Gendered Geoscience for Territorial Sustainability: Integrating Geodiversity, Community Knowledge, and Acoustic Biodiversity in La Guajira

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ABSTRACT– This paper presents the outcomes of a research and innovation initiative developed within the Orquídeas Postdoctoral Program, promoted by the Ministry of Science, Technology, and Innovation of Colombia. The project was led by a female group: a postdoctoral fellow, a young researcher, a senior scientist, and a science communication manager from the School of Applied Sciences and Engineering at Universidad EAFIT, in close collaboration with a leader from the Fundación Movimiento Feminista Niñas y Mujeres Wayuu (MFNMW). Together, we co-designed and implemented a territorial exploration framework that bridges scientific methods with ancestral wisdom, with a strong emphasis on gender equity, intercultural dialogue, and sustainable landscape management.

The study focuses on geodiversity and morphometric diversity in La Guajira, a region of exceptional geological and cultural value. We identified 30 Sites of Geological Interest (SGIs) through integrated GIS analysis, field validation, and participatory mapping. Our findings indicate a strong correlation between morphometric and geological diversity, influenced by the structural dynamics of the Oca and Cuisa faults and the hydrological role of the Ranchería River.

The initiative emphasizes intergenerational learning, the leadership of women in geosciences, and the contributions of local communities, especially Wayuu women, to sustainable resource governance. It aligns with Colombia's national science missions in Bioeconomy and Territory, Science for Peace, and the Human Right to Food, and incorporates acoustic biodiversity related to bats as indicators of ecosystem health.

***Keywords**: Geodiversity, Gender Equity, Geoconservation, Wayuu Knowledge, Hydrological Heritage, Food Security, Acoustic Biodiversity*

I. INTRODUCTION

La Guajira, located in the northeastern corner of Colombia, is a region of exceptional geological and cultural significance. Its diverse landscapes range from arid deserts and coastal plains in the Baja Guajira, to sedimentary basins and river systems in the Media Guajira, and complex mountainous terrains in the Alta Guajira, which includes the Sierra Nevada de Santa Marta and the Serranía de la Macuira. This physiographic diversity corresponds with a rich geological framework shaped by tectonic interactions, active fault systems such as the Oca and Cuisa faults [1], [2], and varying lithological formations that provide fertile ground for investigating geoheritage, natural resources, and landscape evolution.

Beyond its geological attributes, La Guajira is home to the Wayuu people—an Indigenous community of Colombia and Venezuela, whose millennia-old traditions are deeply rooted in a system of beliefs and values where the criteria of life and death are intertwined with a culture of survival through water, the control of natural resources, the recognition of human and non-human beings. Wayuu peoples have been challenged by environmental and territorial circumstances throughout history, what makes them examples of adaptation and resilience.

Their definition of territory is based on the cultural and natural interaction. The Earth (*Mmá* in Wayuunaiki) embodies femininity and is connected to the ancestral cemeteries where the natural equilibrium of the territory take place as the beginning and the ends of a Wayuu life. The ancestors that laid on the Wayuu cemeteries are the guides of the family through the dreams together with the nonhuman spirits such as the wind, the rain, the sun, the constellations, the plants, and the animals [3], the older ancestors, each e'iruku (family system) is represented with a totem of protection related to an animal [4].

A key element of their cultural and social identity are their mechanisms for conflict resolution based on their own form of governance, which is structured around the principle of e*'iruku*, as well as the central role of the spoken and a compensation system. This is grounded in the traditional mediator: the *Pütchipü'üi* (Wayuu Palabrero). This Wayuu Normative System is inscribed on the UNESCO Representative List of the Intangible Cultural Heritage of Humanity since 2010 [5].

However, recent studies show that, although it continues to be a legitimate and still-used system, there is a weakening of the institution as new generations of *palabreros* move away

from traditional conceptions, lacking full awareness of the role and responsibility they hold in ensuring the social and territorial harmony of the Wayuu. This has led to the proposal of initiatives aimed at identifying new organizational processes to strengthen indigenous justice. For instance, through dialogue for the transfer of knowledge that includes non-traditional actors such as youth and women [6].

Even though the Normative System is based on the role of man, women are the base of the cultural identity transmission and the representation of the relationship with the nature and the territory. "The Wayuu identity is inherited from the mother. The Wayuu social organization is matrilineal, with kinship defined through the maternal line and expressed through families" [3]. Women are represented in their cosmology as "guardian figures of the Wayuu territory and teach both men and women to respect and protect the land to preserve life, as noted by Weilder Guerra Curvelo (as cited in [3]). Wayuu women are gaining on the empowerment and leadership to defend their territories and the role of women; we can see now women authorities. But they are continually facing many challenges for the survival of the families (health, food justices, access to potable water...) and the protection of nature and the territories. That is why initiatives such as the *Movimiento Feminista Niñas y Mujeres Wayuu* (MFNMW), with who we collaborate in this research, promotes diversity in a comprehensive and intersectional manner, with a feminist, community and intercultural perspective. Denounces, among other manners, all types of megaprojects that threaten the survival of indigenous communities and nature, which represent the mother of all living beings [7].

The dialogue between the academical and the Wayuu communities giving the voice to women, is a key element to increase the holistic knowledge and other tools for the empowerment of Wayuu women and for the emergence of new perceptions of the actions for the territory and the Earth.

The environmental and cultural values just presented converge to make La Guajira an ideal case study for exploring the intersections between geodiversity, bio-cultural heritage, and sustainable development with a gender perspective [8], [9].

This research aims to characterize the spatial distribution of geodiversity across La Guajira using remote sensing, morphometric analysis, and participatory mapping, and to identify and document Sites of Geological Interest (SGIs) based on both scientific and community-based criteria. The project applies a quantitative geodiversity assessment methodology adapted to regional conditions [10], [11], complemented by qualitative inputs from local knowledge holders, especially from Indigenous women leaders.

A distinctive feature of this initiative is its focus on gender equity in science, technology, engineering, and mathematics (STEM). Women have historically been underrepresented in STEM, including the earth sciences. In [12], Burek and Higgs pointed out the barriers that geosciences women have been facing. Starting with the stereotypes and cultural barriers that were supposed opposite to science, based on its definition by the masculine characteristics' objective and reasonable. In this way women were barred from scientific societies or demotivated on their seek of professional and academical jobs. When they manage to find a job, it was frequently in precarious conditions, such as in voluntary bases with no payment. As the authors highlighted "women had to have a pioneering spirit because society as a whole did not support the ambitions of women to follow their geological interests until the late 20th century."

According to Kölbl-Ebert and Turner [13], Women have been pioneers in geoscience disciplines, but their recognition or academic credit did not follow or have been forgotten. Sometimes because their research was incorporated into the publications of the men for whom they worked and those that were able to publish in their name was only for other publics such a Women or Children [12]. In Latin America, the lack of political, economic and social rights Women before the 20 centuries, make almost impossible to find constancy of women in geology. The first references were from women that came from wealthy families [14], as it was the case in Europe in the centuries before [12]. In this sense, women had struggle for decades to change male opinion and find their place in the STEM.

In the 20 centuries the actions to balance the place of women in sciences and geosciences have been considerably increasing, with laws, fundings, projects, associations, conferences and networks. However, as some authors have recently shown, despite the notable progress at different levels, women in the field remain underrepresented in positions of leadership and influence and across the sectors of academia, research, and industry [15], [16]. Specially for the case of postdoctorates, who struggle with structural barriers between the dependence on the supervisor for its future and the conditions to balance with the family responsibility [16].

The project from which this publication come, is a response to the strategies that could "create an environment where women are empowered to flourish, contribute, and ultimately shape the future of the field" [16]. The project not only is part of a national strategy to generate opportunities for women in science, but gives the opportunity to create networks, female role models and mentoring that could help the professional growth of women and to retain young researcher in STEM fields.

This project confronts that gap directly by promoting a collaborative modelled entirely by women from diverse disciplines, life paths, and cultural backgrounds. The team included a senior researcher, a postdoctoral fellow, a young female investigator, a communication specialist, and a Wayuu community leader, reflecting an intentional strategy for feminist and intercultural knowledge co-production in the context of scientific diplomacy and territorial sustainability.

Moreover, the project contributes to Colombia's national science missions—Bioeconomy and Territory, Science for Peace, and the Human Right to Food—by generating territorial data that support environmental governance,

geotourism, and food-water-energy nexus planning. It also addresses broader global commitments such as the 2030 Sustainable Development Goals, particularly those related to gender equality (SDG 5), quality education (SDG 4), clean water and sanitation (SDG 6), and life on land (SDG 15).

Through this integrated framework, the research not only expands scientific knowledge of geodiversity in La Guajira but also opens pathways for inclusive territorial management and the empowerment of women and Indigenous communities in STEM and environmental governance.

II. PROJECT CONTEXT AND MISSION ALIGNMENT

This project is framed within Colombia's Orquídeas Postdoctoral Program, which promotes inclusive research and innovation led by women scientists. Implemented by the School of Applied Sciences and Engineering at Universidad EAFIT, the project aligns directly with three of the national Science, Technology, and Innovation Missions, offering a territorialized contribution to sustainable development in La Guajira.

A. Bioeconomy and Territory

The exploration and mapping of geodiversity and morphometric diversity serve as a foundation for geo-ecotourism initiatives and the valuation of geological and natural resources through a bioeconomic lens. By identifying Sites of Geological Interest (SGIs), the project provides a strategic input for sustainable tourism planning, contributing to regional income generation and environmental education. Local rock formations, hydrological systems, and desert ecosystems—such as the Macuira Mountains and the Taroa Dunes—are positioned as geosites that hold not only scientific value, but also potential for community-managed tourism models based on geoconservation and natural product valorization [11], [17].

B. Science for Peace

La Guajira is a region marked by historical tensions over land use, resource access, and ethnic marginalization. The project contributes to the Science for Peace mission by promoting intercultural governance mechanisms, where scientific methods are complemented by Wayuu ancestral knowledge and inclusive dialogues among stakeholders. Through participatory mapping and community workshops, the initiative enhances territorial capacities and fosters conflict transformation strategies based on environmental stewardship and collective memory, especially among women and youth in the Wayuu communities.

C. Human Right to Food

Hydrological heritage, especially that related to the Ranchería River and associated aquifers, plays a vital role in sustaining local livelihoods. By analyzing morphometric indicators such as drainage density and topographic wetness, the project identifies priority zones for agroecological resilience, irrigation planning, and water security. These insights contribute to a deeper understanding of the water-food nexus in arid and semi-arid environments and support the construction of resilient production systems in line with local traditions and ecological conditions [18].

Together, these mission alignments reinforce the role of geoscientific research as a transformative tool for inclusive development and feminist innovation. The work bridges territorial intelligence, gender justice, and biocultural sustainability, contributing to the broader Latin American agenda for equality, sustainability, and peace.

III. METHODOLOGY

This research employed a mixed-methods approach combining quantitative geospatial techniques with qualitative, participatory, and intercultural methodologies. The goal was to characterize the spatial patterns of geodiversity in La Guajira and identify Sites of Geological Interest (SGIs) through a process that integrates scientific rigor and community-based knowledge.

A. Remote Sensing and GIS-Based Morphometric Analysis

We utilized Digital Elevation Models (DEMs) derived from ALOS PALSAR 12.5 data and high-resolution satellite imagery to generate a series of morphometric indices critical for understanding terrain heterogeneity. These included:

- Slope Gradient – to determine landscape steepness and potential erosional dynamics.
- Drainage Density – to assess the distribution and intensity of fluvial networks.
- Relief Amplitude – to identify vertical variations in terrain and structural prominence.
- Topographic Wetness Index (TWI) – to evaluate areas of moisture accumulation and potential hydrological sensitivity.

These indexes were processed in ArcGIS 10.8 and QGIS, enabling a morphometric classification of the territory into distinct geomorphological units.

B. Participatory Mapping and Validation of SGIs

We conducted three participatory mapping workshops in Media and Alta Guajira with Wayuu communities, particularly involving women, youth, and elders. These spaces allowed for the co-identification of SGIs based on cultural significance, ancestral narratives, and perceived landscape transformations.

Community cartographers and local guides contributed to ground-truthing efforts, helping validate remote sensing outputs with situated knowledge. This participatory layer was essential to legitimize and culturally enrich the SGI selection process.

C. Hydrogeological Data Integration

Given the central role of water in La Guajira's socio-ecological systems, we incorporated hydrogeological datasets focusing on the Ranchería River Basin, a crucial hydrological corridor that connects the Alta, Media, and Baja Guajira regions. We analyzed:

- Aquifer recharge zones and hydrostratigraphic units, using secondary data from regional studies.
- Flow regime patterns, derived from hydrological stations and precipitation records.
- Territorial water access disparities, especially in areas affected by mining, agriculture, or coastal aridity.

The river was treated not only as a physical hydrological system, but also as a cultural and biopolitical axis structuring livelihoods, land use, and ecosystem services.

D. Acoustic Biodiversity Monitoring

To incorporate an ecological perspective and assess biodiversity indirectly through bioacoustics, we conducted pilot monitoring of bat echolocation calls at selected SGIs. Using ultrasonic detectors (e.g., Pettersson D240X and AudioMoth), recordings were collected at dusk in areas with varying degrees of vegetation cover and geological substrate. Bats (Chiroptera) were selected as bioindicators due to their sensitivity to landscape fragmentation and ecosystem quality. Soundscape analysis provides an additional layer to assess the interplay between abiotic diversity and biological resilience.

IV. RESULTS AND DISCUSSION

The results of the study reveal a differential spatial distribution of geodiversity across the three main physiographic zones of La Guajira—Alta, Media, and Baja. The Alta Guajira and Baja Guajira exhibit significantly higher geodiversity values compared to the Media Guajira, due to the combined influence of diverse lithological units, morphotectonic activity, and varied hydro-climatic conditions. This pattern is consistent with field observations and supported by morphometric indices derived from remote sensing.

A. Geodiversity and Structural Control

A strong correlation was observed between areas of high geodiversity and the presence of major geological structures, particularly the Oca and Cuisa faults (figure 1). These fault systems play a central role in shaping the region's structural relief, influencing erosion patterns, drainage networks, and sediment deposition. The tectonic uplift associated with these faults has contributed to the formation of prominent geomorphological features such as escarpments, fluvial terraces, and mountain front zones, especially along the flanks of the Serranía de Jarara, Serranía de Cosinas, and Serranía de la Macuira [2], [19].

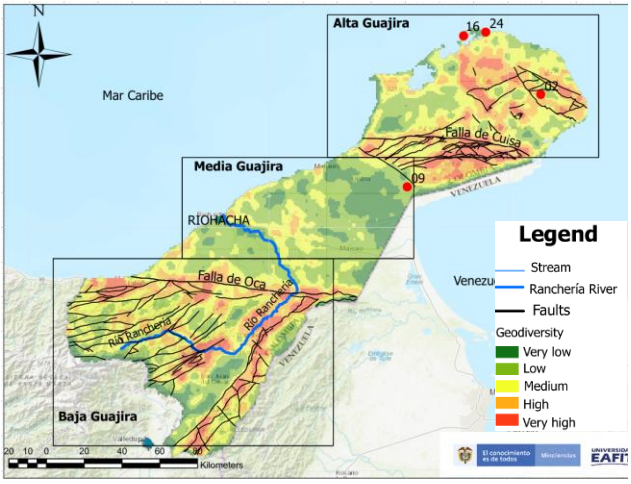

Figure 1. Map of structural features and geodiversity of La Guajira. Original contribution.

B. Spatial Identification of SGIs

Based on the integration of scientific criteria and community validation, 30 Sites of Geological Interest (SGIs) were identified throughout the territory. These sites reflect the region's geological richness, ranging from igneous outcrops and fossil-bearing formations to unique landforms shaped by aeolian, fluvial, and coastal dynamics. Notable SGIs include the Pilón de Azúcar, the dune fields of Taroa, and the carbonate platforms near Bahía Hondita, each holding significant scientific, cultural, and educational value.

C. Role of Morphometric Indices

The use of morphometric indices such as the Topographic Wetness Index (TWI), Slope Gradient, Drainage Density, and Relief Amplitude provided valuable insights into the dynamics of landscape evolution. In Alta Guajira, high relief and dissection values indicate active structural processes and enhanced erosional regimes. Conversely, Media Guajira, characterized by broad sedimentary basins and lower slope gradients, exhibits more subdued topographic and hydrological complexity.

These metrics allowed for a quantitative assessment of terrain heterogeneity and aided in the prioritization of conservation zones with high morphometric and geodiversity convergence. This is aligned with the approaches outlined by Argyriou [10] and Brilha [11], supporting objective landscape classification for geoconservation planning.

D. Bioacoustic Monitoring and Acoustic Diversity

Complementary to the geodiversity analysis, acoustic monitoring of bat species was conducted in selected SGIs to assess biodiversity indicators in relation to morphometric and geological diversity. Acoustic richness was notably higher in Alta and Baja Guajira, where terrain heterogeneity supports diverse roosting habitats and foraging niches. In contrast, Media Guajira, with its flatter relief and simplified vegetation structure, exhibited reduced acoustic activity and species richness.

The presence of phyllostomid and molossid species across hydrogeological corridors, particularly along the Ranchería River, underscores the ecological connectivity facilitated by geodiversity. These results affirm the value of integrating acoustic diversity metrics in the spatial evaluation of geoconservation and land-use planning.

E. Implications for Territorial Management

The findings underscore the need to recognize geodiversity as a key input in territorial governance, particularly in bio-geo-culturally diverse regions like La Guajira. The SGIs not only represent geological phenomena but also serve as sites of memory, identity, and ecological connectivity. Their identification reinforces the value of territorial approaches that integrate scientific, cultural, and community-based knowledge systems.

Moreover, the correlation between geodiversity and acoustic biodiversity highlights the multifunctional role of geological landscapes in sustaining ecological services. This integrated perspective aligns with Colombia's science and innovation missions in bioeconomy, peacebuilding, and the human right to food.

V. GENDER AND TERRITORIAL IMPACT

This research initiative is grounded in a process that addresses inequities on multiple levels. We demonstrate the

capacity of women to conduct science; we work in a field that is relatively new within the geosciences, sometimes dismissed as 'non-science' by peers; we affirm our presence in the STEM community by publishing our fieldwork; and we defend dialogue between disciplines as well as between scientists and communities, bridging gaps across different forms of knowledge and giving voice and recognition to ancestral knowledge in the conception of geodiversity.

Every step of the project, from its conception, was co-defined with a female Wayuu leader, who also belongs to a historically excluded group. We included the voices of non-traditional actors in the territory, such as women and children, in the scientific process. They actively participated in knowledge production, and their data was treated as equally important as the systematic data obtained through traditional geological methodologies. We also sought to give voice to non-human beings, such as bats, in order to obtain a more holistic narrative of geodiversity in the territory from multiple perspectives. All fieldwork was conducted with respect for the territory and in close collaboration with the communities who obtain somehow the recognition for their participation.

This project is entirely carried out by a multidisciplinary team of women, who may serve as role models for others—a strategy highlighted as essential by many authors [12], [14], [15], [16]. Female mentorship has also been emphasized as a crucial asset [16], supporting our ability to navigate the complexities of academia and careers in the geosciences, while maintaining the confidence and resilience needed to shape our future.

VI. DISCUSSION

6.1. Integrated Landscape Exploration

This project approached the assessment of geodiversity through a regional-scale lens (1:100,000), which allowed for the identification and classification of geological and geomorphological diversity across a broad and complex territory. The region of La Guajira—located at the northernmost tip of Colombia—hosts a striking variety of landscapes, ranging from coastal plains and desert dunes to mountain ridges and fluvial terraces. This heterogeneity is closely tied to the interaction of lithological variability, tectonic structures, and contrasting climatic regimes.

Key geomorphological and geological features mapped include the Sierra Nevada de Santa Marta (SNSM)—a tectonically active massif with sharp altitudinal gradients—and the Macuira National Natural Park, a unique humid enclave in an otherwise arid landscape. Structural elements such as the Oca and Cuisa faults provide evidence of ongoing tectonic activity, shaping escarpments, fault scarps, and influencing drainage evolution. The combination of remote sensing data, geostatistical modelling, and field validation facilitated a comprehensive understanding of how Earth surface processes and deep geological structures shape the territory.

This integrated exploration highlights the importance of recognizing the abiotic components of the landscape not merely as a physical substrate but as dynamic systems that underpin ecological resilience, cultural narratives, and socio-economic activities.

6.2. Correlation Between Geodiversity and Morphometric Diversity

One of the key contributions of this study is the empirical demonstration of a bidirectional relationship between geodiversity and morphometric diversity. Areas characterized by heterogeneous lithologies, intense tectonic deformation, and active geomorphological processes—particularly in Alta and Baja Guajira—display higher values in terrain complexity indicators such as slope gradient, relief amplitude, topographic wetness index (TWI), and drainage density.

These morphometric patterns mirror and reinforce the geodiversity hotspots, providing a methodological basis for spatial prioritization in conservation planning. Moreover, the convergence of high morphometric variation and geodiversity served as a guide for the identification of 30 Sites of Geological Interest (SGIs), which reflect both scientific significance and cultural relevance. These SGIs are not only repositories of geological information but also symbolic landmarks for local communities.

The correlation confirms the value of combining quantitative geospatial analyses with qualitative territorial knowledge, supporting integrated landscape governance models that reflect both natural and cultural diversity.

6.3. Geodiversity and Ecosystem Services

The Ranchería River Basin emerged as a central hydrological and cultural axis that organizes the territorial dynamics of La Guajira. Originating in the highlands of the Sierra Nevada de Santa Marta, the *river* traverses' different climatic zones and geomorphological regions before discharging into the Caribbean Sea. This fluvial corridor plays a critical role in regulating access to water for agriculture, livestock, domestic use, and biodiversity maintenance, particularly in arid and semi-arid zones.

- In Alta Guajira, communities rely on spring-fed systems and mountain runoff.
- In Media Guajira, the most agriculturally productive subregion, the demand for water is highest due to irrigation and livestock.
- In Baja Guajira, proximity to the sea and low precipitation result in severe water stress, exacerbated by extractive activities and climate variability.

The study also explored the acoustic diversity of bats in selected SGIs, using bioacoustics as a proxy for broader biodiversity assessment. Preliminary findings suggest a positive relationship between geodiversity and ecological complexity, reinforcing the idea that abiotic heterogeneity supports biotic richness. This is particularly relevant for ecosystem services such as pollination, seed dispersion, and pest regulation, which are mediated by chiropteran species.

In sum, the interaction between geological diversity, hydrological regimes, and biodiversity underscores the relevance of geodiversity as a foundational layer in territorial sustainability and food security strategies, especially in Indigenous and rural contexts. That is why the participative mapping is crucial to confirm the structure of the territory (places, activities, natural and cultural elements, communities' placements, communication paths, etc.) that will help in the geodiversity management and the definition of priorities that have a territorial context.

VII. CONCLUSIONS

- There is a direct correlation between geodiversity and morphometric diversity, particularly in Alta and Baja Guajira, where structural and lithological complexity converge.
- Tectonic activity, notably along the Oca and Cuisa fault systems, shapes significant landscape features, drives morphogenesis, and contributes to the formation of geodiversity hotspots.
- Thirty Sites of Geological Interest (SGIs) were identified through a process combining spatial modeling and participatory validation. These SGIs represent a valuable knowledge base for geoconservation, education, and community-led ecotourism.
- The integration of geodiversity into territorial management enhances the ability to address multiple challenges, including climate adaptation, biodiversity conservation, and disaster risk reduction. It also contributes to more inclusive and culturally relevant planning frameworks.
- Water—as both a biophysical resource and a cultural symbol—emerges as a central axis for governance, cooperation, and sustainability. Its management must consider geohydrological, ecological, and sociopolitical dimensions to ensure long-term resilience and food security. The project, its horizontal mentorship model and the methodologies applied, promoting intergenerational learning, field-based training, and ethical co-production of knowledge in local and rural contexts strengthened the scientific capacity of women in geosciences in Colombia, particularly in territories historically underrepresented in STEM fields, and expand the scope of women's leadership in science and innovation.

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