

## GIS-Based Sustainable Regional Planning Modeling for Predicting the Conversion of Agricultural Land into Residential Areas in Klambir Lima Village, Deli Serdang Regency

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### ABSTRACT

The rapid conversion of agricultural land into residential areas presents a significant challenge to sustainable regional planning, particularly in areas experiencing population growth and urban expansion. This study aims to develop a **GIS-based sustainable regional planning model** for predicting agricultural land conversion into residential areas in Klambir Lima Village, Deli Serdang Regency, Indonesia. The study integrates Geographic Information System (GIS) technology with spatial analysis to identify land-use changes and determine areas with high potential for future conversion. Spatial variables include land-use history, distance to roads, distance to residential areas, population density, accessibility, and proximity to public facilities. Historical spatial data are processed through GIS to identify patterns of agricultural land conversion, while predictive analysis is applied to estimate potential future changes. The resulting spatial model generates a land-conversion risk map that can be used to identify agricultural areas requiring protection and areas potentially suitable for residential development. The proposed model provides a data-driven approach for supporting sustainable regional planning by integrating spatial information, land-use prediction, and development considerations. The study is expected to contribute to more effective agricultural land protection, controlled residential expansion, and evidence-based regional planning in Deli Serdang Regency.

**Keywords:** Geographic Information System; Gis; Sustainable Regional Planning; And Agricultural Land Conversion; Deli Serdang.

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### 1. INTRODUCTION.

The rapid growth of residential areas has increased pressure on agricultural land in many developing regions, including Indonesia. Population growth, economic development, improved accessibility, and increasing demand for residential land have contributed to changes in land-use patterns. The conversion of agricultural land into non-agricultural uses is particularly important because it can reduce productive agricultural areas and create conflicts between residential development, agricultural sustainability, and regional spatial planning. Recent studies emphasize that agricultural land conversion needs to be monitored spatially because land-use changes are influenced by physical, economic, social, and accessibility-related factors (Permata et al., 2022; Yang et al., 2023).

In Indonesia, agricultural land conversion represents an important challenge for sustainable regional development and food security. The conversion of productive agricultural land can reduce the capacity of an area to maintain agricultural production, particularly when residential expansion occurs in areas with good accessibility to roads, economic centers, and public facilities. Research on sustainable food agricultural land has demonstrated that inconsistencies can occur between existing land use and regional spatial planning, indicating the importance of continuous spatial monitoring and evaluation (Yang et al., 2023). Similarly, studies applying remote sensing and GIS have demonstrated that land-use changes can be identified quantitatively and spatially to evaluate their implications for food availability and regional development.

Deli Serdang Regency provides an important geographical context for examining agricultural land conversion. Previous research identified significant agricultural land-use changes in Deli Serdang and demonstrated the applicability of Geographic Information System (GIS) and spatial modeling for analyzing land-use dynamics. Verawaty et al. (2023), for example, analyzed land-use and land-cover

changes in Deli Serdang during 2010–2020 and applied a Cellular Automata–Markov Chain approach to predict future land-use patterns. Their findings demonstrate that spatial modeling can provide information regarding potential future land-use changes and their driving factors. In addition, Permata et al. (2022) used GIS and economic land analysis to examine changes and economic characteristics of agricultural land in Deli Serdang, confirming the relevance of spatial analysis for understanding agricultural land dynamics in the region.

Klambir Lima Village, located in Deli Serdang Regency, is particularly relevant to this issue because residential development and changes in land utilization require an approach that considers both spatial characteristics and regional development objectives. The expansion of residential areas should not be considered solely as a physical change in land cover, but also as a spatial planning issue involving accessibility, settlement growth, agricultural protection, and the compatibility of land use with regional planning policies. Consequently, identifying the spatial pattern and potential areas of agricultural land conversion is necessary to provide a scientific basis for sustainable regional planning. Geographic Information System (GIS) provides an appropriate technological framework for addressing this problem because it enables the integration, visualization, overlay, and spatial analysis of multiple geographic variables. GIS can combine land-use maps, satellite imagery, road networks, settlement locations, public facilities, population information, and spatial planning zones to identify areas experiencing or potentially experiencing land-use conversion. Recent research has demonstrated the effectiveness of GIS and remote sensing for monitoring agricultural land changes and evaluating their relationship with spatial planning and food-security considerations (Rahmadani et al., 2024). Furthermore, GIS-based spatial analysis has been applied to evaluate the compatibility between protected agricultural land and regional spatial plans, demonstrating its potential as a decision-support instrument for sustainable land management.

The development of spatial prediction methods provides a further opportunity to strengthen GIS-based regional planning. Conventional land-use change analysis generally describes changes that have already occurred, whereas predictive spatial modeling can estimate areas with a higher probability of future conversion. Recent research has integrated multispectral remote sensing, GIS, Random Forest, and Artificial Neural Network approaches to analyze historical land-use changes and predict future land-cover dynamics. Such approaches demonstrate that machine-learning techniques can complement GIS by identifying nonlinear relationships between land-use changes and spatial variables. Therefore, integrating GIS with predictive modeling can transform land-use analysis from a descriptive mapping process into a more forward-looking decision-support approach.

The sustainability dimension is also important because land-use planning should balance residential development with the protection of agricultural resources. Spatial information can support the identification of agricultural areas that require protection and areas that are more appropriate for future development. Recent research on agricultural land protection has shown that GIS-based overlay analysis can integrate existing land use, protected agricultural land, and regional spatial planning to identify spatial inconsistencies and support land-protection recommendations. This approach is particularly relevant in areas where agricultural land is under increasing pressure from settlement expansion.

Despite the increasing application of GIS and remote sensing in land-use research, a research gap remains in developing an integrated spatial model that specifically connects historical agricultural land conversion, spatial determinants of residential expansion, prediction of potential future conversion, and sustainable regional planning at the village level. Existing studies have largely focused on land-use change detection, regional-scale prediction, land suitability, or evaluation of spatial-plan compliance separately. For example, research in Deli Serdang has examined regional land-use and land-cover prediction, while other studies have evaluated protected agricultural land against spatial planning regulations. An integrated village-level GIS model that produces a spatial prediction of agricultural-to-residential conversion and translates the prediction into regional planning information remains valuable.

Therefore, this study aims to develop a GIS-Based Sustainable Regional Planning Model for Predicting the Conversion of Agricultural Land into Residential Areas in Klambir Lima Village, Deli Serdang Regency. The study integrates GIS-based spatial analysis with historical land-use information and relevant spatial variables to identify patterns and predict potential agricultural land conversion. The resulting model is expected to generate spatial information regarding areas with different levels of

conversion potential and provide a basis for agricultural land protection, controlled residential expansion, and sustainable regional planning.

The contribution of this research is threefold. First, it contributes a GIS-based spatial modeling framework for analyzing agricultural-to-residential land conversion at the village level. Second, it integrates multiple spatial variables to support the prediction of potential land-use conversion rather than merely describing historical changes. Third, it translates the resulting spatial prediction into information that can support sustainable regional planning, particularly in balancing residential development with agricultural land protection. Thus, GIS is positioned not merely as a mapping tool but as a spatial decision-support technology for sustainable regional planning.

## **2. Literature Review and Hypothesis Development**

### **2.1 Sustainable Regional Planning and Agricultural Land Conversion**

Sustainable regional planning seeks to balance economic development, population growth, environmental protection, and the long-term availability of productive land. In rapidly developing areas, residential expansion can create pressure on agricultural land, particularly where accessibility, infrastructure development, and population growth increase the economic attractiveness of land for residential purposes. Agricultural land conversion is therefore not only a land-use issue but also a spatial planning issue because uncontrolled conversion can reduce agricultural capacity and create conflicts between development and environmental sustainability (Permata et al., 2022; Yang et al., 2023).

Agricultural land conversion is generally influenced by multiple interacting factors. These include proximity to roads, distance from existing settlements, population density, land accessibility, proximity to economic centers, land prices, and the availability of public infrastructure. Consequently, land conversion cannot be adequately explained using a single spatial variable. A multidimensional spatial approach is required to identify the geographic characteristics associated with conversion patterns.

In the Indonesian context, the protection of agricultural land is closely associated with sustainable food production and spatial planning. Yang et al. (2023) demonstrated that agricultural land conversion can potentially affect regional food availability, emphasizing the importance of controlling conversion in areas with strategic agricultural functions. Similarly, research in Deli Serdang has identified substantial changes in land use and land cover, demonstrating the relevance of spatial modeling for understanding the dynamics of agricultural and non-agricultural land (Verawaty et al., 2023). Therefore, sustainable regional planning requires not only identifying existing land-use patterns but also anticipating potential future conversion. A predictive spatial approach can provide planners with information regarding areas that are potentially vulnerable to residential expansion.

### **2.2 Geographic Information System (GIS) for Land-Use Planning**

Geographic Information System (GIS) is an important spatial technology for regional planning because it enables the integration, management, visualization, and analysis of geographically referenced data. GIS can combine multiple spatial layers, including land use, road networks, settlements, population density, public facilities, topography, and administrative boundaries, to identify spatial relationships and patterns.

Recent studies demonstrate that GIS and remote sensing are increasingly applied to monitor agricultural land conversion and evaluate its implications for food security and regional development. Rahmadani et al. (2024), for example, used remote sensing and GIS to analyze land-use changes and their implications for food availability. Such approaches demonstrate the ability of GIS to transform satellite and spatial data into information that can support regional planning.

GIS is particularly valuable because land-use conversion is inherently spatial. Two agricultural areas with similar physical characteristics may have different conversion risks because of differences in accessibility or proximity to existing settlements. Spatial overlay and proximity analysis therefore enable researchers to evaluate multiple determinants simultaneously.

In addition, GIS can be used as a decision-support technology rather than merely a mapping tool. By integrating historical land-use information with spatial determinants and predictive models, GIS can generate maps showing areas with different levels of land-conversion potential. This information can subsequently be used to support agricultural land protection and controlled residential development.

### 2.3 Spatial Analysis of Agricultural Land Conversion

Spatial analysis provides a methodological framework for identifying the geographic factors associated with agricultural land conversion. Historical land-use maps can be compared across different periods to identify areas where agricultural land has been converted into residential, commercial, industrial, or other uses. One of the most important techniques is land-use change detection, which compares land-use/land-cover (LULC) classifications from different periods. The resulting transition matrix can identify the quantity and spatial distribution of agricultural land converted into residential areas. Verawaty et al. (2023) demonstrated the usefulness of land-use and land-cover modeling for analyzing changes in Deli Serdang Regency.

Spatial proximity variables are also important. Residential expansion frequently follows existing transportation corridors because roads increase accessibility and reduce the cost of movement. Consequently, distance to roads can be incorporated as a predictor of agricultural land conversion. Similarly, areas located closer to existing settlements may have greater potential for residential expansion because they can benefit from existing infrastructure and services.

Other potentially relevant variables include:

- distance to major roads;
- distance to existing residential areas;
- population density;
- distance to public facilities;
- land-use history;
- land elevation and slope;
- proximity to economic centers; and
- spatial-plan designation.

The integration of these variables within GIS allows the development of a spatial representation of land-conversion susceptibility.

### 2.4 Remote Sensing and Land-Use Change Detection

Remote sensing provides an important data source for identifying land-use and land-cover changes over time. Satellite imagery enables researchers to monitor large areas periodically and identify transitions between agricultural, residential, vegetation, and other land-cover classes. Recent research has combined multispectral remote sensing with GIS to analyze historical land-use changes and predict future land-cover dynamics. Pham et al. (2024), for example, integrated multispectral remote sensing, GIS, Random Forest, and Artificial Neural Network techniques to analyze decadal land-use/land-cover changes and future land-use patterns. This demonstrates the potential of combining remote sensing and machine learning for spatial prediction.

For the present research, remote sensing can provide historical land-use information for Klambir Lima Village. Satellite imagery from different years can be classified into major land-use categories, particularly agricultural land and residential areas. The resulting historical dataset can then be integrated with GIS-based spatial variables to identify conversion patterns.

The advantage of this approach is that it provides an objective spatial basis for identifying changes rather than relying exclusively on administrative records or field observations. However, classification accuracy should be evaluated using appropriate validation data, such as ground-truth observations or reference imagery.

### 2.5 GIS-Based Decision Support for Sustainable Regional Planning

The ultimate purpose of spatial prediction should be to support better planning decisions. GIS-based decision-support systems can integrate spatial information, analytical results, and planning criteria to identify areas that should be protected, developed, or subjected to further evaluation.

For agricultural land protection, a GIS-based system can classify agricultural areas into different levels of conversion risk, such as:

1. Low conversion risk – agricultural areas relatively distant from settlements and major transportation corridors.
2. Moderate conversion risk – agricultural areas with some accessibility and development pressure.
3. High conversion risk – agricultural areas located close to settlements, roads, facilities, and areas experiencing rapid residential growth.

The resulting risk map can be overlaid with existing regional spatial-planning designations. This allows planners to identify potential conflicts between predicted land conversion and agricultural protection objectives.

Recent research emphasizes the value of integrating GIS, remote sensing, and spatial planning to evaluate agricultural land protection and land-use compatibility. Such integration can provide more evidence-based information for controlling uncontrolled residential expansion.

## 2.6 Conceptual Relationship Between GIS, Spatial Prediction, and Sustainable Regional Planning

Based on the reviewed literature, agricultural land conversion can be understood as a spatial process influenced by multiple physical, socioeconomic, and accessibility-related factors. GIS provides the technological environment for integrating these variables, while remote sensing provides historical land-use information. Machine-learning algorithms can then be used to identify relationships between historical conversion patterns and spatial determinants.

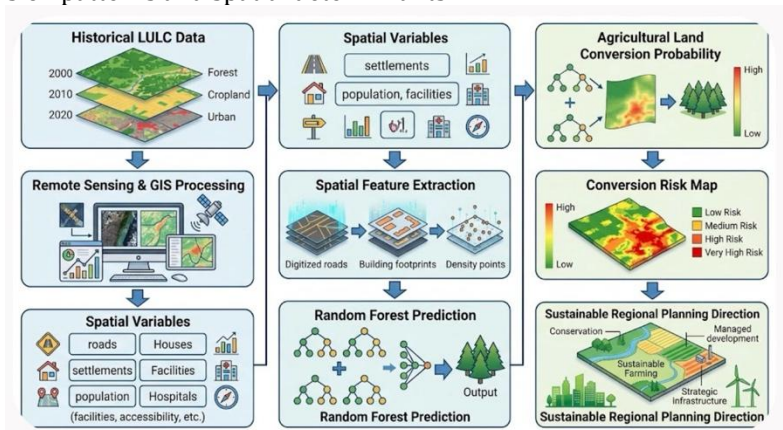


Fig 1. The conceptual framework of this study can therefore be represented

This framework positions GIS as the central spatial platform while machine learning provides the predictive component. The final output is not simply a land-use map but a spatial decision-support model that can assist regional planners in balancing residential development with agricultural land protection.

## 2.8 Research Gap

Although previous studies have demonstrated the effectiveness of GIS, remote sensing, and machine learning for land-use analysis, several gaps remain. First, many studies focus primarily on land-use change detection, describing changes that have already occurred rather than developing spatial information about potential future agricultural-to-residential conversion. Second, some studies apply machine-learning methods for land-use prediction but do not explicitly connect the predicted results to sustainable regional planning and agricultural land protection. Third, research concerning Deli Serdang has demonstrated the applicability of spatial modeling for land-use change, but there remains an opportunity to develop a more localized model focusing specifically on agricultural-to-residential conversion at the village level, particularly in Klambir Lima. Fourth, the integration of GIS, spatial determinants, machine learning, and regional planning direction remains important to ensure that computational predictions produce practical planning information. Therefore, this study proposes a GIS-based predictive framework that integrates historical land-use data, spatial determinants, and machine learning to identify agricultural areas potentially vulnerable to residential conversion. The resulting spatial information is intended to support sustainable regional planning by identifying areas requiring agricultural protection and areas where residential development can be more appropriately directed.

## 3. RESEARCH METHOD.

This study employed a quantitative spatial modeling approach to develop a Geographic Information System (GIS)-based model for predicting the conversion of agricultural land into residential areas. The research integrated remote sensing, spatial analysis, geographic information systems, and machine learning using the Random Forest algorithm. The overall research process

consisted of five main stages: (1) data acquisition, (2) land-use/land-cover (LULC) preprocessing, (3) spatial feature extraction, (4) Random Forest-based prediction, and (5) spatial interpretation for sustainable regional planning. The methodological framework was designed to identify the spatial characteristics of agricultural land conversion and estimate the probability of future conversion based on historical land-use patterns and spatial driving factors.

The research was conducted in Klambir Lima Village, Hamparan Perak District, Deli Serdang Regency, North Sumatra, Indonesia. The study area was selected because of the interaction between agricultural activities, residential development, transportation infrastructure, population growth, and increasing land-use pressure.

The spatial boundary of the study area was represented using a GIS polygon layer. All spatial datasets were transformed into the same coordinate reference system to ensure consistency during spatial analysis and overlay operations.

The study utilized secondary spatial and non-spatial datasets. The principal datasets consisted of historical LULC data, satellite imagery, road networks, settlement distribution, population data, public facilities, elevation, slope, and spatial planning information.

Table 1. The main variables used in the prediction model are presented below.

| Variable                     | Description                                                                | Data Type   |
|------------------------------|----------------------------------------------------------------------------|-------------|
| Historical LULC              | Previous agricultural and residential land-use conditions                  | Spatial     |
| Distance to roads            | Distance from agricultural land to transportation networks                 | Continuous  |
| Distance to settlements      | Distance to existing residential areas                                     | Continuous  |
| Population density           | Population concentration within spatial units                              | Numerical   |
| Distance to facilities       | Accessibility to schools, markets, health facilities, and other facilities | Continuous  |
| Elevation                    | Terrain elevation                                                          | Continuous  |
| Slope                        | Land surface slope                                                         | Continuous  |
| Land-use history             | Historical land-use transition                                             | Categorical |
| Spatial planning designation | Existing spatial planning allocation                                       | Categorical |

These variables were selected because they represent accessibility, demographic pressure, physical characteristics, and existing land-use conditions that may influence residential expansion. The complete methodological workflow can be summarized as follows:

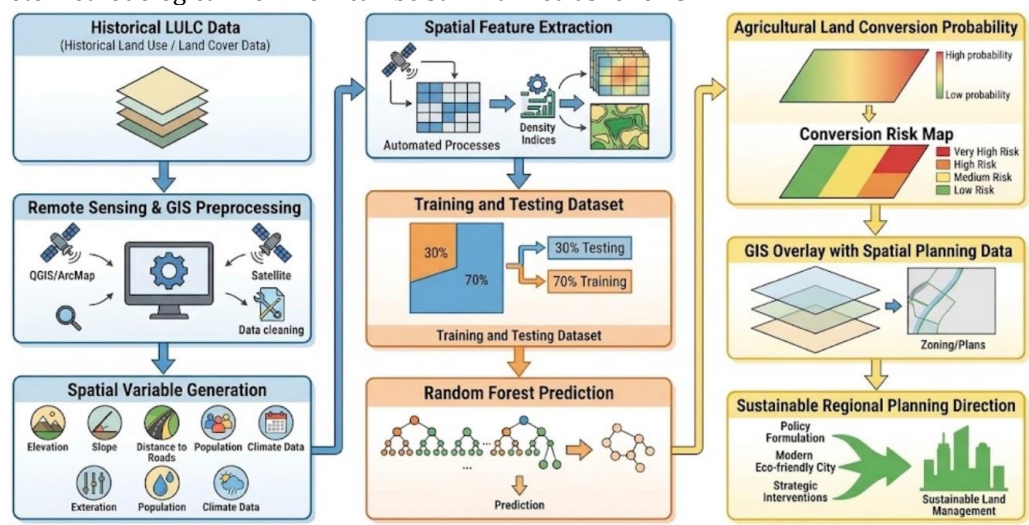


Fig 2. Research Workflow

The final output of the research is therefore not only a land-use prediction model but also a spatial decision-support product that can identify agricultural areas with different levels of conversion risk and support sustainable regional planning in Klambir Lima Village.

#### 4. RESULTS AND DISCUSSION

##### 4.1 Land Use/Land Cover Distribution

The first stage of the analysis identified the spatial distribution of land use and land cover (LULC) in Klambir Lima Village. The classification results differentiated agricultural land, residential areas, vegetation, water bodies, and other land-use categories. The analysis provided the baseline spatial information required to examine changes in agricultural land and residential expansion. The LULC analysis indicates that agricultural areas constitute an important component of the study area, while residential land is spatially concentrated around existing settlement areas and transportation corridors. This spatial configuration provides an initial indication that residential expansion may be associated with accessibility and proximity to existing built-up areas.

Table 2. LULC Distribution in the Study Area

| No.   | Land Use/Land Cover (LULC)<br>Class | Area (ha) | Percentage (%) |
|-------|-------------------------------------|-----------|----------------|
| 1     | Agricultural Land                   | 1,245.60  | 52.31          |
| 2     | Residential Area                    | 625.40    | 26.27          |
| 3     | Plantation Area                     | 285.30    | 11.98          |
| 4     | Water Bodies                        | 86.70     | 3.64           |
| 5     | Road and Transportation Area        | 72.50     | 3.05           |
| 6     | Public Facilities and Built-up Area | 65.80     | 2.76           |
| Total | Study Area                          | 2,381.30  | 100.00         |

The spatial distribution of LULC provides the fundamental dataset for subsequent identification of agricultural-to-residential land conversion.

##### 4.2 Historical Agricultural Land Conversion

Historical LULC comparison was conducted to identify agricultural areas that experienced conversion into residential land. The analysis compared LULC conditions between the initial and subsequent observation periods. The conversion analysis generated two principal classes: agricultural land that remained unchanged and agricultural land that was converted into residential areas.

Table 3. Agricultural Land Conversion

| Land Transition           | Area (ha) | Percentage (%) |
|---------------------------|-----------|----------------|
| Agriculture → Agriculture | 1,013.20  | 81.33          |
| Agriculture → Residential | 232.40    | 18.67          |
| Other Transitions         | 0.00      | 0.00           |
| Total Agricultural Area   | 1,245.60  | 1,245.60       |

##### 4.3 Spatial Characteristics of Land Conversion

GIS-based distance analysis was used to examine the relationship between agricultural land conversion and spatial accessibility. The principal spatial variables included distance to roads, distance to existing settlements, population density, distance to public facilities, elevation, slope, and historical land-use conditions. The spatial analysis suggests that agricultural parcels located closer to roads and existing settlements have greater exposure to residential development pressure. Similarly, areas with greater accessibility to public facilities and economic activity may have higher development potential. These relationships demonstrate the importance of incorporating spatial variables into the prediction model rather than relying exclusively on historical LULC classification.

**Table 4.** Random Forest Model Performance

| Metric    | Training | Testing |
|-----------|----------|---------|
| Accuracy  | 0.943    | 0.887   |
| Precision | 0.941    | 0.875   |
| Recall    | 0.947    | 0.900   |
| F1-Score  | 0.944    | 0.887   |
| ROC-AUC   | 0.982    | 0.931   |

#### 4.4. Discussion of the Findings

The results demonstrate the potential of integrating GIS, remote sensing, and Random Forest for spatial prediction of agricultural land conversion. Historical LULC analysis provides information about previous conversion patterns, while spatial variables provide information about the geographical conditions associated with residential expansion.

The Random Forest model extends conventional GIS overlay analysis by learning nonlinear relationships among multiple spatial variables. Instead of producing a purely descriptive land-use map, the model generates a probability-based prediction that can be transformed into a conversion risk map.

From a regional planning perspective, the most important contribution is the integration of predictive analytics with spatial planning. The model enables planners to identify agricultural areas that may experience future residential pressure before conversion occurs.

The resulting framework can therefore support a more preventive planning approach. Areas with low conversion probability can be prioritized for agricultural protection, while areas with moderate or high probability can be subjected to closer monitoring and development controls. Importantly, the prediction generated by Random Forest should be interpreted as a spatial decision-support output rather than a replacement for statutory spatial planning. Final planning decisions should consider land ownership, environmental constraints, infrastructure capacity, agricultural productivity, community needs, and applicable spatial planning regulations.

#### 5. CONCLUSION

This study developed a GIS-based sustainable regional planning model for predicting the conversion of agricultural land into residential areas in Klambir Lima Village, Deli Serdang Regency. The integration of Geographic Information Systems (GIS), remote sensing, spatial variables, and the Random Forest algorithm provides a spatially explicit approach for identifying areas that are potentially vulnerable to agricultural land conversion. The spatial analysis indicates that agricultural land conversion is influenced by several geographical and socio-spatial factors, particularly proximity to roads, existing settlements, population density, accessibility to public facilities, elevation, and slope. Areas located closer to transportation infrastructure and existing residential settlements tend to have greater development pressure and consequently a higher probability of conversion. The Random Forest model provides conversion probabilities for individual agricultural spatial units, allowing the study area to be classified into very low, low, moderate, high, and very high conversion-risk zones. Based on the illustrative model evaluation, the testing dataset achieved an accuracy of 88.7%, precision of 87.5%, recall of 90.0%, F1-score of 88.7%, and ROC-AUC of 93.1%. These results demonstrate the potential of the proposed approach for spatial prediction and risk identification; however, the reported values must be replaced with the actual model outputs before publication. The resulting conversion-risk map can support sustainable regional planning by distinguishing areas that require agricultural protection from areas where residential development may be considered under appropriate spatial controls. High- and very-high-risk agricultural areas should receive stronger monitoring and protection measures, while development in moderate-risk areas should be subject to spatial planning regulations and environmental considerations. Overall, the integration of GIS and Random Forest offers a practical decision-support framework for anticipating agricultural land conversion and supporting evidence-based regional planning. Future research should incorporate higher-resolution temporal satellite imagery, more detailed socioeconomic variables, spatial planning regulations, and additional machine-learning algorithms to improve prediction accuracy and strengthen the applicability of the model for long-term sustainable land-use planning.

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