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Spatial-Morphological Dynamics of Clan-Based Settlements (Huta) Using Landscape Metrics in Sihapas Barumun Subdistrict, 2005–2025

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ABSTRACT

The development of road infrastructure often triggers morphological transformations in traditional settlements that remain tied to local customs and culture. Investigating these dynamics is theoretically crucial for understanding how the spatial resilience of indigenous communities adapts to modern connectivity networks. This study aims to analyze the morphological transformations and spatial patterns of clan-based settlements (huta) in Sihapas Barumun Subdistrict using a time-series approach over the period 2005–2025. The research method involved consistent digitization of satellite imagery at a fixed mapping scale of 1:3,000 and a Minimum Mapping Unit (MMU) threshold of 1,000 m², integrated with landscape metric modeling using FRAGSTATS software. Quantitative analysis results indicate a significant structural shift from an isolated fragmentation phase (2005–2015) toward a phase of consolidated corridor agglomeration (2015–2025). The active expansion phase is characterized by increasing values of Number of Patches (NP) and Patch Density (PD) due to the presence of new expansion patches. Conversely, during the convergence phase, the NP and PD values decrease, indicating the physical consolidation of settlement polygons due to infill development. This linear compaction is validated by an Aggregation Index (AI) value of 88.57% and a Largest Patch Index (LPI) of 0.0660 in 2025, demonstrating a morphological evolution from a clustered point pattern to a continuous rectangular corridor pattern. Structurally, the stability and direction of settlement distribution are adaptively controlled by genealogical social structures based on clans and customary land tenure amidst the pull of road modernization. The scientific contribution of this study is the introduction of a hybrid spatial-cultural evaluation framework that demonstrates that when formal administrative boundaries become blurred due to massive physical building growth, traditional territorial logic remains resilient in regulating rural spatial configurations.

Keywords: *Spatial Patterns, Huta, Marga, FRAGSTATS, Corridor Agglomeration*

ABSTRAK

Perkembangan infrastruktur jalan sering kali memicu transformasi morfologi ruang permukiman tradisional yang masih terikat dengan adat dan budaya lokal. Investigasi terhadap dinamika ini sangat penting secara teoritis untuk memahami bagaimana ketahanan spasial masyarakat adat beradaptasi dengan poros konektivitas modern. Penelitian ini bertujuan untuk menganalisis transformasi morfologi dan pola spasial permukiman berbasis marga (huta) di Kecamatan Sihapas Barumun secara time-series pada periode 2005–2025. Metode penelitian dilakukan dengan digitasi citra satelit secara konsisten pada skala pemetaan tetap 1:3.000 dan ambang batas Minimum Mapping Unit (MMU) 1.000 m² yang diintegrasikan dengan pemodelan metrik lanskap menggunakan software FRAGSTATS. Hasil analisis kuantitatif menunjukkan terjadinya pergeseran struktural yang signifikan dari fase fragmentasi terisolasi (2005–2015) menuju fase aglomerasi koridor yang terkonsolidasi (2015–2025). Fase ekspansi aktif ditandai dengan meningkatnya nilai Number of Patches (NP) dan Patch Density (PD) akibat adanya huta ekspansi baru. Sebaliknya, pada fase konvergensi, nilai NP dan PD menurun sebagai bukti penyatuan fisik poligon permukiman akibat pengisian ruang-ruang kosong (infill development). Pemadatan linear ini divalidasi oleh nilai Aggregation Index (AI) sebesar 88,57% dan Largest Patch Index (LPI) sebesar 0,0660 pada tahun 2025, yang membuktikan terjadinya evolusi morfologi dari pola titik mengelompok menjadi pola koridor persegi panjang kontinu. Secara struktural, stabilitas dan arah sebaran permukiman dikendalikan secara adaptif oleh struktur sosial genealogis berbasis marga dan penguasaan tanah ulayat di tengah tarikan modernisasi jalan. Kontribusi ilmiah dari penelitian ini adalah pengenalan kerangka evaluasi hibrida spasial-budaya yang membuktikan bahwa ketika batas

administratif formal kabur akibat pertumbuhan fisik bangunan yang masif, logika teritorial adat tetap tangguh dalam mengatur konfigurasi spasial perdesaan.
Kata kunci: Pola Spasial, Huta, Marga, FRAGSTATS, Aglomerasi Koridor

1. INTRODUCTION

The development of road transportation infrastructure in rural areas serves as a key catalyst for regional development, forming connectivity corridors that accelerate the conversion of land use from undeveloped areas to residential zones (Bintarto, 1983). However, conventional theories of spatial modernization often overlook the internal resilience of traditional settlement structures operating under non-market socio-cultural paradigms. In North Sumatra, particularly among the Angkola-Mandailing people, rural spatial patterns are not formed randomly by economic forces alone, but are strictly regulated by patrilineal genealogical ties manifested in clan-based settlement units known as huta (Saidah et al., 2025). Structurally, the spatial growth of huta is regulated by the Dalihan Na Tolu customary system, which defines the social and territorial relationships between suhut groups (the clans that founded the huta) and anak boru groups (the wife-taking groups), ensuring that the core of traditional settlements develops in a centralized, nucleated, and family-based pattern (Ria & Ikaputra, 2020).

In the field of settlement geography, previous research has relied heavily on qualitative descriptive approaches or simple map visualizations, which lack the computational capacity to objectively measure changes in spatial geometry over time. To address these limitations, quantitative modeling using landscape ecology concepts via FRAGSTATS software has been widely adopted to examine the phenomena of urban sprawl, land fragmentation, and peri-urban dynamics (Tv et al., 2012; Makalalag et al., 2024). However, a critical research gap persists in the existing literature: previous applications of landscape metrics have almost exclusively treated the analyzed landscapes as purely physical-economic or biological entities, and have completely failed to model rural spaces characterized by strict customary land tenure systems. Consequently, there is a lack of structural understanding regarding how traditional kinship mechanisms counteract or adapt to the linear corridors generated by modern transportation networks. Therefore, the main research question of this study is: how do patrilineal kinship ties and road infrastructure development actively interact in driving the spatiotemporal configuration and structural consolidation of clan-based settlements?. To answer this question, this study introduces a precise hybrid spatial-cultural evaluation framework. The novelty of this study lies in the application of FRAGSTATS landscape metrics at the class level within a traditional rural context, executed at a highly detailed fixed mapping scale of 1:3,000 and a strict Minimum Mapping Unit (MMU) threshold of 1,000 m² to accurately capture the spatial integration of traditional building clusters.

The objective of this study is to map the multi-temporal physical evolution of huta from 2005 to 2025 at 5-year intervals using core quantitative metrics including Number of Patches (NP), Patch Density (PD), Aggregation Index (AI), and Largest Patch Index (LPI). Furthermore, this study explicitly clarifies the structural role of the Dalihan Na Tolu kinship system in regulating the direction, compactness, and spatial resilience of corridor-agglomeration settlement patterns amid the pressures of modern infrastructure.

2. METHODOLOGY

This study employs a descriptive quantitative approach integrated with spatial analysis and qualitative sociographic validation. The quantitative framework is used to calculate and model the geometric transformations of traditional settlements, while the sociographic approach is applied to interpret these physical changes based on clan structures.

2.1 Study Location and Spatial Data Consistency

This study was conducted in Sihapas Barumun Subdistrict, Padang Lawas Regency, North Sumatra Province, which is geographically located at 1°19'5'' North Latitude and 99°39'18" East Longitude, covering an area of approximately 48.25 km². The temporal scope covers a 20-year period (2005–2025), analyzed in strict 5-year intervals (2005, 2010, 2015, 2020, and 2025).

To maintain structural and temporal consistency throughout the monitoring period, a multi-sensor satellite database was constructed using SPOT-5 imagery (for 2005, 2010, and 2015) and Sentinel-2 imagery (for 2020 and 2025). Since these sensors have different native spatial resolutions, all spectral bands were resampled to a standardized raster grid cell size of 10 × 10 meters during the preprocessing phase. This grid size was directly aligned with the native resolution of Sentinel-2 to ensure geographic consistency without over-interpolating the historical data.

2.2 Visual Interpretation and Digitization Protocol

Settlement polygons (huta) were extracted from satellite imagery through on-screen digitization using ArcGIS 10.4 software. To eliminate spatial generalization bias and ensure a high level of precision for rural morphology, all digitization work was strictly conducted at a fixed mapping scale of 1:3,000. Furthermore, a strict Minimum Mapping Unit (MMU) threshold of 1,000 m² was consistently applied. This threshold serves to ensure that small non-residential structures (such as rice field huts or temporary livestock pens) are systematically excluded, thereby capturing only functional and socio-culturally active village complexes. To evaluate the accuracy of the visual interpretation results, topological verification and post-digitization validation tests were conducted on 30 randomly selected field control points, yielding an overall interpretation accuracy rate of 93.3%. After the extraction stage, the vector polygons were converted into a binary raster format, where a code of 1 represents the settlement class (huta) and a code of 0 represents the non-settlement background. This binary raster then served as the primary input for class-level spatial processing using FRAGSTATS 4.2 software.

2.3 Quantitative Modeling of Landscape Metrics

Of the many landscape ecology frameworks available in FRAGSTATS, four class-level metrics were selected to mathematically represent the processes of nucleation, fragmentation, compaction, and linear dominance occurring in rural landscapes:

1. Number of Patches (NP): Measures the total number of discrete settlement polygons, serving as a basic proxy for assessing the intensity of spatial fragmentation or the emergence of new settlement expansions.

$$NP = \sum_{\{i=1\}}^{m} n_i$$

Here, n_i is the total number of polygons (patches) in settlement class i, and m is the number of classes.

2. Patch Density (PD): Standardizes the number of polygons per 100 hectares of the total landscape area (A) to evaluate the spatial intensity of settlement nucleation.

$$PD = \frac{NP}{A} \times 10.000 \times 100$$

Where A represents the total area of the study area's landscape in square meters.

3. Aggregation Index (AI): Quantifies the frequency of pixel adjacencies within the same settlement class to measure the degree of physical compactness and horizontal clustering along transportation corridors.

$$AI = \sum_{i=1}^{m} \frac{gii}{\max gii} \left(\frac{Pi}{\sum_{i=1}^{m} Pi} \right) \times 100$$

Where gii indicates the number of pixel intersections within the same settlement class in the raster, and max gii represents the maximum theoretical number of pixel intersections for that settlement class under the highest density conditions.

4. Largest Patch Index (LPI): Calculates the percentage of the total landscape area occupied by the largest core settlement polygon, in order to identify the emergence of dominant spatial growth centers.

$$LPI = \left(\frac{\max(a_{ij})}{A} \right) \times 100$$

Where $\max(a_{ij})$ is the area of the largest settlement polygon (m²) in settlement class i out of all polygons from j=1 to n.

2.4 Qualitative Sociographic Analysis

To avoid a purely descriptive analysis of quantitative fluctuations in index figures, a sociographic verification procedure was applied in this study. Primary qualitative data on the historical distribution of customary land and kinship structures were collected through in-depth, semi-structured interviews with a single, carefully selected key informant. This informant was selected using purposive sampling based on strict elite criteria: holding the highest institutional authority as the head of the customary institution (Raja Adat / Pucuk Pimpinan Lembaga Adat) at the subdistrict level, and possessing comprehensive genealogical knowledge regarding the history of the establishment of suhut groups (founding clans of huta) and anak boru (clans receiving brides) throughout the villages in Sihapas Barumun.

The use of a single key informant with high authority at the subdistrict level aims to ensure that the synthesis of macro-level customary law data and data on land tenure across formal administrative boundaries can be conducted comprehensively. To ensure the reliability of the information and minimize bias, interview data were tested through rigorous analytical triangulation by matching the informant's oral transcripts with secondary data in the form of village monographs, sub-district administrative profiles, and local government records of customary boundary demarcations. Finally, these verified traditional socio-spatial dynamics are correlated with FRAGSTATS metric results to explain the socio-cultural forces governing the agglomeration of these corridors.

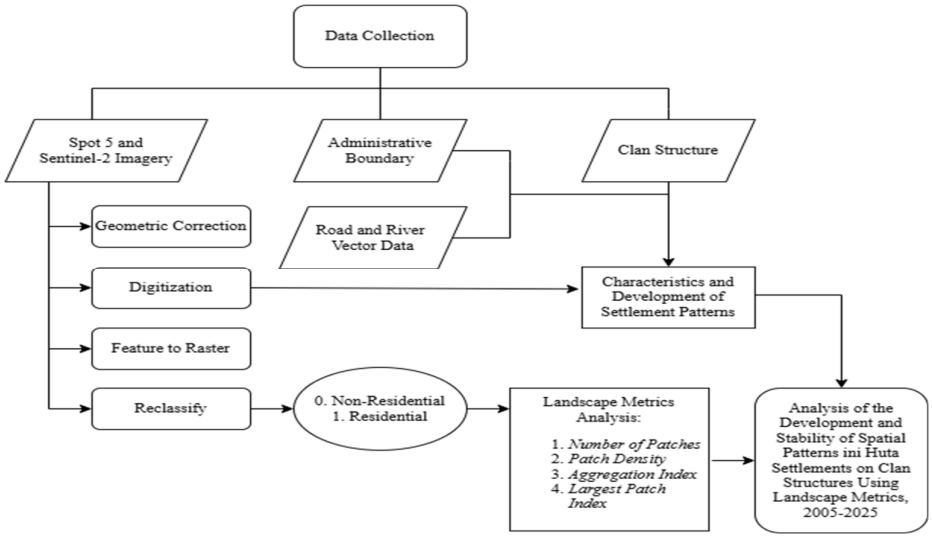


Figure 1. Research Flowchart

3. RESULT AND DISCUSSION

3.1 Quantification of Landscape Metrics Using FRAGSTATS

To accurately measure the geometric configuration of settlement classes (huta), landscape metrics were calculated at the class level using FRAGSTATS 4.2 software, treating non-settlement classes as the background. The results of mathematical calculations for the four main landscape metrics Number of Patches (NP), Patch Density (PD), Aggregation Index (AI), and Largest Patch Index (LPI) over the 20-year monitoring period summarize the internal dynamics of fragmentation and convergence in the region, which are presented in detail in Table 1.

Table 1. FRAGSTATS Calculation Result

Year	Number of Patches	Patch Density	Largest Patch Index	Aggregation Index
2005	17	0.1552	0.0133	83.0476
2010	21	0.1917	0.0142	82.3529
2015	23	0.21	0.0308	83.3691
2020	18	0.1643	0.0447	86.9657
2025	15	0.137	0.066	88.573

Source: *Researchers, 2026*

Based on the data in Table 1, highly dynamic spatial fluctuations were observed, which can be structurally divided into two contrasting sub-periods. From 2005 to 2015, the landscape underwent a phase of active expansion and fragmentation, during which the NP value increased from 17 to 23 units, linearly followed by a rise in the PD value from 0.1552 to 0.2100 per 100 hectares. This quantitative trend mathematically confirms the physical emergence of isolated new satellite huta settlements along the newly paved asphalt road corridor.

Conversely, entering the second sub-period from 2015 to 2025, the trend reversed dramatically. The NP value shrank from 23 to 15 units, and the PD value decreased to 0.1370 per 100 hectares. This decrease in the number of polygons does not indicate a decline in

residential growth but rather serves as empirical evidence of an intensive process of spatial convergence and consolidation. This is validated by regional cohesion metrics; the AI index surged sharply after 2015, peaking at 88.57% in 2025. This physical consolidation is further supported by the LPI value, which continued to grow, reaching 0.0660% by the end of the observation period, indicating that the largest residential polygon has expanded significantly to become the dominant spatial growth nucleus in the subdistrict.

3.2 Comparative Analysis and the Unique Typology of the Huta Corridor

To establish scientific novelty and a strong theoretical contribution in this study, the empirical spatial transformations observed in Sihapas Barumun Subdistrict must be critically evaluated against established archetypes of spatial growth in the geographical literature. By contextualizing our quantitative metrics within a broader regional development paradigm, we can determine whether the corridor agglomeration occurring within this indigenous community's territory represents the structural sprawl commonly observed or constitutes a truly unique socio-spatial phenomenon.

Table 2. Comparative Matrix of Regional Spatial Transformation Models

Spatial Typology & Key Literature	Methodological Focus & Evaluation Scale	Primary Socio-Economic & Institutional Driving Forces	Core Morphological Process & Mathematical Metric Trends	Final Spatiotemporal Structural Outcome
Conventional Urban Sprawl Model *(Tv et al., 2012; Makalalag et al., 2024)*	Purely Quantitative: Class and landscape-level metric tracking via FRAGSTATS grids.	Unregulated land market capitalism, capital-driven speculation, and weak municipal zoning deregulation.	Continuous, irreversible landscape fragmentation and chaotic land-use leapfrogging *(NP and PD continuously increase, while AI drops over time).*	Highly disorganized, fragmented, and decentralized low-density built-up patches.
Traditional Macro-Settlement Hierarchy *(Ria & Ikaputra, 2020)*	Qualitative Normative: Conceptual-historical literature review and ethno-architectural case mapping	Customary agrarian resource allocation, collective ancestral defense, and *Dalihan Na Tolu* ceremonial spaces.	Gradual macroscopic horizontal expansion from isolated compound clusters into macro-political entities *(Sosor → Lumban → Huta → Horja → Bius)* (No landscape metrics applied)	Hyper-segregated, static, and independent nucleated customary compounds centered around communal assets.
Sihapas Barumun Customary Corridor *(This Study, 2026)*	Hybrid Framework: Fine-grained class-level FRAGSTATS modeling (10×10 m grid) integrated with subdistrict elite sociography.	Decoupling effects of centrifugal modern road infrastructure connectivity versus centripetal patrilineal land tenure.	Temporary active expansion followed by rapid, intensive horizontal infill re-cohesion *(NP rises to 23, then falls significantly to 15; AI surges to a peak of 88.57% by 2025).*	Continuous, linear rectangular corridor agglomeration physically merging across formal village administrative limits.

The structural comparison matrix presented in Table 2 reveals a highly intriguing typological trajectory, while also underscoring the methodological and theoretical novelty of this study. Within the conventional paradigms of urban geography and land-use planning, as exemplified by the standard models of Tv et al. (2012) and Makalalag et al. (2024), the introduction of high-accessibility transportation infrastructure invariably triggers permanent landscape fragmentation. Because land allocation under free-market capitalism is controlled by open economic forces and land speculation, commercial and residential growth manifests as chaotic, scattered, and uncoordinated expansion. These dynamics are mathematically captured through an endless increase in the Number of Patches (NP) and a significant decrease in the Aggregation Index (AI) over a multi-decade timeline.

Conversely, models of traditional indigenous settlements, such as the macro-hierarchy evaluated by Ria and Ikaputra (2020), show that ancestral spaces are structurally configured to maintain spatial separation. Their normative qualitative analysis illustrates how traditional Batak settlements expanded step-by-step from microscopic clusters (sosor) into broader socio-political networks (horja and bius) to preserve shared agricultural assets and maintain concentric ceremonial centers. However, their descriptive framework lacks the computational capacity to account for how contemporary infrastructure corridors distort and alter these ancient configurations.

This study successfully bridges this striking methodological divide by employing a hybrid quantitative-sociographic framework. The findings indicate that the physical dynamics of huta settlements in Sihapas Barumun Subdistrict do not follow the chaotic trajectory of free-market dispersion, nor are they trapped within the confines of static and isolated traditional complexes. Quantitative fluctuations in our metrics where the initial expansion phase (NP surging from 17 to 23) was drastically reversed during the convergence phase (NP shrinking to 15, while the Aggregation Index surged to a peak of 88.57% in 2025) provide clear empirical evidence of a unique infill re-cohesion process.

This distinctive spatiotemporal behavior is directly explained by the internal sociocultural dynamics of the Dalihan Na Tolu genealogical system. Because local customary institutions strictly regulate the allocation and use of clan-owned communal land (pangeahan ni huta / toru ni lobu) for their members, the strong centrifugal economic pull of road modernization is adaptively internalized by the community. When the upgraded highway corridor acts as a spatial attractor, the new generation of suhut clans (founder clans) and anak boru (bride-receiving clans) do not disperse haphazardly or fragment the rural landscape. Instead, they align with traditional rules of shared resource governance, deliberately engaging in horizontal infill development by establishing modern residential units within the margins of vacant historical gardens (pargodungan) that are directly linked to pre-existing huta clusters. This drastic long-term consolidation, validated by high AI values and an increase in the Largest Patch Index (LPI), fundamentally confirms that while formal village administrative boundaries have become a physical, functional, and geographical illusion on the ground due to continuous building densification, the logic of customary territoriality and the underlying system of shared facility management remain remarkably resilient. Traditional kinship mechanisms act as a structural centripetal force that stabilizes the direction of growth, allowing for physical modernization along transportation corridors without losing the indigenous spatial identity and the socio-ecological cohesion of the indigenous community.

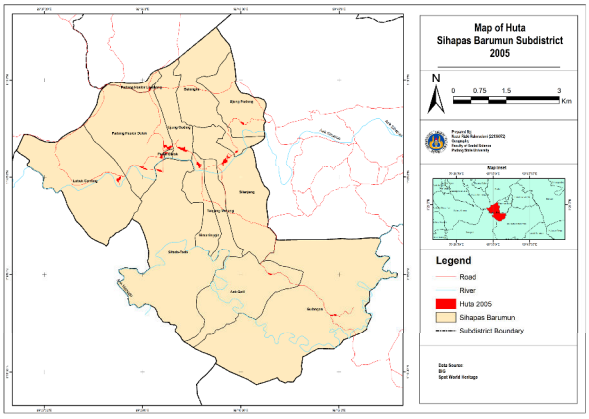


Figure 2. Map of Huta 2005

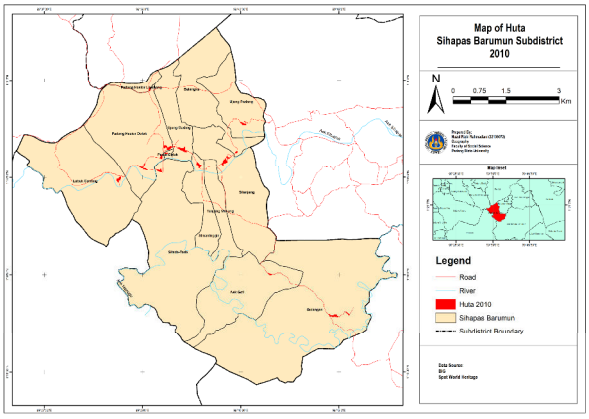


Figure 3. Map of Huta 2010

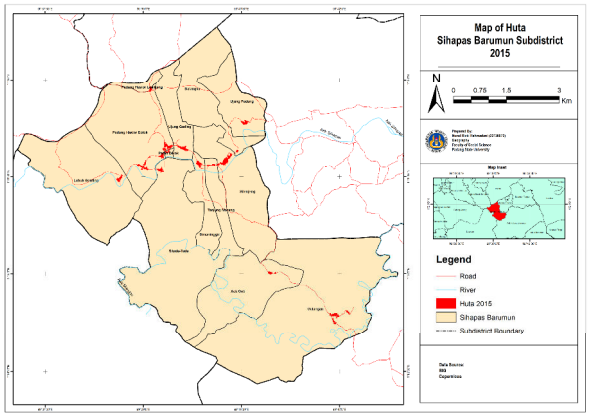


Figure 4. Map of Huta 2015

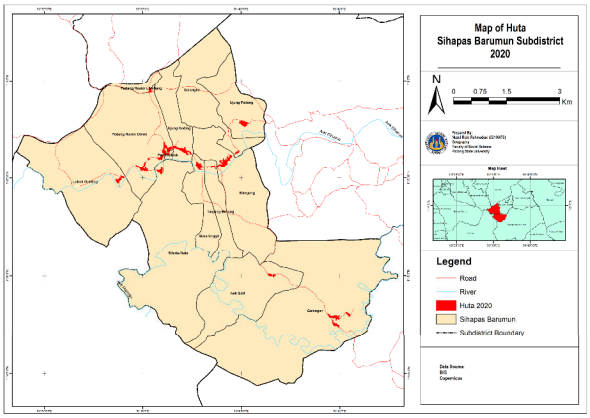


Figure 5. Map of Huta 2020

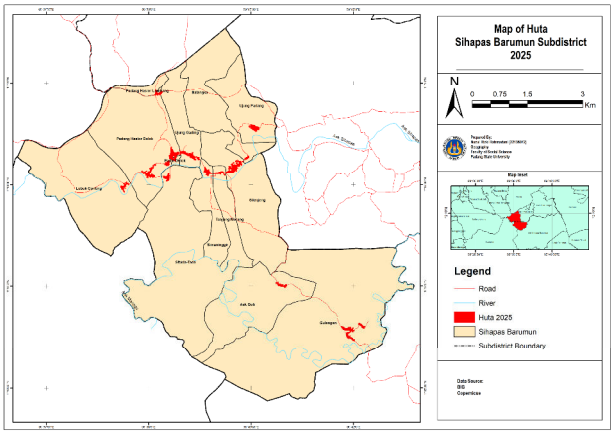


Figure 6. Map of Huta 2025

4. CONCLUSION

4.1 Key Findings

Based on integrated spatiotemporal analysis and the quantification of landscape metrics, this study concludes that traditional clan-based settlements (huta) in Sihapas Barumun Subdistrict have transformed from a pattern of isolated, fragmented clusters into a highly consolidated corridor agglomeration pattern along the main road network. The implementation of the class-level FRAGSTATS framework empirically demonstrates that this transformation is non-linear. The landscape underwent a phase of temporary active expansion marked by the

emergence of new satellite huta complexes. This phase was subsequently replaced by an intensive phase of spatial convergence, during which infill development absorbed all the vacant agricultural space that had originally separated the individual clusters. By the end of the monitoring period, these formerly separate entities had physically merged into a single mass of buildings forming a continuous rectangular corridor that penetrated formal boundaries.

4.2 Theoretical Implications

Scientifically, these findings contribute to the introduction of a spatial-cultural hybrid framework in settlement geography. While standard urban landscape metrics use aggregation parameters to capture how the forces of industrialization consolidate land fragments into a single massive plot (Tv et al., 2012), this study highlights distinct socio-spatial drivers. In Sihapas Barumun, the physical re-cohesion of the landscape is governed by the centripetal mechanics of the Dalihan Na Tolu patrilineal kinship system. Strict customary prohibitions against the sale of clan communal land prevent the chaotic fragmentation of land caused by market capitalism. Conversely, this system compels new generations of suhut and anak boru clans to build their modern homes adjacent to the core of their ancestral villages. This interaction demonstrates that modern connectivity axes can reshape the physical form of space, while the cultural framework maintains the resilience of the genealogical structure within it.

4.3 Policy and Practical Implications

From a regional planning perspective, local governments must operationalize these empirical findings by integrating clan customary land boundaries directly into the district Spatial Master Plan (RTRW). Since formal village administrative boundaries have become functionally and geographically illusory on the ground due to continuous building densification, relying on old cartographic boundaries is no longer relevant for sustainable development. Local governments need to implement a specific “Indigenous Settlement Zone” overlay policy. This planning mechanism will legalize clans’ collective land rights, set building density quotas along major transportation corridors, and minimize the potential for agrarian conflicts resulting from massive corridor densification

4.4 Limitations and Directions for Future Research

This study is primarily limited by its reliance on two-dimensional land cover data extracted from medium-resolution imagery, which does not yet capture vertical building densification or internal architectural modifications within the historic huta complex. Additionally, the qualitative sociographic foundation relies on a single key informant from the local elite at the subdistrict level. Although verified through rigorous analytical triangulation, future research should utilize high-resolution three-dimensional spatial modeling (such as LiDAR) combined with multi-clan household surveys. This expansion will enable future researchers to model micro-spatial volume transformations and assess how corridor densification affects the long-term socio-ecological resilience of indigenous communities.

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