DYNAMICS OF LULC CHANGES IN COMMUNAL LANDS: A SOCIO-CULTURAL AND SPATIAL ANALYSIS IN BUKITTINGGI CITY, INDONESIA

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ABSTRACT

This research investigates Land Use and Land Cover (LULC) transformations in Bukittinggi City and its surroundings, focusing on the impacts of urban expansion and shifts in communal land ownership. The research aims to model LULC changes from 2024 to 2050 and identify key environmental, social, economic, and cultural drivers. Using satellite imagery from Landsat 7 ETM+ (2009) and Landsat 8 OLI (2022), along with Digital Elevation Models (DEM) and shapefile data, the research applied the Cellular Automata-Markov Chain method for spatial and temporal modeling. Field surveys and interviews with 100 respondents provided additional insights into communal land management practices. Regression analysis was used to evaluate the influence of multiple factors on LULC changes. The findings reveal extensive LULC shifts, particularly the conversion of agricultural land to settlements, driven by high accessibility, flat terrain, and economic incentives. Communal land, traditionally managed under matrilineal systems, faces fragmentation due to weak regulations and external investments. Projections show a 1,231.74 ha reduction in agricultural land by 2050, with significant communal land losses in Gadut and Ladang Laweh. These results underscore the urgent need for sustainable land management strategies to balance urban development with ecological and cultural preservation. Strengthening customary laws, empowering traditional leaders, and implementing integrated urban planning are critical. Proactive policies addressing environmental, social, economic, and cultural dimensions are essential to ensure the sustainability of communal land for future generations.

Key-words: *Communal land; Land ownership; Matrilineal customary; LULC; Bukittinggi*

1. INTRODUCTION

Land is an essential natural resource fundamental to sustaining human life. With the global population growing, the demand for land increases, despite the earth's limited land availability. This widening gap emphasizes the critical need for effective resource management and well-planned land-use strategies to ensure sustainable development in the long run. The escalating need for land drives continuous changes in land-use patterns (Kalfas et al., 2024). These shifts in Land Use and Land Cover (LULC) often disrupt degraded ecosystem services, such as water regulation, carbon sequestration, and biodiversity preservation (Petrosillo et al., 2023). Ecosystem services play a vital role in maintaining the fragile equilibrium between living and non-living components of ecosystems (Oktorie et al., 2019). However, while global land scarcity and its implications remain critical, this research focuses on specific local challenges in Bukittinggi, West Sumatra. There is a pressing need to understand how global land scarcity manifests at the local level particularly in regions with unique cultural and environmental dynamics by examining current LULC and its implications for sustainable development, including the effects on ecosystem services, settlement expansion, and agricultural productivity.

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The research also projects future LULC changes under various socio-economic and environmental scenarios, providing predictive insights into possible transformations and their consequences. Finally, it investigates evolving patterns of communal land ownership, especially in the context of urban expansion, demographic pressures, and technological advancements that may reshape traditional governance structures.

As a tropical country abundant in natural resources, Indonesia boasts remarkable ethnic diversity, with various groups presenting unique cultures, languages, and traditions (Forshee, 2006). Among its regions, West Sumatra is distinctive due to its cultural identity shaped by a matrilineal system, where lineage and inheritance are passed through the maternal line. This practice, uncommon across most of Indonesia, significantly influences land ownership, inheritance customs, and local LULC, thereby shaping broader regional LULC trends (Parker, 2024; Ikhwan et al., 2023). Consequently, cultural practices such as matrilineality play a critical role in shaping LULC and ownership patterns. The matrilineal societies in Bukittinggi City and the surrounding Agam Regency in West Sumatra serve as illustrative examples. Communal land ownership, governed by customary tribal laws, defines these regions. Communal land is managed by tribal leaders, and inheritance is typically passed down to women to preserve the cultural legacy for future generations (Nurdin, 2022; Irawati et al., 2024; Gazi et al., 2024). Beyond inheritance or communal identity, this system profoundly impacts land management practices by ensuring that land remains a communal resource, fostering collective responsibility and sustainability. Tribal leaders play a pivotal role in decision-making processes related to land use, balancing ecological preservation with community needs. Advancements in technology are rapidly transforming the traditional roles of society leaders, posing potential risks to the preservation of communal land a fundamental aspect of tribal identity. In Bukittinggi City, a growing population fueled by natural increase and migration, along with soaring land prices, has compelled many residents to seek housing beyond urban regions. This mounting pressure on land resources presents substantial challenges to communal land, which, according to customary law, is allocated exclusively to tribal members and cannot be sold or transferred (Martial et al., 2012; Ikhwan et al., 2021). The decline or disappearance of traditional norms, alongside demographic pressures and urban expansion, underscores the urgency of comprehensively examining communal land dynamics to ensure sustainable management.

Emerging technologies such as Remote Sensing and Geographic Information Systems (GIS) present both opportunities and obstacles for managing communal land. These tools facilitate precise, data-driven tracking of spatial transformations, offering critical insights into land-use patterns. However, their implementation may disrupt traditional governance systems rooted in local cultural practices. This research employs satellite data, including Landsat 7 Enhanced Thematic Mapper Plus (ETM+) imagery from 2009 and Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) imagery from 2022, sourced from the United States Geological Survey (USGS). These datasets enable detailed temporal analysis of LULC changes within the research location. Furthermore, a Digital Elevation Model (DEM) is utilized to examine topographic factors influencing land-use dynamics (Saleem et al., 2019), providing valuable insights into settlement expansion and environmental constraints.

The research aims to model LULC changes from 2024 to 2050 and identify key environmental, social, economic, and cultural drivers. While previous research has extensively examined LULC dynamics, the unique aspects and future projections of communal land, especially regarding shifts in ownership and usage, remain underexplored. Integrating remote sensing and GIS technologies introduces an innovative approach to filling these gaps by enabling accurate spatial modeling and predictive analysis of land-use trends. Additionally, earlier studies often overlooked the socio-cultural and ecological dimensions that significantly influence land-use changes within communal systems. These factors are essential for policymakers aiming to preserve the sustainability of Communal Land for future generations. By merging state-of-the-art geospatial technologies with cultural and environmental perspectives, this research provides a holistic framework for understanding the interplay between traditional practices, development pressures, and technological advancements in shaping LULC dynamics in matrilineal societies.

2. DATA AND METHODS

2.1. Research location

The research location covers Bukittinggi City and its surrounding sub-districts, including Guguk Panjang, Mandiangin Koto Selayan, and Aur Birugo Tigo Baleh. Situated approximately 90.3 kilometers to the north of Padang City, the capital of West Sumatra Province, the region is highly accessible, with an average travel time of about 2 hours and 35 minutes. Known for its rich cultural heritage and strategically advantageous location, Bukittinggi City serves as the primary focus of this research location. A detailed map illustrating the research location is provided in **Figure 1** below.

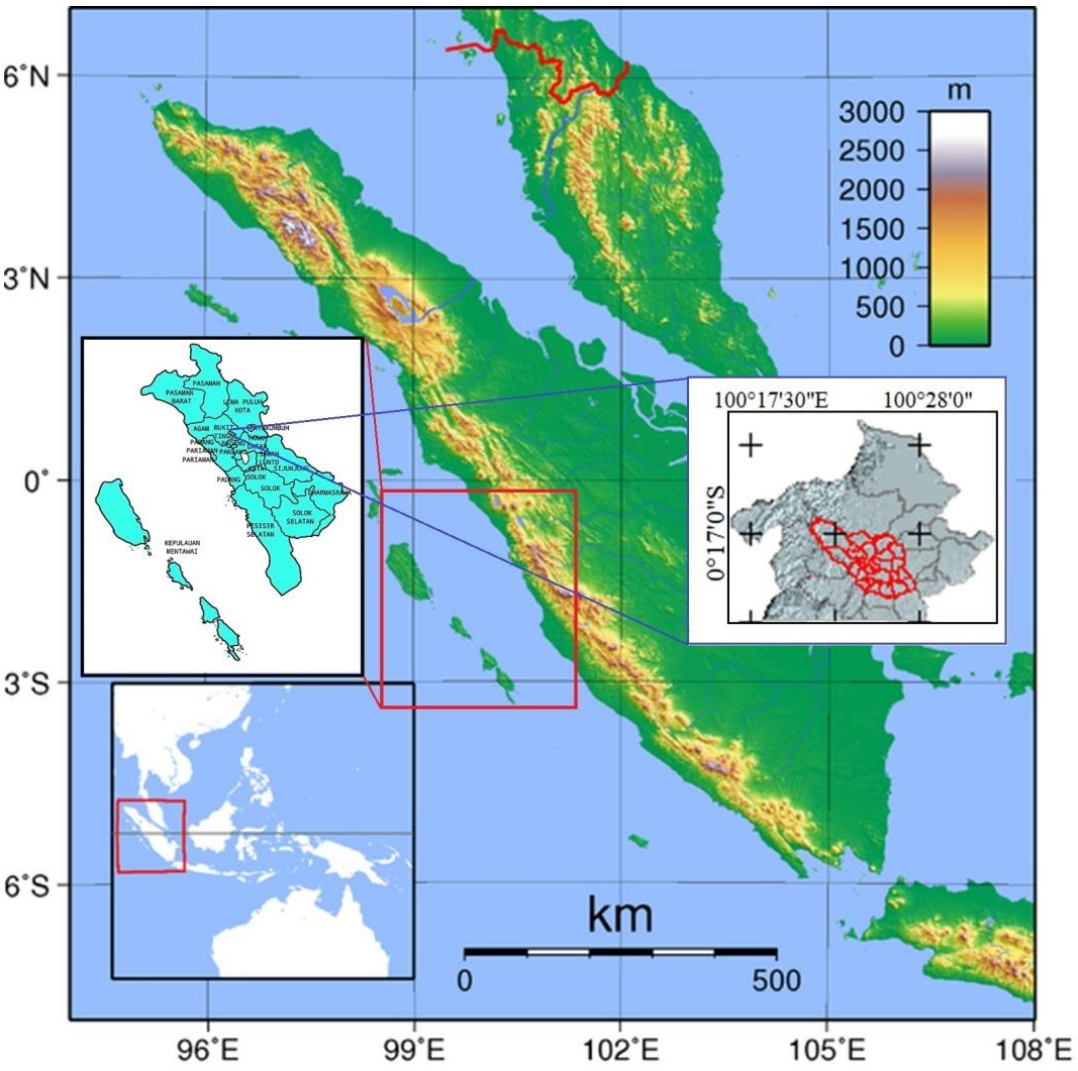

Fig. 1. Map of the research location.

2.2. Data sources and research design

This research incorporates diverse data sources to fulfill its objectives. The primary datasets consist of satellite imagery from Landsat 7 ETM+ (2009) and Landsat 8 OLI (2022), acquired from the United States Geological Survey (USGS). These datasets are pivotal for analyzing and modeling spatial changes in LULC projected for 2024, 2030, and 2050. Additionally, Digital Elevation Model (DEM) data from Indonesia's Geospatial Information Agency (BIG) will be utilized to create maps

showcasing key topographic attributes such as hill gradients, slopes, and elevation. The research also integrates shapefile or SHP data, which includes infrastructure-related information, such as roads and administrative centers to enhance the spatial analysis.

2.3. Stages of research implementation

This research employs a quantitative research design with a spatial approach as the primary analytical framework. The methodology includes field surveys to collect respondent data and validate results using ground-truthing techniques. The research process is divided into three main phases, namely pre-field, field, and post-field, as described below:

- Pre-field phase: In this phase, datasets from satellite imagery, DEM, and secondary data from relevant governmental sources are gathered and processed. Supervised classification is applied to the satellite imagery to identify LULC categories. Concurrently, SHP data are converted into Euclidean distance metrics, serving as predictors for modeling LULC changes for 2024, 2030, and 2050. A major task in this phase is the development of LULC models for 2024, alongside the random generation of sample points to assess prediction accuracy for 2024, 2030, and 2050.
- Field phase: During this phase, researchers visit pre-identified sample points to validate the modeled LULC data through field observations. If the accuracy assessment achieves a threshold of 85% or higher, the model is refined and extended to predict LULC changes for 2034 and 2044. Ground validation efforts are complemented by interviews with 100 respondents, including society members and traditional leaders, to collect qualitative insights on communal land management practices. Respondents were selected through purposive sampling to ensure the inclusion of individuals directly involved or knowledgeable about communal land management. This data enhances the robustness and credibility of the modeling results.
- Post-field phase: The post-field phase focuses on analyzing the outcomes of accuracy tests and field surveys while comparing the modeled predictions with actual LULC conditions observed in the field. If the accuracy remains above 85%, the model is further extended to project LULC changes for 2030 and 2050. Qualitative data collected from the respondents were systematically coded, categorized, and triangulated with quantitative data to provide a comprehensive understanding of the dynamics of communal land management. Data from interviews regarding shifts in communal land management are compiled and analyzed using descriptive statistics. Furthermore, multiple regression analysis is applied to examine the influence of environmental, social, economic, and cultural variables on observed LULC transformations on communal land.

2.4. Data analysis techniques

To achieve the objectives of this research specifically the spatial analysis and modeling of LULC changes for 2024, 2030, and 2050 atmospheric corrections on Landsat imagery are required. These corrections follow established formulations detailed in prior research (Suasti et al., 2020; Putra et al., 2023; Dewata et al., 2024)

$$L\lambda = \frac{L_{Max} - L_{Min}}{255 * \mathrm{DN} + L_{Min}}$$

where L_{Min} and L_{Max} (mW cm².sr.μm) are spectral files of each band on digital numerals with values of 0 and 255 respectively, and $L\lambda$ are spectral files.

Before modeling of LULC changes it is necessary to know the size of the transition matrix (Yin et al., 2023; Su et al., 2023) to determine the magnitude of changes in built land in the research location with the following formula

$$U_{ij}\begin{pmatrix} U_{11} & \cdots & U_{1n} \\ \vdots & \ddots & \vdots \\ U_{n1} & \cdots & U_{nn} \end{pmatrix}$$

where ij = 1.2 representing LULC before and after transfer; n is the number of LULC types (Neissi et al., 2020; Su et al., 2023), U_{ij} is the transfer area to determine the extent of changes in

LULC in the research location is determined by determining the magnitude of the transition matrix value in Markov Chain Cellular Automata with the following formulation.

$$S(t+1) = P_{ij} x\, S(t)$$

where $S(t)$ and $S(1)$ are types of LULC at time t and $t+1$ (Su et al., 2023).

Markov Chain Cellular Automata combines probabilistic transitions with spatial constraints to simulate LULC changes. The characteristics of spatial variables are not sufficient as a consideration in the Markov chain process, so it is necessary to know the temporal and spatial changes of various natural processes simulated by Cellular Automata, including LULC changes, can be formulated as follows.

$$S(t, 1+1) = f(S(t), N)$$

where S is the set of sellers, N is the cellular, t and $t, 1+1$ represent the period, and f is the cell transition rule.

This formulation accounts for interactions between neighboring cells, enhancing the spatial realism of the model. The modeling results need to be tested for accuracy to determine whether the model created is acceptable or not (Das et al., 2021). To test the accuracy of modeling results, the Kappa index is used with the following formulation.

$$Kappa = \frac{P_0 - P_e}{1 - P_e} \begin{pmatrix} K_{Histo} = \frac{P\max - P_e}{1 - P_e} \\ K_{loc} = \frac{p_0 - P_e}{P\max - p_e} \end{pmatrix} Kappa = K_{histo} x\, K_{Loc}$$

where P_0 is the correct observation purpose, P_e is the fraction expected to be agreed, and $P_{\max}$ is the number of cells taken up by each cell of the class.

The Kappa index is widely recognized as a robust metric for assessing the reliability of classification models. This ranges from 1, indicating the correct value, to 0 indicating the wrong sample, while K_{Loc} has a value between -1 to 1, where 1 indicates the correct location. To determine the magnitude of LULC changes, especially on built-up land, extraction was carried out on the results of modeling LULC changes in 2024, 2030, and 2050 to determine the number of buildings in the future. Regions that did not experience changes in communal land ownership were given a weight value of 0.33, regions that experienced changes in ownership that were not too much were given a weight of 0.66, and regions that experienced many changes in communal land ownership were given a weight of 1 (Huang et al., 2023). This weighting is based on the results of interviews with respondents who know about communal land and analyzed using center points of a region. The spatial distribution of ownership changes was mapped using ArcGIS, enabling a detailed understanding of ownership patterns. This was analyzed using the Inverse Distance Weighted (IDW) technique in ArcGIS to obtain spatial models of changes in communal land ownership using the following formulation.

$$Z * (X_p) = \sum_{i=1}^{n} \lambda_i \, . Z(x_i) with \sum_{i=1}^{n} \lambda_i = 1. \lambda_i = \frac{D_i^{-a}}{\sum_{i=1}^{n} D_i^{-a}}$$

where λ_i is the weight at i D_i is the distance from the point ii to the point not recognized, and a is the weight of the distance.

To determine the factors influencing LULC changes on communal land, descriptive analysis techniques and multiple regression analysis were applied (Parven et al., 2022; Duijndam et al., 2023) to determine the effect of each factor on changes in communal land ownership. The formulations used are as follows.

$$Y_{it} = X_{it}\beta + C_i + \varepsilon_{it} t = 1,2 \ldots \ldots T$$

Where Y_{it} is the desired modeling result for each group i in year t, X_{it} is the observed vector 1 $\times K \times$k, β is the estimated parameter, C_i is a special group that is not observed randomly, and ε_{it} is an error that varies between time and group.

This approach captures the temporal and spatial heterogeneity in LULC dynamics.

3. RESULTS AND DISCUSSIONS

3.1. Model of LULC

Simulation results for 2024, 2030, and 2050, as depicted in **Figure 2**, show the spatial distribution of LULC changes in the research location. The model identifies significant increases in built-up areas, reductions in forest cover, shifts in agricultural zones, and fragmentation of communal land. These changes were modeled using the Cellular Automata-Markov Chain method, which integrates both temporal and spatial dimensions of LULC dynamics. The graph accompanying **Figure 2** quantitatively highlights the extent of these changes, with urban expansion emerging as the dominant trend. This expansion significantly affects other LULC categories, including a decline in communal land areas.

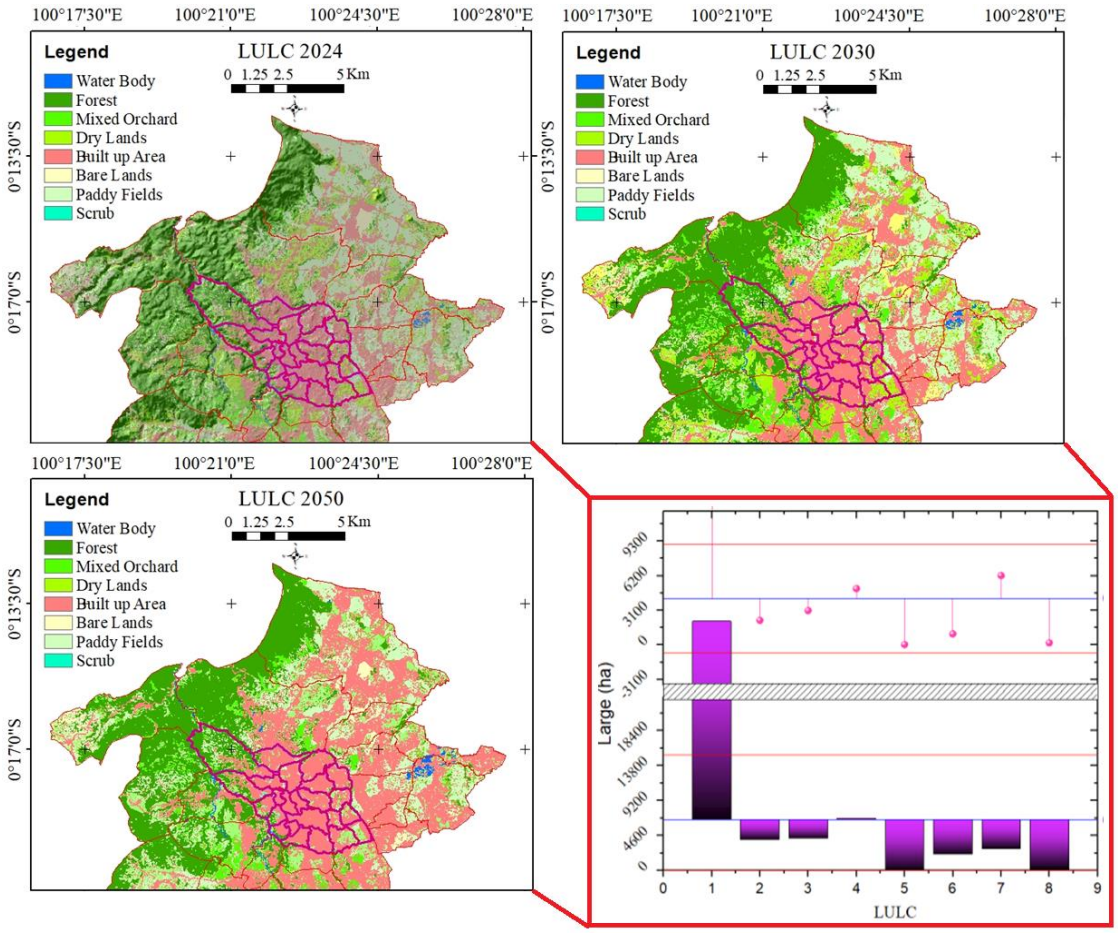

Fig. 2. The LULC changes (Maps) in Bukittinggi City and surrounding: Comparison between 2024, predicted 2030, and predicted 2050 with region distribution analysis.

In **Figure 2** above, the LULC changes in Bukittinggi City and its surrounding for 2024 are depicted alongside projections for 2030 and 2050. This figure illustrates substantial transformations, particularly the conversion of agricultural land, primarily paddy fields, into non-agricultural uses. In 2024, the total area of paddy fields was recorded at 3,688.65 ha. By 2030, this area is projected to decline to 3,319.33 ha, reflecting a reduction of 369.18 ha. By 2050, a further decrease to 2,456.91 ha is estimated, marking an additional reduction of 862.42 ha from 2030. Overall, the total reduction in paddy field area between 2024 and 2050 is expected to reach 1,231.74 ha.

This decline is primarily attributed to the conversion of paddy fields into built-up areas, a trend that is particularly pronounced in areas with flat terrain and easy access to road networks. These factors facilitate the transformation of agricultural land into urban settlements. Additionally, the graph within Figure 2 highlights a consistent decline in LULC categories such as paddy fields, mixed orchards, bare lands, and scrublands from 2024 to 2050, while built-up areas show a steady annual increase. The conversion of agricultural land, especially paddy fields, into urban settlements raises significant concerns for food security. The diminishing agricultural areas could lead to reduced local food supply, increasing dependency on external food sources. Moreover, urbanization often introduces risks of pollution or contamination of remaining agricultural lands, which might directly affect food safety. These risks not only impact the economy but also pose serious public health challenges, particularly for societies reliant on local produce.

This urban expansion poses potential challenges for land ownership patterns and could gradually diminish the extent of communal land, traditionally managed by indigenous societies in the areas. However, as of now, these changes have not posed an immediate threat to the survival of communal land systems. These findings highlight the mounting pressures of urbanization on agricultural resources and traditional LULC patterns, which could negatively impact not only food security but also public health and socio-cultural sustainability. To address these challenges, it is imperative to implement sustainable land management strategies that balance development needs with the preservation of local ecosystems and cultural heritage. Furthermore, **Figure 3** provides further insights into this trend by modeling the expansion of settlement LULC from 2024 to 2050.

The maps illustrate a steady growth in built-up areas, primarily driven by urbanization and population growth. In 2024, settlements were predominantly concentrated within central urban zones. By 2030 and 2050, these settlements are projected to expand significantly into previously agricultural and undeveloped areas. The combined map (2024-2050) illustrates the cumulative impact of these changes, revealing a substantial transformation in land use, particularly in areas with favorable topography and accessibility. These findings emphasize the importance of integrating considerations for human health and food security into urban planning policies. Efforts to mitigate the loss of agricultural land should incorporate strategies to ensure food safety, minimize pollution risks, and address potential public health challenges stemming from land use changes. Proactive measures are essential to ensure sustainable development that meets the needs of future generations while preserving the region's environmental and cultural assets.

Figure 3 shows the transformation of settlement between 2024 and 2050. In 2024, settlement areas were predominantly concentrated in Bukittinggi City and the southeastern portions of the research location. By 2030, settlement expansion is projected to extend significantly toward the western region. Furthermore, by 2050, settlement is anticipated to expand further, with extensive development spreading into the western and northwestern areas. The projected changes in settlement from 2024 to 2030 indicate an increase of approximately 538.11 ha. During the subsequent period, from 2030 to 2050, settlement areas are expected to expand by an additional 1,626.57 ha, representing a marked acceleration in urban growth. This rapid settlement expansion poses significant challenges to the preservation of communal land within the research location. Communal land, traditionally governed and utilized by indigenous tribes, relies on strong kinship systems and adherence to customary laws. Regions with well-established cultural and legal frameworks may have greater resilience in maintaining and protecting communal land against encroachment. Moreover, the expansion of settlements and agricultural land conversion could pose severe threats to local food security by reducing arable land availability and potentially exacerbating pollution risks. These

changes not only influence the socio-cultural and environmental dimensions but also have direct implications for human health. Potential contamination of local food supplies, arising from pollution linked to urbanization and land use changes, underscores the need to integrate food safety and public health considerations into LULC management strategies.

This analysis underscores the critical need for sustainable urban planning and strategic LULC policies to mitigate the negative impacts of settlement growth on traditional land systems and the socio-cultural heritage of indigenous societies. Proactive measures should also address the interconnected challenges of maintaining food security and ensuring public health amidst rapid urbanization. This requires a comprehensive approach that balances urban development with the preservation of indigenous practices, natural resources, and public well-being.

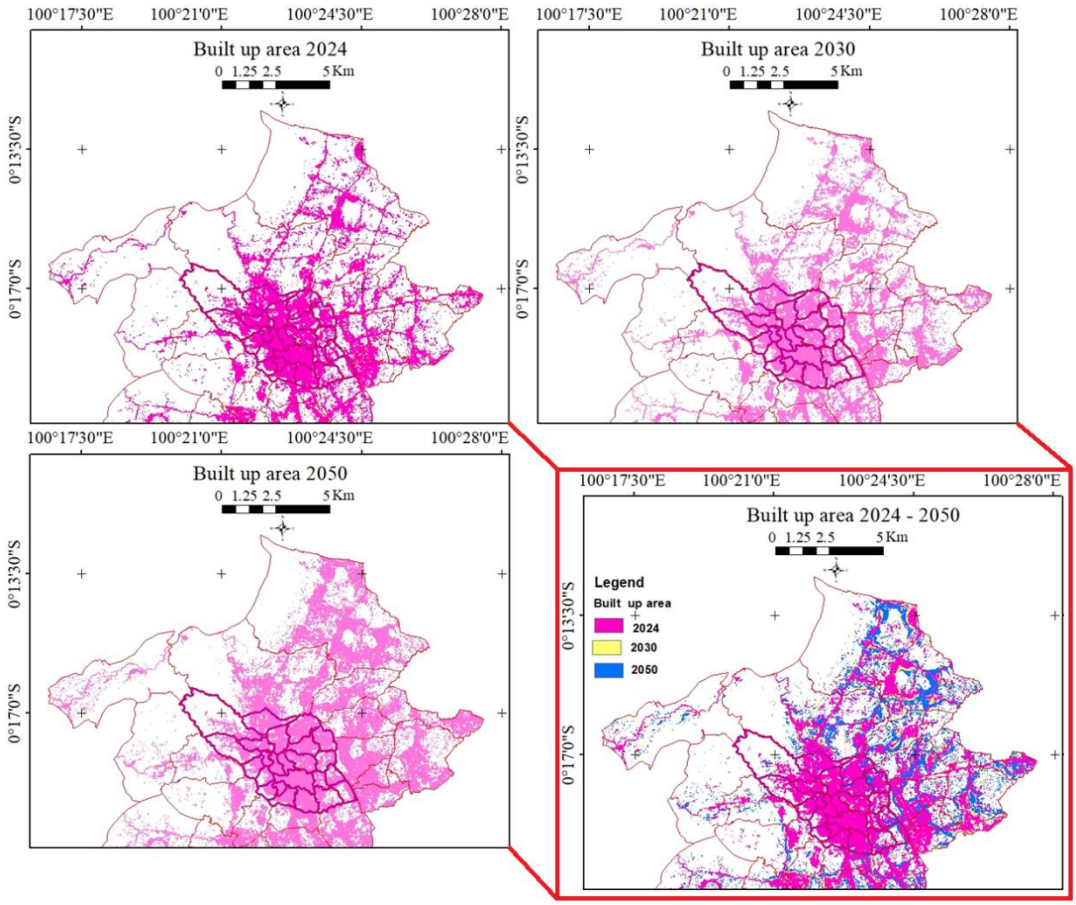

Fig. 3. Spatial dynamics of built-up area expansion in Bukittinggi City (Maps): Changes from 2024 to 2050 with predicted growth analysis.

3.2. Model of LULC in communal land

Transformations in LULC within the research location can be grouped into two main categories: 1) LULC changes without alterations in land ownership, and 2) LULC changes accompanied by shifts in land ownership. In **Figure 4** highlights these changes, the left map shows the spatial distribution of communal land experiencing varying levels of change categorized as low, medium, or high. Areas with the highest changes are mainly located near urban centers and along major infrastructure routes, where settlement growth is most evident. The graph in **Figure 4** shows a rising trend in land

ownership transitions and a rapid increase in built-up areas, demonstrating a clear link between urbanization and the transformation of communal land.

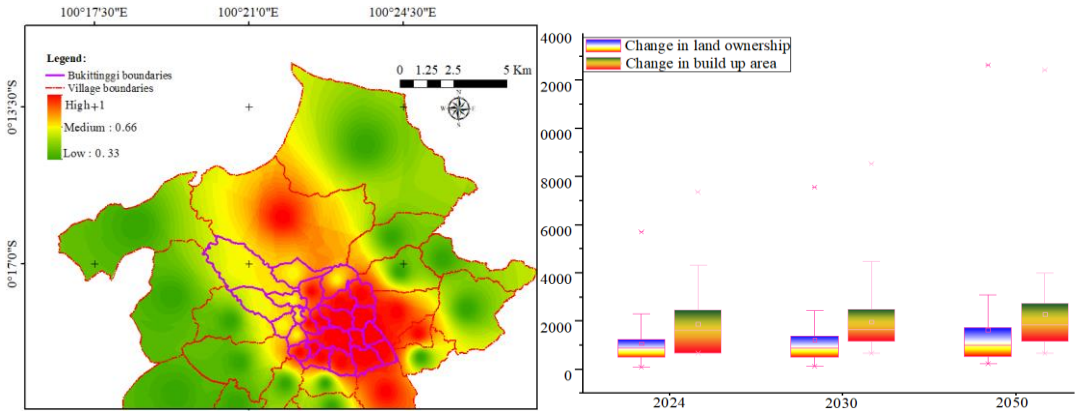

Fig. 4. Model of communal land changes (Map) and statistical analysis of communal land and built-up area transformations (2024–2050).

In **Figure 3** above shows the spatial and temporal dynamics of LULC and ownership changes on communal land within the research location between 2024 and 2050. It highlights regions with a high potential for LULC transitions, which are often accompanied by changes in land tenure. The pattern of LULC change for settlements follows a southeast-to-northwest trajectory. The southeastern regions experience the most pronounced changes in LULC and ownership due to their favorable characteristics, including flat terrain and abundant groundwater resources, which make them highly suitable for settlement expansion. In contrast, the northwestern regions exhibit fewer changes in communal land ownership. This is attributed to less fertile soil, deeper groundwater levels, and frequent drought conditions, making these regions less desirable for settlement or agricultural activities. **Figure 3** also illustrates specific changes in settlement development and land tenure on communal land. Gadut and Ladang Laweh Villages emerge as areas under significant pressure, highlighting their vulnerability. Gadut Village has the highest growth in settlement buildings and land ownership transitions. In 2024, Gadut had 4,019 settlement buildings, alongside 80 recorded cases of land ownership changes. By 2030, the number of buildings is projected to rise to 4,724, with 94 cases of ownership transitions. By 2050, the figures are expected to reach 7,055 buildings and 141 instances of ownership changes. Similarly, Ladang Laweh demonstrates considerable shifts, although to a slightly lesser extent, with a notable increase in both settlement development and land ownership transitions during the same period.

This increasing trend in LULC and ownership changes is primarily attributed to weak regulatory frameworks governing communal land use and tenure. The absence of robust regulations enables the conversion of communal land into private ownership, often without sufficient consideration for the cultural and communal significance of these lands. This lack of oversight poses significant risks to the preservation of communal land and its socio-cultural importance. Furthermore, the diminishing availability of agricultural land due to settlement expansion raises critical concerns about food security and public health. Reduced local food supply can lead to increased dependence on imported food, which may not always meet the safety standards required to prevent contamination or pollution. The contamination risks are particularly heightened in areas experiencing rapid urbanization and inadequate waste management practices. These issues underscore the potential impacts of LULC changes on food safety and human health, emphasizing the need for comprehensive land management policies. These findings underscore the complex interplay between LULC changes and land ownership dynamics, emphasizing the need for sustainable land management policies. Such policies must address both the spatial impacts of land conversion and the socio-economic ramifications of

ownership shifts. Additionally, integrating food security and public health considerations into these policies is crucial to ensuring long-term resilience and sustainability. Proactive measures, such as promoting sustainable agricultural practices, strengthening food safety regulations, and implementing robust urban waste management systems, are essential to mitigate the adverse effects of LULC changes on local societies.

3.3. Factors influencing changes in communal land ownership

Changes in communal land ownership, particularly concerning settlement LULC within the research location, are influenced by a range of factors. These factors can be broadly categorized into environmental, social, economic, and cultural dimensions, each contributing significantly to the dynamics of land tenure and usage. A comprehensive breakdown of these factors is provided in **Table 1** and **Figure 5** below:

Table 1.

Factors affecting changes in communal land ownership.

Var		N	Min	Max	Mean	Std. Dev	Var		N	Min	Max	Mean	Std. dev
Environment	X1	100	0.33	1.00	0.73	0.28	Economic	X12	100	0.33	1.00	0.56	0.30
	X2	100	0.33	1.00	0.71	0.31		X13	100	0.33	1.00	0.60	0.32
	X3	100	0.33	1.00	0.70	0.29		X14	100	0.33	1.00	0.53	0.29
	X4	100	0.33	1.00	0.66	0.31		X15	100	0.33	1.00	0.74	0.30
	X5	100	0.33	1.00	0.65	0.31		X16	100	0.33	1.00	0.73	0.31
Social	X6	100	0.33	1.00	0.60	0.31	Culture	X17	100	0.33	1.00	0.62	0.31
	X7	100	0.33	1.00	0.72	0.32		X18	100	0.33	1.00	0.52	0.27
	X8	100	0.33	1.00	0.70	0.32		X19	100	0.33	1.00	0.56	0.29
	X9	100	0.33	1.00	0.59	0.31		X20	100	0.33	1.00	0.47	0.24
	X10	100	0.33	1.00	0.78	0.30		X21	100	0.33	0.66	0.41	0.14
	X11	100	0.33	1.00	0.72	0.28	Comunal Land	Y22	100	10.27	16.98	13.32	1.33

Table 1 and **Figure 5** provide a descriptive statistical analysis of the variables influencing changes in LULC and ownership of communal land within the research location. These variables are categorized into four main dimensions (environmental, social, economic, and cultural), each evaluated using specific parameters. The analysis is based on data collected from 100 respondents with relevant knowledge or experience related to communal land.

- Environmental factors, including city existence (X_1), agricultural land (X_2), distance to the city center (X_3), customary forest (X_4), and natural resources (X_5), exhibited mean values ranging from 0.65 to 0.73, with standard deviations between 0.28 and 0.31. These results suggest moderate variability in the influence of environmental conditions on communal land ownership.
- Social factors, such as population (X_6), community attitudes (X_7), the role of community leaders (X_8), the matrilineal system (X_9), and customary law (X_{10}), recorded the highest mean value of 0.78 (customary law) and a standard deviation of 0.30. These findings emphasize the critical role of social norms and structures in shaping changes in communal land ownership.
- Economic factors, including livelihood (X_{12}), agricultural profit sharing (X_{13}), investment (X_{14}), market existence (X_{15}), and welfare (X_{16}), had mean values ranging from 0.56 to 0.60, with standard deviations between 0.30 and 0.32. These results reflect the economic pressures driving transitions in communal land use.
- Cultural factors, such as local wisdom (X_{17}), migration (X_{18}), mutual cooperation (X_{19}), traditional deliberation (X_{20}), and traditional leadership (X_{21}), showed the lowest mean value of 0.41, with standard deviations ranging from 0.14 to 0.37. This indicates that weakening cultural practices and traditions significantly facilitate changes in communal land ownership.

The variable representing changes in communal land ownership (X_{22}) had a mean value of 16.98 and a standard deviation of 1.33, indicating considerable variability in the extent of ownership changes across different areas. The analysis revealed that a minimum value of 0.33 corresponds to

regions where strong customary laws and traditions protect communal land, while a maximum value of 1.00 represents regions with weaker customary governance, making ownership transitions more likely. Among the factors, social elements particularly customary law were identified as the most influential, while cultural elements had the least impact. To gain deeper insights, multiple regression analysis was conducted to evaluate the combined effects of these variables. The analysis revealed that social and economic factors are the most significant drivers of changes in communal land ownership, while the weakening of cultural traditions further accelerates these transitions. These findings highlight the importance of strengthening customary laws, preserving cultural practices, and addressing economic pressures to safeguard communal land. Developing sustainable policies that holistically address environmental, social, economic, and cultural dimensions is essential for managing changes in communal land ownership effectively.

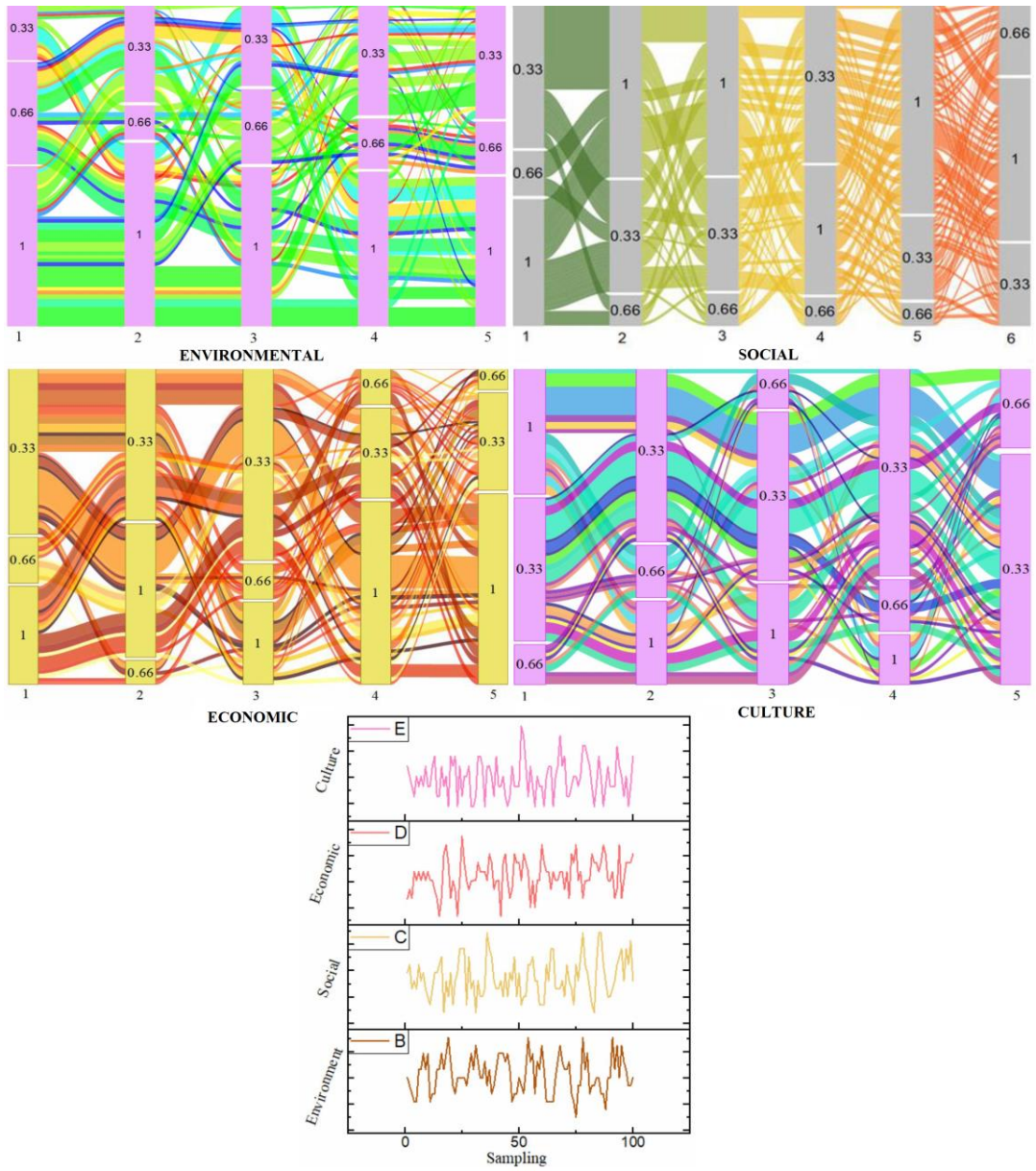

Fig. 5. Factors influencing changes (Graphs) in communal land use and ownership.

5. DISCUSSION

Based on the results of previous studies, changes in LULC on communal land within the research location are often accompanied by changes in land ownership. However, there are instances where changes in LULC occur without ownership changes. LULC changes involving ownership transitions are typically found in built-up areas used for settlement purposes (Admasu et al., 2023; Wen et al., 2024). Conversely, LULC changes without ownership alterations are more common in agricultural land and settlements governed by strong customary regulations and laws (Duijndam et al., 2023; Choudhury et al., 2019), particularly on communal land. Findings from the LULC model corroborate this, showing that urban expansion and population growth in Bukittinggi City significantly impact the utilization and fragmentation of communal land, especially near urban borders and areas with high economic activities.

In regions with strong customary regulations, communal land can only be utilized by the society that traditionally owns it, as governed by the matrilineal system. Changes in LULC accompanied by ownership transitions are prevalent in Bukittinggi City and its surroundings, driven by high land prices, weak regulations, and reduced efforts to preserve communal land. Weak regulatory frameworks, combined with external investments, exacerbate the vulnerability of communal lands to conversion and fragmentation. Predicted LULC changes for 2030 and 2050 indicate a consistent reduction in communal land areas, primarily due to the conversion of agricultural zones, such as paddy fields, into urban settlements. By 2050, this reduction is expected to reach critical levels, posing a serious threat to the traditional LULC system in the region. The diminishing agricultural land raises critical concerns regarding food security and public health. As agricultural zones shrink, local food supply might decline, increasing dependency on external food sources and elevating the risk of food shortages. Furthermore, changes in LULC, especially involving urban settlements, could introduce risks of pollution or contamination, which directly impact food safety and public health.

Regions experiencing the most significant changes in communal land ownership include Gadut, Ladang Laweh, Kubang Putih, Pasia, Ampang Gadang, Biaro, Batu Taba, and Taluakampek Suku villages. These locations are characterized by favorable topographical conditions, such as flat terrain and easy access to road networks, making them attractive for settlement development and urban investors. Such ownership changes result in a reduction of communal land owned by specific tribes, potentially leading to the complete loss of communal land for some tribes. This loss threatens not only the land but also the cultural identity of indigenous tribes, as communal land serves as a cornerstone for validating tribal recognition. To address these challenges, the development of stronger legal frameworks and community-based governance systems is essential. Strengthening customary regulations and incorporating them into formal land-use planning could mitigate the impacts of urbanization and external pressures. Furthermore, fostering participatory decision-making processes involving traditional leaders, local societies, and policymakers can bridge the gap between cultural preservation and sustainable development.

These transformations underscore the vulnerability of indigenous societies to external pressures, including urbanization and weakened customary governance systems. Several factors influence changes in LULC on communal land, categorized as follows:

- Environmental factors: The distance from Bukittinggi City is a critical environmental determinant influencing changes in communal land, especially ownership transitions. Population pressure and high land prices in Bukittinggi trigger land use changes, predominantly for settlement purposes (Zheng et al., 2024; Zhang et al., 2014). Additionally, regions with infertile agricultural land or limited natural resources are more likely to experience ownership transitions due to reduced agricultural productivity and increased attractiveness for non-agricultural developments.
- Social factors: Population growth and education levels significantly influence ownership changes. A large population in Bukittinggi City, combined with low education levels, facilitates the buying and selling of communal land (Duijndam et al., 2023; Choudhury et al., 2019). Weakening social cohesion and declining roles of customary leaders further diminish the community's capacity to

resist external pressures. Strengthening community-based governance and enhancing public awareness through education could play a pivotal role in safeguarding communal land.

- Economic factors: Low economic levels and external investments are major drivers of changes in communal land use and ownership. Investments from external parties, particularly along roadsides, have led to the construction of shophouses. These buildings are often co-developed by communal land owners and external investors, with ownership eventually transferring to investors who sell the properties to third parties (Chen et al., 2023; Sari et al., 2023). This trend is especially pronounced in regions with high accessibility and market potential, where land values rise rapidly.
- Cultural factors: Cultural shifts, including the declining influence of traditional leaders and weakening customary regulations, significantly contribute to changes in land use and ownership. For example, the traditional role of mothers in guiding nieces during decision-making has diminished, as parents now prioritize their children's upbringing (Tang et al., 2023; Wang et al., 2023). Revitalizing cultural practices and empowering traditional governance structures through legal and financial support can help mitigate these shifts. The erosion of mutual cooperation practices and deliberative processes further accelerates these changes, undermining the communal ethos that once protected these lands.

6. CONCLUSIONS

The changes in LULC in Bukittinggi City and its surroundings demonstrate a complex dynamic with significant impacts on communal land. Urbanization, economic growth, and population pressure have driven substantial transformations in LULC patterns, including the conversion of agricultural and forested lands into settlements. Communal land, traditionally governed by customary laws, is increasingly fragmented due to urban expansion and economic pressures. The findings reveal that LULC changes accompanied by shifts in land ownership are prevalent in settlements, particularly in regions with high accessibility and economic value. Environmental, social, economic, and cultural factors collectively influence these changes. Projections for 2030 and 2050 indicate a significant decline in communal land, particularly in locations with advantageous topographical and economic conditions, such as Gadut and Ladang Laweh. Environmental factors, such as proximity to urban centers and declining agricultural productivity, accelerate LULC transitions. The diminishing availability of agricultural land poses a serious threat to local food security, potentially disrupting food supplies and increasing the risks of malnutrition in vulnerable societies. Furthermore, the rapid urbanization and conversion of agricultural land raise concerns about pollution and contamination risks, which may directly impact public health. These issues underline the interconnectedness of LULC changes, human health, and food security. Social factors, including population growth and the diminishing influence of traditional leaders, further exacerbate ownership changes. Economically, external investments play a significant role in converting communal land for commercial purposes, while cultural factors, such as the weakening of customary practices and laws, intensify these transformations. These changes not only threaten the sustainability of communal land but also undermine the traditional identity of indigenous societies, whose recognition is closely tied to their communal land. The loss of communal land diminishes the social and cultural value systems that have been passed down through generations. To address these challenges, sustainable land management strategies are essential to balance development needs with the preservation of ecosystems and cultural heritage. Strengthening customary regulations, empowering traditional leaders, and implementing comprehensive urban planning are crucial to protecting communal land from further fragmentation. Proactive policies that integrate environmental, social, economic, and cultural dimensions must be adopted to ensure communal land remains a vital resource for future generations.

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