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Geospatial Modeling of Agricultural Land Use Change and Its Environmental Implications Using CA–Markov Model in Aceh Besar, Indonesia

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Abstract: Agricultural land use change is an important issue in regional development because it has direct implications for food security and environmental sustainability. This study aims to analyze changes in agricultural land use and model the projected changes and environmental implications using a geospatial approach based on Cellular Automata-Markov (CA-Markov) in Aceh Besar Regency, Indonesia. Land use data for 2012, 2018, and 2024 were analyzed using the Geographic Information System and Land Change Modeler. The classification accuracy test showed an overall accuracy value of 95% and a kappa coefficient of 0.95, which indicates an excellent level of accuracy. The results of the analysis of land use changes for the 2012–2024 period show that agricultural land has decreased significantly due to conversion into settlements and shrubs. CA–Markov modeling yields a high validation rate with a Kstandard value of 0.92. The projected land use in 2032 shows that the downward trend of agricultural land is expected to continue if effective control of space use is not carried out. The findings of this study confirm the importance of geospatial modeling as the basis for spatial planning and sustainable agricultural land protection to support the development of environmentally sound regions.

Keywords: Agricultural Land; Aceh Besar; Cellular Automata–Markov (CA–Markov); Geographic Information Systems; Geospatial Modeling; Land Use Change

Introduction

Land use change is a spatial phenomenon closely linked to regional development dynamics and population growth. As a limited natural resource, land experiences increasing pressure due to the growing demand for space for settlements, infrastructure, and various economic activities (Anindita & Syarifudin, 2022; Ardi & Priyoga, 2023). These pressures lead to continuous transformation of land functions, which consequently alters spatial structures and environmental conditions. From a sustainability perspective, land use change has become a critical issue because it simultaneously influences ecological balance, economic development, and social welfare. Conceptually, land represents the result of complex interactions between natural processes and human activities that shape landscapes with distinct physical and socio-economic characteristics (Basu et al., 2025; Myga-Piątek, 2023). Changes in land systems affect not only spatial patterns but also ecological processes such as energy flows, hydrological cycles, and ecosystem stability. In the context of sustainable development, agricultural land plays a strategic role because it is directly associated with food security, farmers' livelihoods, and environmental carrying capacity (Firdiansyah et al., 2021). However, the conversion of agricultural land to non-agricultural uses tends to be permanent and difficult to reverse, making it a major concern in spatial planning and land management policies.

Population growth and regional development that are not accompanied by effective spatial control frequently trigger extensive agricultural land conversion

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(Anggraini et al., 2025). This phenomenon occurs not only in urban areas but also in rural regions with agrarian economic bases. Aceh Besar Regency in Aceh Province represents one of the areas where agricultural land plays a fundamental role in supporting the local economy and food security, as most residents rely on farming and rice cultivation as their primary livelihood. Nevertheless, increasing demands for residential areas and other non-agricultural activities have intensified land conversion pressures in this region. Land use data indicate a decline in agricultural land between 2012 and 2024, with significant transitions into settlements and shrubland. The reduction of agricultural land not only affects farmers' economic conditions but also contributes to environmental degradation, including disrupted water catchment systems, increased surface runoff, and declining watershed quality (Khattak et al., 2025). Although the Regional Spatial Plan (RTRW) functions as a regulatory instrument to control spatial utilization and maintain balance between conservation and development (Mulya et al., 2022), its implementation often encounters challenges due to weak supervision and increasing development pressures. These conditions highlight the need for analytical approaches capable of monitoring and predicting spatial land use dynamics accurately.

Advances in remote sensing and Geographic Information Systems (GIS) technologies provide powerful tools for analyzing land use changes spatially and temporally (Purnamasari, 2026). Multitemporal satellite imagery enables quantitative identification of land conversion patterns, change trajectories, and the intensity of land transformation over time (Rai et al., 2024; Singh et al., 2025). Among the widely applied approaches, the Land Change Modeler (LCM) facilitates the analysis of historical land change and the identification of transition trends (Kamagate et al., 2025; Zahir et al., 2021). To enhance predictive accuracy, LCM is often integrated with the Cellular Automata–Markov (CA–Markov) model, which combines Markov transition probabilities with spatial neighborhood rules to simulate future land use patterns realistically (Leta et al., 2021). This integrated model enables both temporal prediction and spatial distribution analysis of land use changes. However, studies applying CA–Markov modeling to evaluate agricultural land dynamics and environmental implications in Aceh Besar Regency remain limited, as most previous research has focused primarily on descriptive land change analysis without integrating predictive modeling with spatial planning frameworks. Therefore, this research aims to analyze land use changes in Aceh Besar Regency during the 2012–2024 period and to project land use patterns for 2032 using the CA–Markov model. The study also evaluates the implications of these changes for environmental sustainability and spatial planning policies. The findings are expected to provide scientific evidence that can support regional planning, agricultural land protection, and sustainable land resource management in Aceh Besar Regency.

Method

Types and Approaches to Research

This study uses a descriptive research method with a geospatial-based quantitative approach (Anand & Batra, 2021; Dedy Miswar et al., 2020). The descriptive approach is used to describe the conditions and dynamics of changes in agricultural land use that occur in Aceh Besar Regency in a certain period of time, while the quantitative approach is used to analyze the magnitude of change, transition probability, and land use projections numerically and spatially.

The geospatial approach is applied to analyze the distribution, patterns, and changes in land use based on spatial (spatial) and temporal aspects (Banerjee & Palit, 2024). Spatial analysis was carried out using Geographic Information System (GIS) technology and remote sensing (Wu & Zhang, 2024), while temporal analysis was carried out through the study of multitemporal land use data in 2012, 2018, and 2024 as the basis for modeling changes and projections until 2032.

Research Location and Time

This research was carried out in Aceh Besar Regency, Aceh Province, which is geographically located at the coordinates of 5.05°–5.75° North Latitude and 94.99°–95.93° East Longitude, with an area of ±2,903.49 km². Administratively, Aceh Besar Regency consists of 23 sub-districts and 604 gampongs/villages. Data processing and analysis was carried out at the Remote Sensing and Cartography Laboratory, Department of Soil Science, Faculty of Agriculture, Syiah Kuala University. The research implementation time lasts from September 2025 to January 2026.

Data and Data Sources

The data used in this study consist of both spatial and non-spatial data sources. The spatial data include land use maps of Aceh Besar Regency for the years 2012, 2018, and 2024 obtained from the Forest Area Stabilization Center (BPKH) Region XVIII Aceh. In addition, the administrative boundary map of Aceh Besar Regency was obtained from the Indonesian Motherland Web, and the Regional Spatial Plan (RTRW) map of Aceh Besar Regency for the 2012–2032 period was used as a reference for spatial planning analysis. Meanwhile, the non-spatial data consist of field survey data (ground checks) conducted to test the accuracy of land use classification, as well as supporting literature in the form of books, scientific journal articles, research reports, and regulations related to land use and spatial planning. These data sources were utilized to support both the spatial analysis and the interpretation of land use change dynamics in the study area.

Tools and Software

The equipment and software used in this research *support* the processes of spatial data processing, analysis, and visualization. The primary equipment includes a laptop, stationery, and a Global Positioning System (GPS) device used to record coordinate points during field verification activities. Several software applications were employed in the analysis process. ArcGIS 10.8 was used for spatial data processing, map preparation, and geospatial analysis. TerrSet software was utilized to conduct Land Change Modeler (LCM) analysis and Cellular Automata–Markov (CA–Markov) modeling for land use change prediction. Google Earth Pro was used to support visual verification and image interpretation, particularly in identifying land cover characteristics. Microsoft Excel was used for processing tabular data and calculating statistical values related to land use change, while Microsoft Visio was used to design and visualize the research workflow.

Research Stages

This research was conducted through three main stages, namely the preparation stage, the pre-analysis stage, and the analysis stage. The preparation stage involved collecting both spatial and non-spatial data, conducting a literature review related to land use change and spatial modeling, and preparing the hardware and software required for the research process. At this stage, adjustments were also made to the land use classification system based on applicable classification standards to ensure consistency in the analysis.

The pre-analysis stage focused on preparing the spatial data before conducting the main modeling process. This stage included the initial processing of land use data for 2012, 2018, and 2024 in shapefile format. The vector data were then converted into raster format using ArcGIS 10.8 to enable further spatial modeling analysis. Afterward, the raster data were converted into ASCII format so that they could be processed using the TerrSet software. An accuracy test of land use classification was conducted using the confusion matrix method by comparing the classification results with actual field conditions obtained through ground checks. The classification accuracy was evaluated using overall accuracy values and the Kappa coefficient as indicators to determine the reliability of the land use data used in the analysis.

Stages of Analysis

The analysis stage represents the core component of this research and involves several analytical procedures. The first step is the analysis of land use changes using the Land Change Modeler (LCM) in TerrSet software to identify changes in agricultural land use during the period 2012–2024. This analysis produces information regarding gains, losses, and transition matrices between land use classes. The results of the land use change analysis were then used to construct a Markov chain-based Transition Probability Matrix (TPM), which describes the probability of each land use class transitioning to another class over time.

Furthermore, Cellular Automata–Markov (CA–Markov) modeling was applied to project land use patterns in Aceh Besar Regency for the year 2032. This model integrates Markov transition probabilities with Cellular Automata spatial neighborhood rules to generate a spatially explicit projection of future land use distribution. To ensure the reliability of the model, a validation process was conducted by comparing the projected land use map for 2024 with the actual land use data for the same year. The level of model accuracy was assessed using Kappa statistics, including Kstandard, Klocation, and Knot indices. Finally, the projected agricultural land use map for 2032 was analyzed in relation to the Aceh Besar Regency RTRW through spatial overlay techniques. This analysis was conducted to evaluate the level of spatial conformity and to identify potential conflicts in future land utilization based on the regional spatial planning framework.

Result and Discussion

Classification and Accuracy of Land Use in Aceh Besar Regency

The initial stage of analysis in this study is the preparation and evaluation of land use maps in Aceh Besar Regency in 2012, 2018, and 2024. Land use data was obtained from the Forest Area Stabilization Center (BPKH) Region XVIII Aceh and classified into seven land use classes, namely water bodies, forests, open land, settlements, agriculture, rice fields, and shrubs. This classification is the main basis for the analysis of changes and modeling of land use projections.

The accuracy test was carried out to assess the level of conformity between the results of land use classification and the actual conditions in the field. The confusion matrix method is used by comparing the data from the classification results to the ground check points obtained through field surveys. The results of the accuracy test showed that the land use classification has a very high level of accuracy and is suitable for further analysis.

Table 1. Results of the Land Use Classification Accuracy Test in Aceh Besar Regency

Accuracy Indicators	Value
Overall Accuracy	95%
Kappa Accuracy	0,95
Categories Accuracy	Excellent

The high value of overall accuracy and kappa coefficient shows that the resulting land use map is able to accurately represent the actual conditions of the research area. Thus, this data is considered reliable as an input in the analysis of land use change and CA–Markov modeling.

The results of the land use classification accuracy test in Aceh Besar Regency showed a very high level of accuracy with an overall accuracy value of 95% and a kappa coefficient of 0.95. This high accuracy value indicates that the land use map used has been able to reliably represent the actual conditions in the field. Methodologically, an accuracy rate above 85% has met the feasibility standards for land use change analysis and spatial modelling (Liu et al., 2023).

The reliability of land use classification is a key factor in CA–Markov modeling, as errors in the early stages will have a direct impact on the results of change analysis and projections (Chen & Wang, 2024). According to Khattak et al., (2025), the quality of input data is the main determinant in the success of Cellular Automata-based modeling of land use change (Shabrinna, 2021). Thus, the results of the high accuracy test in this study strengthen the validity of all subsequent stages of analysis.

These findings are in line with research (Purboyo et al., 2024) which confirms that the combination of multitemporal land use data and confusion matrix-based accuracy tests can increase the reliability of land change analysis, especially in areas with complex spatial use dynamics such as peri-urban and agricultural areas.

Changes in Agricultural Land Use for the 2012–2024 Period

The analysis of land use change was carried out using the Land Change Modeler (LCM) in the TerrSet software. This analysis aims to identify the magnitude of changes in agricultural land use and land conversion patterns that occurred during the 2012–2024 period. The results of the analysis show that agricultural land has experienced a significant decrease in area, especially due to conversion to residential and shrub classes.

This change reflects the increasing pressure on regional development which has implications for the reduced availability of productive agricultural land (Romero-Cano et al., 2025). In addition, the dynamics of land use change also show a shift in land function influenced by the needs of space and economic activities of the community.

Table 2. Changes in Land Use in Aceh Besar Regency in 2012–2024

Land Use Class	Area 2012 (ha)	Area 2024 (ha)	Change (ha)
Forest	103.618,42	106.391,12	+2.772,70
Open Land	1.684,48	10.951,96	+9.267,48
Water bodies	2.371,32	2.567,63	+196,31
Bushes	116.512,39	101.640,84	−14,871.55
Settlements	4.945,04	12.989,74	+8.044,70
Rice Fields	20.017,45	20.688,36	+670,91
Agriculture	40.462,31	34.381,75	−6.080,56

The decrease in agricultural land area by 6,080.56 ha during the observation period shows a tendency to change land use that needs serious attention, considering the strategic role of agricultural land in supporting food security and environmental sustainability.

The results of the analysis of land use changes for the 2012–2024 period show a significant decrease in agricultural land area, which is 6,080.56 ha. This decline was mainly triggered by the conversion of agricultural land into settlements and bushes. This phenomenon reflects the increasing pressure of regional development along with population growth and the need for non-agricultural space.

Theoretically, changes in agricultural land use are a consequence of the interaction between social, economic, and spatial policy factors (Mekuria et al., 2020; Mengist et al., 2023). stated that the conversion of agricultural land in developing regions is generally influenced by settlement expansion, changes in livelihoods, and weak control of space utilization. This condition is also reflected in Aceh Besar Regency, which experienced a significant increase in residential classes during the observation period.

The results of this study are in line with the findings Rambe et al., (2023) in the Sumatra region which shows that agricultural land tends to decline due to urban sprawl and infrastructure development. Decline in agricultural land in the long term has the potential to threaten local food security and reduce the carrying capacity of the environment, especially in maintaining hydrological balance and soil quality (Basu et al., 2025).

Model Validation and Probability of Land Use Transition

Model validation was carried out to assess the reliability of CA–Markov modeling in predicting land-use change. Validation was carried out by comparing the results of the 2024 land use projection with the existing land use data in 2024. The validation results show that the model has an excellent level of suitability, making it feasible to use it for land use projections until 2032.

In addition to validation, transition probability analysis is carried out to determine the tendency of changes between land use classes (Kumar et al., 2023). The transition probability matrix shows that farmland has a considerable chance of transitioning to shrub and residential classes, although some still retain their original function.

Table 3. CA–Markov Model Validation Results

Validation Index	Value
Kno	0.93
Klocation	0.95
Klocation Strata	1.00
Kstandard	0.92
Category	Excellent

A Kstandard value of 0.92 indicates a very high level of match between the simulation results and the actual conditions. This indicates that the CA–Markov model is able to represent the dynamics of spatial land use change well.

The results of the validation of the CA–Markov model showed a Kstandard value of 0.92 which was included in the very good category. This value indicates that the model is able to simulate spatial land-use change patterns with a high degree of conformity to actual conditions (Li et al., 2025). The high values of Klocation and Kno also show that the model is not only quantitatively accurate, but also precise in the spatial placement of land changes (Keleş et al., 2025).

Conceptually, the advantage of the CA–Markov model lies in its ability to integrate temporal (Markov chain) and spatial (Cellular Automata) aspects. According to (Zhang et al., 2023), this approach is very effective for modeling land use changes that are gradual and influenced by spatial neighborhood patterns, such as agricultural land conversion around built-up areas (Rehberger et al., 2023).

Transition probability analysis shows that farmland has a considerable chance of turning into settlements and shrubs . This pattern indicates that farmland is in a vulnerable position to conversion pressure. These findings are consistent with research (Hasan et al., 2020) which found that agricultural land classes generally have a high probability of transitioning to built-up land use in areas with medium to high development rates (Mekuria et al., 2020).

Projected Changes in Agricultural Land Use in 2032 and Its Implications

CA–Markov modeling is used to project the land use of Aceh Besar Regency until 2032. The projections are based on land use data for 2012 and 2024 and the resulting transition probability matrix. The projection results show that agricultural land is still expected to experience a decline in area, while residential land and shrubs tend to increase.

The decline in agricultural land area by 2032 shows that without effective control of space use, the pressure on agricultural land will continue and have the potential to cause environmental implications such as a decrease in land carrying capacity and an increased risk of environmental degradation (Chaudhari, 2021).

Table 4. Projected Land Use Area of Aceh Besar Regency in 2032

Land Use Class	Area 2024 (ha)	Projected 2032 (ha)	Change (ha)
Forest	106.391,12	102.464,90	−3.926,22
Open Land	10.951,96	3.335,13	−7.616,83
Water bodies	2.567,63	2.316,05	−251,58
Bushes	101.640,84	112.216,41	+10.575,57
Settlements	12.989,74	16.440,05	+3.450,31
Rice Fields	20.688,36	20.885,19	+196,83
Agriculture	34.381,75	31.950,86	−2,430.89

The results of this projection confirm that agricultural land in Aceh Besar Regency is still facing considerable pressure on conversion of functions. Therefore, the results of this research can be used as a basis for the formulation of policies to control the use of space and protect sustainable agricultural land.

The results of the 2032 land use projections show that the downward trend of agricultural land is expected to continue, with a decrease of 2,430.89 ha compared to 2024. On the other hand, residential land and shrubs are projected to increase in area. This pattern suggests that without effective policy interventions, the pressure on agricultural land will be even greater in the future.

Ecologically, the reduction of agricultural land can have an impact on decreasing water catchment capacity, increasing surface runoff, and potentially increasing the risk of flooding and environmental degradation. According to (Shanmugam et al., 2024; Widayani et al., 2023), the change in land use from agriculture to built areas is one of the main factors in the decline of ecosystem services in the tropics.

The results of this projection also indicate a potential incompatibility between future land use conditions and regional spatial plans. This is in line with the findings of Gao et al., (2024) who affirm that inconsistencies between RTRW and actual land use dynamics can accelerate environmental degradation and space use conflicts.

Thus, the results of CA–Markov modeling in this study have important implications as a basis for the formulation of policies to control the transfer of agricultural land use, protect sustainable agricultural land, and strengthen the implementation of RTRW in Aceh Besar Regency.

Conclusion

This study shows that changes in agricultural land use in Aceh Besar Regency took place significantly during the period 2012–2024 and tend to continue until 2032. The results of the analysis based on the Geographic Information System and Land Change Modeler indicate a decrease in the area of agricultural land which is mainly converted into settlements and bushes. This condition reflects the increasing pressure on regional development which has a direct impact on the sustainability of agricultural land. Cellular Automata–Markov modeling yielded an excellent level of accuracy, which was indicated by a kappa coefficient value of more than 0.90, so the model was considered reliable in projecting spatial and temporal land-use changes. The projected land use in 2032 shows that without effective control of space use, the rate of conversion of agricultural land will continue to increase. The implications of these changes not only have an impact on food security and the agricultural economy, but also have the potential to reduce the carrying capacity of the environment. Therefore, the results of this study emphasize the importance of strengthening spatial planning policies and protecting sustainable agricultural land as an effort to support the development of environmentally friendly regions.

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Author Contributions
Conceptualization, O.A.D. and M.R.; methodology, O.A.D.; software, O.A.D.; validation, O.A.D., M.R. and J.A.; formal analysis, O.A.D.; investigation, O.A.D.; resources, O.A.D.; data curation, O.A.D.; writing—original draft preparation, O.A.D.; writing—review and editing, O.A.D

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