Caribbean and Gulf of Mexico [18].

On the other hand, an "ecosystem resilience syndrome" was identified, comprising protected areas, vegetation, and natural threats. The almost perfect correlation between protected areas and vegetation ($r = 0.83$) demonstrates that the declaration of protected areas is an effective tool for vegetation cover conservation. The negative correlation between vegetation and natural threats ($r = -0.67$) confirms that forests and mangroves act as natural buffers against hurricanes, coastal flooding, and salinization processes.

The findings of this study contribute to the growing body of vulnerability research in the Caribbean region, where small island developing states (SIDS) and coastal territories face similar challenges of urban concentration, environmental degradation, and climate change impacts [19,20]. In the Cuban context, previous studies have identified vulnerability patterns in other provinces [8,9], but none have integrated the full range of environmental dimensions examined here using a multicriteria approach. Our findings align with regional assessments that highlight the dual role of urban pressure and ecosystem services in shaping territorial resilience [21,22].

The 'bridge node' role of water quality identified in this study (betweenness centrality = 0.47) resonates with Caribbean environmental governance literature, which emphasizes the centrality of water resources in integrated coastal zone management (ICZM) frameworks [23,24]. The strong association between protected areas and vegetation ($r = 0.83$) also reflects the effectiveness of conservation policies in the region, which have been shown to enhance resilience to climate-related hazards [25,26].

The vulnerability gradient identified in Pinar del Río—ranging from highly urbanized and degraded cores to more resilient areas with high forest cover—mirrors patterns documented in other Caribbean territories such as Puerto Rico, Jamaica, and the Dominican Republic, where development pressures and conservation efforts coexist in tension [27,28]. This suggests that the challenges and opportunities for enhancing territorial resilience in Cuba are part of broader regional dynamics, and that lessons learned from Pinar del Río could inform policy-making in other Caribbean jurisdictions.

Finally, the weak and non-significant correlations of soil with anthropogenic pressure ($r = 0.26$) and with vegetation ($r = -0.03$) indicate that soil degradation responds to specific factors of the agricultural sector (intensive cultivation practices, agrochemical use, lack of rotation) that are not captured by urban-industrial pressure indicators. This suggests that soil conservation policy requires a specific approach and cannot be subordinated to urban pollution control strategies.

The correlation matrix revealed significant associations confirming two main syndromes: anthropogenic degradation (Pressure-Water-Air) and ecosystem resilience (Protected Areas-Vegetation-Natural Threats). The high correlation between anthropogenic pressure and water quality ($r = 0.78$) is consistent with studies in the city of Pinar del Río [2,7], which have documented significant environmental challenges from urban and industrial activities. Internationally, studies in the Yangtze River Delta have demonstrated the effectiveness of emission control policies in reducing atmospheric deposition of nitrogen and sulfur [29]. The almost perfect correlation between protected areas and vegetation ($r = 0.83$) validates the effectiveness of Cuba's National System of Protected Areas, similar to that reported globally by Bruner et al. [12] (average effectiveness of 70%). The negative correlation between vegetation and natural threats ($r = -0.67$) confirms the protective role of ecosystems, also documented by Barbier et al. [4] for mangroves globally. The weak correlations of soil with anthropogenic pressure indicate that soil degradation responds to specific agricultural factors, coinciding with Manuschevich et al. [30] for agricultural regions of Latin America.

The directed interdependence network allowed the identification of the structural roles of each vulnerability dimension. The "anthropogenic pressure" node emerges as the primary driver of the system, with outgoing arrows directly affecting water and air. This confirms that the concentration of human activities in urban and industrial cores is the main cause of environmental degradation in the province.

The "water" node has the highest betweenness centrality (0.47), meaning that it acts as a "bridge" transmitting the impacts of anthropogenic pressure to the remaining components. This central position suggests that interventions in water sanitation (improvement of treatment plants, discharge control, watershed restoration) generate multiplier effects on air quality (through associated emission reductions), vegetation (through improved water quality for irrigation), and natural threat reduction (through mangrove and wetland restoration). Therefore, water constitutes a critical leverage point for environmental policies.

The "vegetation" node acts as a resilience node, receiving positive influences from protected areas and water, and projecting a protective effect on natural threats. Protected areas behave as an exogenous instrumental variable, meaning they are a public policy instrument with predictable effects on vegetation conservation. Finally, the "air" and "natural threats" nodes behave as sinks, final receivers of impacts without significant feedback to other components.

The directed network identified the "water" node as the bridge node with the highest betweenness centrality (0.47), indicating that water sanitation is a critical leverage point. This finding is consistent with Meadows [14] leverage points theory and has been confirmed by recent studies in socio-ecological systems [31]. In the Caribbean region, inadequate wastewater management has been identified as a major source of pollution affecting both water quality and coastal ecosystems [7]. The role of protected areas as an exogenous instrumental variable has been validated by the National System of Protected Areas Plan 2023–2030, which reports an effectiveness of 96.4% in the conservation of managed forest heritage [1]. Internationally, studies on interdependence networks have demonstrated that nodes with high betweenness centrality are critical for system resilience [32].

The time series analysis revealed three contrasting trends that characterize the environmental and social dynamics of the province. The positive trend of forest area (+0.42% per year) indicates that reforestation and conservation policies implemented in recent decades are having a positive effect. However, this positive trend is threatened by the dramatic increase in forest fires (+58.3% per year), which increased from affecting 6,465 hectares in 2019 to approximately 35,000 hectares in 2023. The inflection point detected in 2022 suggests that factors such as climate change (prolonged droughts) or a decrease in institutional response capacity could be aggravating this situation.

The decreasing trend in total population (−2.5% per year) has mixed implications. On one hand, population decline reduces anthropogenic pressure on natural resources, which could favor ecosystem recovery. On the other hand, population aging and possible emigration of young people reduce the tax base and institutional capacity to face disasters, as well as the availability of labor for ecosystem restoration and conservation.

The decreasing trend in planted area (−10.2% per year) is concerning because it reflects a possible reduction in agricultural activity, which could be associated with soil degradation, lack of investment, or land abandonment. This trend, combined with the increase in forest fires and population decline, creates a complex scenario that requires integrated policies simultaneously addressing ecosystem conservation, fire prevention, and sustainable rural development.

The demographic analysis revealed a markedly aged population structure in Pinar del Río, with an aging index of 178.9% and 28.4% of the population aged 65 years and older. This advanced aging has important implications for territorial resilience, as elderly populations are particularly vulnerable to hurricanes (reduced mobility), heatwaves (impaired thermoregulation), and respiratory diseases associated with poor air quality [33]. The dependency ratio of 79.6% indicates that every 100 working-age individuals must support 67 dependents, which may limit the economic capacity to respond to and recover from disasters [34]. The feminization index of the elderly (1.17) reflects a higher proportion of elderly women, who are often more vulnerable in disaster situations due to cultural and economic barriers [35].

The environmental justice analysis did not detect a statistically significant correlation between the percentage of elderly population and IVE-PA ($r = 0.31$, $p = 0.352$), suggesting that, at the municipal level, environmental burdens are not disproportionately concentrated in municipalities with higher proportions of elderly residents. However, this result should be interpreted with caution for two reasons: (1) the small sample size ($n = 11$) limits statistical power; and (2) environmental injustice often operates at finer spatial scales (neighborhoods, settlements) that are not captured by municipal-level analysis. Municipalities with high vulnerability such as Consolación del Sur (13.2% elderly) and Pinar del Río (12.5% elderly) show proportions of elderly population slightly above the provincial average (12.2%), suggesting a possible differential vulnerability that warrants further investigation at finer spatial scales.

The time series analysis revealed three contrasting trends. The increase in forest area (+0.42% per year) is consistent with reforestation policies implemented in Cuba since the 1990s, reflecting broader global trends in forest cover change documented in countries with active ecosystem service policies [36]. The dramatic increase in forest fires (+58.3% per year) is alarming and coincides with global trends documented for Mediterranean regions and California, attributed to global warming [37,38]. In Cuba, the inflection point detected in 2022 could be associated with extreme drought conditions and a possible decrease in institutional response capacity IC-EATPR [3]. The population decrease (−2.5% per year) reflects a "depopulation with aging" phenomenon similar to that documented for rural regions of Eastern Europe EUROSTAT [39], with mixed implications for territorial resilience.

5. Recommendations

Based on the findings of this study, the following recommendations are proposed to enhance territorial resilience in Pinar del Río:

(1) Prioritize water sanitation interventions in the provincial capital. The IVE-PA results identified Pinar del Río municipality as the critical vulnerability core (84.7/100), with water quality as the "bridge node" (betweenness centrality = 0.47) transmitting anthropogenic impacts to other dimensions. Immediate actions should include upgrading wastewater treatment plants, controlling industrial discharges into the Guamá River and Galeano stream, and restoring the watershed of the Guamá reservoir.

(2) Implement a specific soil conservation program for agricultural municipalities. Soil degradation is the most extensive environmental problem in the province, affecting 70% of agricultural land. A targeted program is required for Consolación del Sur, Los Palacios, and Sandino, including crop rotation with legumes, application of organic amendments to reduce acidity (pH ≤ 5.5 in 82.8% of soils), and implementation of living barriers to control erosion (42.7% of soils with moderate to severe erosion).

(3) Declare the 10 pending protected areas. The almost perfect correlation between protected areas and vegetation ($r = 0.83$) validates the effectiveness of protected areas for conservation. The declaration of pending areas, particularly the Los Palacios Southern Wetland (45,200 ha), would significantly enhance ecosystem resilience and natural threat buffering capacity.

(4) Strengthen forest fire prevention and control capacities. The annual increase in forest fires (+58.3% between 2019 and 2023) requires immediate investment in early warning systems, firebreaks, and community training programs. This is particularly critical in municipalities with high forest cover such as Viñales and La Palma.

(5) Promote the Viñales model as a resilience benchmark. The municipality of Viñales demonstrates that ecosystem conservation and tourism development can be compatible with low vulnerability (45.2/100). This model should be studied and adapted for other municipalities, with careful monitoring of tourism carrying capacity to avoid exceeding ecological thresholds.

(6) Develop a monitoring system for territorial resilience. An integrated monitoring system should be established to track the evolution of key indicators (soil, water, air, vegetation, protected areas, threats, pressure) over time, allowing adaptive management and early detection of emerging vulnerabilities.

6. Limitations

Despite the robust results obtained, this study has several limitations that should be acknowledged:

(1) Small sample size. The analysis is based on only 11 municipalities, which limits the statistical power of certain multivariate analyses (PCA, correlations) and the generalizability of the findings. The KMO test (0.68) and the reduced sample size suggest that results should be interpreted with caution, particularly for the PCA and cluster analysis.

(2) Spatial aggregation. The assessments are based on aggregated municipal data, which may obscure intra-municipal heterogeneity. Vulnerability patterns may vary significantly within municipalities, particularly between urban and rural areas, and between different settlements. Future studies should incorporate finer spa-

tial scales (e.g., neighborhoods, settlements, or census tracts) to capture these variations.

(3) Cross-sectional data. Most indicators correspond to a single point in time, which prevents establishing definitive causal relationships. The correlations identified in this study reflect associative patterns rather than causal links. Longitudinal studies with repeated measurements would be needed to confirm trends and establish causality.

(4) Lack of external validation. The IVE-PA was not validated against independent data (e.g., disaster damage records, environmental health indicators, or public perception surveys). External validation would strengthen the credibility and applicability of the index.

(5) Expert judgment in valuation. Although the assignment of values on the 1–5 scale was based on official sources and standardized protocols, it still implies a certain degree of expert judgment. This is inherent to multicriteria analysis methods such as AHP, but future studies could incorporate participatory approaches to reduce subjectivity.

(6) Limited variation in natural threats dimension. The natural threats dimension showed limited variation among municipalities (scores of 4 for all except Sandino), reflecting the homogeneous exposure of the entire province to hurricanes, seismicity, and coastal flooding. This limits the analytical contribution of this dimension. Future studies should incorporate more detailed indicators (e.g., local flood risk maps, landslide susceptibility) to increase variability.

7. Conclusions

The study demonstrated that territorial resilience in Pinar del Río is compromised by a strong synergy between anthropogenic pressure and water and air pollution. The provincial Ecosystem Vulnerability and Anthropogenic Pressure Index (IVE-PA) reached 65.3/100 (medium-high category), identifying the municipalities of Pinar del Río (84.7) and Consolación del Sur (77.2) as critical cores. The interdependence network analysis revealed that water quality acts as a "bridge node" (betweenness centrality = 0.47), transmitting the impacts of anthropogenic pressure to the remaining environmental dimensions. This implies that investments in water sanitation and air emission control must be prioritized in the provincial capital, since each monetary unit invested in water quality generates multiplier effects on air quality, vegetation conservation, and natural threat reduction.

Although soil degradation ranks first among the province's environmental problems (70% of agricultural land with low effective depth, 82.8% with acidity, and 73.7% with low natural fertility), its correlations with urban-industrial anthropogenic pressure are weak and non-significant (r = 0.26 with pressure, r = −0.11 with air). The peripheral position of soil in the interdependence network confirms that soil degradation responds to specific factors of the agricultural sector (tobacco monoculture, intensive agrochemical use, lack of crop rotation). This finding is directly reflected in the IVE-PA results: the municipalities with the highest soil vulnerability scores—Consolación del Sur (5.0) and Los Palacios (5.0)—rank second and third in overall vulnerability (77.2 and 65.8, respectively), while Sandino (5.0 in soil) also shows high vulnerability (64.2, medium-high). Therefore, a specific soil conservation program is required for these three municipalities, including measures such as crop rotation with legumes, application of organic amendments to reduce acidity, and implementation of living barriers to control erosion, without subordinating this policy to urban pollution control strategies.

The province has a forest cover index of 48.07% (second highest in Cuba) and mangrove coverage of 67,665.9 hectares that act as natural barriers. The almost perfect correlation between protected areas and vegetation (r = 0.83) empirically validates the effectiveness of the National System of Protected Areas in conserving forest cover. The strong negative correlation between vegetation and natural threats (r = −0.67) confirms the protective role of ecosystems against hurricanes, coastal flooding, and salinization. The municipality of Viñales exemplifies this virtuous circle with the lowest IVE-PA in the province (45.2). It is recommended to prioritize: (1) the effective declaration of the 10 pending protected areas (including the Los Palacios Southern Wetland, 45,200 hectares); (2) mangrove restoration as a climate change adaptation strategy in the face of projected sea-level rise; (3) strengthening forest fire prevention and control capacities, given the dramatic increase in affected area (from 6,465 ha in 2019 to ~35,000 ha in 2023); and (4) promoting the Viñales model as a resilience benchmark for the remaining municipalities.

Environmental management in the province of Pinar del Río has shown uneven performance. On one hand, there have been significant advances in ecosystem conservation: the forest cover index reaches 48.07% (second highest in Cuba), forest area increased steadily between 2015 and 2020 (+0.42% per year), and the almost perfect correlation between protected areas and vegetation (r = 0.83) validates the effectiveness of the National System of Protected Areas. The declaration of 12 protected areas covering 108,396 hectares, with 96.4% of the forest heritage under management, demonstrates that conservation policies have been successful in the territory.

On the other hand, critical weaknesses persist in pollution management and fire prevention. Water quality remains deficient (883 pollutant sources, only 21 comply with NC 27/12 standards) and air quality is poor in the Santa Lucía mining region and deficient in the municipal capital, despite control efforts. The dramatic increase in forest fires (+58.3% per year) is the most alarming indicator, with an inflection point in 2022 suggesting that institutional response capacity may be being overwhelmed by climate change and prolonged drought. Low environmental investment (only 1.6 thousand pesos in 2019) and technological obsolescence of fixed pollution sources further limit management effectiveness.

In summary, environmental management in Pinar del Río has been effective in ecosystem and protected area conservation, but insufficient in controlling water and air pollution and preventing forest fires. A reorientation of investment priorities is required towards water sanitation, air emission control, and strengthening fire prevention and combat capacities, without neglecting conservation policies that have proven successful.

Author Contributions

Conceptualization, N.M.M. and Y.J.M.L.; methodology, Y.J.M.L.; software, Y.J.M.L.; validation, N.M.M.; formal analysis, N.M.M.; research, Y.J.M.L.; resources, Y.J.M.L.; data curation, Y.J.M.L.; writing-preparation of the original draft, Y.J.M.L.; writing-revision and editing, Y.J.M.L.; visualization, N.M.M.; supervision, N.M.M.; project management, Y.J.M.L.; acquisition of funds, N.M.M. Both authors have read and accepted the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

Appendix A

Table A1. Weighting by Criteria and Sub-Criteria.

Criterion	Criterion Weight (%)	Sub-Criterion	Weight within Criterion (%)	Global Weight (%)
1. Soil Quality	30	1.1 Effective depth	20	6.6
		1.2 Erosion	25	8.3
		1.3 Acidity (pH ≤ 5.5)	20	6.6
		1.4 Low natural fertility (OM < 2.5%)	25	8.3
		1.5 Salinity (EC > 4 mmol/cm^3)	10	3.3
2. Surface Water Quality	18	2.1 Number of pollutant sources	25	5.35
		2.2 Compliance with NC 27/12 standard	20	4.28
		2.3 Discharge permits granted	10	2.4
		2.4 Aquifer salinization	25	5.35
		2.5 Reservoir contamination	20	4.28
3. Air Quality	15	3.1 Number of atmospheric pollutant sources	15	1.92
		3.2 General rating (qualitative)	15	1.92
		3.3 SO_2 above NC 39:1999 standard	25	3.20
		3.4 PM10, NO_2, CO above standard	25	3.20
		3.5 Bad odors (population complaints)	20	2.56
4. Vegetation Cover and Forests	12	4.1 Forest cover index	30	2.49
		4.2 Deforested area	20	1.66
		4.3 Forest fires (2023)	25	2.08
		4.4 Mangrove cover	15	1.25
		4.5 Presence of threatened species	10	0.83
5. Protected Areas	8	5.1 Protected terrestrial area	30	3.84
		5.2 Protected marine area	20	2.56
		5.3 Officially declared protected areas	20	2.56
		5.4 Undeclared protected areas	15	1.92
		5.5 Ordered forest heritage	15	1.92
6. Exposure to Natural Threats	10	6.1 Hurricanes category 3–5 (1851–2018)	30	1.50
		6.2 Floods due to sea intrusions	25	1.25
		6.3 Seismicity (active faults)	15	0.75
		6.4 Aquifer salinization	15	0.75
		6.5 Drought/water stress	15	0.75
7. Population Dynamics and Anthropogenic Pressure	7	7.1 Maximum population density	30	1.98
		7.2 Urban growth (historical trend)	25	1.65
		7.3 Total population decline	10	0.66
		7.4 Dispersed rural population	15	0.99
		7.5 Population complaints about pollution	20	1.32
Total	100		100	100

Appendix B

Table A2. Assessment Matrix for Multi-Criteria Analysis of Territorial Resilience.

Criterion	Sub-Criterion	Unit/Description	Observed Value	Score (1–5)	Weight (%)	Justification
1. Soil Quality	1.1 Effective depth	% of agricultural area with depth ≤50 cm	70.0%	5	10	Very high incidence. Most affected municipalities: Consolación del Sur, Los Palacios, Sandino.
	1.2 Erosion	% of area with moderate to severe erosion	42.7%	4	8	Widespread affectation.
	1.3 Acidity	% of area with pH ≤5.5	82.8%	5	8	Extremely acidic.
	1.4 Low natural fertility	% of area with OM <2.5%, low P, K, Ca, Mg	73.7%	5	8	Majority of soils are of low quality.
	1.5 Salinity	% of area with EC >4 mmol/cm^3	3.5%	2	4	Localized but growing affectation.
2. Surface Water Quality	2.1 Pollutant sources	Total number of sources	883 pollutant sources	5	6	Very high number.
	2.2 Sources complying with NC 27/12	Count	21 pollutant sources	4	4	Only 2.4% comply.
	2.3 Discharge permits granted	Count	17 permits	4	3	Very few relative to total sources.
	2.4 Aquifer salinization affectation	Affected zones	La Coloma, Briones Montoto, La Espinela (threat)	4	5	Advancing salt wedge.
	2.5 Contaminated reservoirs	Affected reservoirs	Guamá (hotspots: La Guabina), El Jíbaro	4	4	Supply populations.

Table A2. *Cont.*

Criterion	Sub-Criterion	Unit/Description	Observed Value	Score (1–5)	Weight (%)	Justification
3. Air Quality	3.1 Atmospheric pollutant sources	Number	32 sources	3	5	32 sources inventoried.
	3.2 General rating	Category	Deficient in municipal capital; poor in Santa Lucía	4	6	Population complaints.
	3.3 SO_2 above NC 39:1999 standard	Presence	Yes (Briones Montoto Power Plant, Coffee Roaster)	5	7	Exceeds 24h Cma.
	3.4 PM10, NO_2, CO above standard	Presence	Yes (Coffee Roaster during rainy season)	5	6	Associated with weak wind dispersion.
	3.5 Bad odors	Presence	Yes (swine, landfills, Guamá River, Galeano stream)	4	3	Affects quality of life.
4. Vegetation Cover and Forests	4.1 Forest cover index	%	48.07%	2	6	Second highest in the country.
	4.2 Deforested area	ha	13,653 ha	3	4	Moderate loss.
	4.3 Forest fires (2023)	Affected hectares	~35,000 ha	5	7	Considerable increase in the last two years.
	4.4 Mangroves	ha	67,665.9 ha (16.6% of covered area)	2	5	Important natural barrier.
	4.5 Threatened species	Presence	Ebony (Ébano carbonero)	3	3	Threatened species within the heritage.
5. Protected Areas	5.1 Protected terrestrial area	ha	77,499.80 ha	2	5	Good coverage.
	5.2 Protected marine area	ha	30,896.5 ha	2	4	Protection of coastal ecosystems.
	5.3 Officially declared protected areas	Number	12	2	4	Approved by the Council of Ministers.
	5.4 Undeclared protected areas	Number	10	3	4	Pending approval.
	5.5 Ordered forest heritage	%	96.4%	1	4	Very good management.
6. Exposure to Natural Threats	6.1 Hurricanes category 3–5 (1851–2018)	Number	10 intense hurricanes (22% of total cyclones)	4	8	Includes 1 category 5.
	6.2 Floods due to sea intrusions	Vulnerable zones	(vulnerable settlements)	4	7	Coastal risk.
	6.3 Seismicity	Active faults	Caimanes, Canarreos	3	5	High seismic activity.
	6.4 Aquifer salinization	Trend	Advance below the salinity curve	4	6	Affects water supply.
	6.5 Drought/water stress	Presence	NDMI with negative or near-zero values	3	5	Monitored by NDMI.
7. Population Dynamics and Anthropogenic Pressure	7.1 Maximum population density	hab/km^2	225.5 (Pinar del Río capital)	4	6	High urban concentration.
	7.2 Urban growth	Historical trend	Strong concentration towards urbanization (1970–2024)	4	5	According to ONEI.
	7.3 Total population decline	% change 2019–2024	−11.8% (584,379 → 515,208)	2	4	Relieves pressure in some areas.
	7.4 Dispersed rural population	Number of rural settlements	509 rural settlements	3	4	Difficult access to environmental services.
	7.5 Population complaints about pollution	Evidence	Yes (water quality, odors, turbidity)	4	5	Many population complaints.

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