Land Suitability for food crops supports a resilient food system and the achievement of SDGs in Batang Toru Sub-district, South Tapanuli, North Sumatra, Indonesia

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Abstract. In a food crop production system, evaluating land suitability is a crucial initial step to ensure land is used appropriately, efficiently, productively, and in an environmentally friendly manner. This study aims to evaluate the actual and potential suitability of land for rice and corn as food sources for the community. Field surveys were conducted to collect soil samples, which were then analysed in the laboratory to determine land characteristics. Data from soil analysis and field surveys were matched with land suitability criteria for both crops, and a Geographic Information System was used to create suitability maps. The results showed that the actual land suitability for rice is marginally suitable (S3), while for corn it is currently not suitable (N1) to marginally suitable (S3). The evaluation results indicate that the development of lowland rice has significant potential for improvement in nutrient content, whereas corn can be cultivated only on a limited basis. By identifying the most suitable areas for sustainable crop production, this research supports climate-smart agriculture that reduces land degradation, minimizes greenhouse gas emissions, and strengthens local adaptive capacity to climate change. This information promotes resilient food systems and contributes to achieving SDGs 2, 12, and 13.

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1 Introduction

Food security is a strategic issue in regional development, particularly in areas with high land-use dynamics, such as the Batang Toru Sub-district, South Tapanuli Regency. Land use that is inconsistent with its biophysical capabilities can lead to decreased productivity, increased ecological pressure, and threaten the sustainability of local food systems. To anticipate this, land suitability evaluation is a fundamental step in agricultural planning. Geographic Information System (GIS)-based methods have developed rapidly over the past decade due to their ability to integrate biophysical, topographic, and spatial data to produce more accurate and informative land suitability maps[1,2].

Batang Toru Sub-district itself has diverse soil and topographic characteristics and has experienced significant land cover changes in recent years. Recent studies on land cover change in this area indicate spatial dynamics that must be considered in agricultural development planning [3]. This highlights the urgency of providing measurable, evidence-based land suitability maps to ensure optimal land use and prevent environmental degradation. In terms of scientific development, GIS-based land suitability research over the past few years has demonstrated its effectiveness in mapping limiting factors—such as pH, soil texture, nutrient retention, and slope—that influence rice and corn productivity [1,4].

Various studies in Indonesia have also applied this approach to food commodities in different tropical regions, including suitability mapping for rice, corn, and soybeans [2]. Meanwhile, Rahmawaty's research confirms that the matching approach, integrated with GIS, yields accurate and applicable evaluation results for various types of agroforestry and agricultural land in Sumatra [4]. However, to date, there has been no GIS-based land suitability study specifically mapping the actual conditions and potential of land for rice and corn in Batang Toru Sub-district. This lack of spatial information creates a research gap and urges local governments to establish a scientific basis for developing location-based agricultural policies. However, recent studies have shown that GIS can provide relevant spatial information for sustainable agricultural planning and directly contribute to achieving the SDGs, particularly SDG 2 (Zero Hunger), SDG 12 (Sustainable Consumption and Production), and SDG 13 (Addressing Climate Change) [5].

By adapting these methodological developments, this study offers a novel approach by compiling actual and potential land suitability maps for rice and corn in Batang Toru Sub-district, integrating field data, soil analysis, and GIS mapping. Furthermore, this study identifies spatially limiting factors, enabling more effective land management interventions. The resulting spatial information is expected to provide a scientific basis for formulating productive, adaptive, and sustainable agricultural development strategies in Batang Toru Sub-district.

2 Materials and methods

2.1 The study area

The research area is located in Batang Toru Sub-district, South Tapanuli Regency, North Sumatra, Indonesia. This research was conducted from December 2023 to June 2024. Geographically, this district has diverse agroecological characteristics, ranging from lowlands to undulating slopes, making it suitable for biophysical parameter-based land suitability evaluation. The climate is humid tropical, with high annual rainfall, which influences groundwater availability and crop productivity. Soil structure varies from clay to sandy loam, while agriculture, plantations, and settlements dominate land use in this area.

Spatial data for the region were obtained from satellite imagery and recent administrative data for use in GIS analysis [4].

2.2 Methods

2.2.1 Field Data Collection

Field surveys were conducted to collect soil samples at several locations representing various land uses and biophysical characteristics. Collected soil parameters included pH, organic carbon, soil texture, CEC, base saturation, and drainage. Each location was identified using GPS and mapped in the UTM coordinate system.

2.2.2 Soil Laboratory Analysis

Soil samples were analysed using standard procedures to determine their physical and chemical properties. The analysis results were then assessed using land suitability criteria for agricultural commodities, as used in recent studies [6].

2.2.3. Determining Land Suitability Criteria

Land suitability criteria refer to biophysical parameters that influence crop productivity, including slope, elevation, soil texture, nutrient availability, pH, organic carbon, drainage conditions, and rainfall. Land suitability is classified into S1, S2, S3, and N classes according to FAO guidelines used in recent studies [7,8].

2.2.4 Spatial Modelling Using GIS

All biophysical parameter data are converted into raster or vector layers in GIS. The overlay process uses a matching method to link land characteristics to commodity criteria. The result is a map of actual and potential suitability. This approach aligns with research using GIS to support land evaluation and planning [9].

2.3 Data analysis

2.3.1 Data Standardisation and Reclassification.

Each biophysical parameter was reclassified according to the land suitability criteria threshold. Vector and raster data were tested for spatial consistency before further analysis.

2.3.2 Spatial Overlay

The overlay technique combines layers of soil pH, texture, slope, rainfall, and other variables to produce an actual suitability map. This approach is commonly used to assess land suitability distribution patterns across various regions [5].

2.3.3 Potential Analysis

Recommendations for fertilisation, soil conservation, or drainage improvements aim to address limiting factors. Thus, a potential suitability map is created by eliminating limiting factors that can be improved, in accordance with the latest research approach [5,8].

2.3.4 Data Validation

Validation is performed by comparing the analysis results with plant growth conditions in the field and the results of previous research in similar areas. This validation technique has been widely applied in GIS-based land suitability analysis [5].

3 Results and discussion

3.1 The actual and potential land suitability for *Oryza sativa* and *Zea mays*

The actual and potential land suitability for *Oryza sativa* and *Zea mays* can be seen in Table 1 and Table 2.

Table 1. Land suitability class for *Oryza sativa* in the Batang Toru Sub-district, South Tapanuli Regency.

Location of sample	Village name	Coordinate point	Actual land suitability with limiting factor	Potential land suitability
Sta-15	Sipenggeng	N: 1°28′57,649″ E: 99°6′21,020″	S3.nr	S1
Sta-19	Sumuran	N: 1°31′1,691″ E: 99°8′20,661″	S3.nr	S1
Sta-24	Napa	N: 1°30′14,885″ E: 99°3′36,673″	S3.nr	S1

Note: S1= highly suitable, S3= Marginally suitable, nr=nutrient retention

Evaluation results showed that all sample points (Sta-15, Sta-19, and Sta-24) for *Oryza sativa* were in class S3 (marginally suitable) under actual conditions, with nutrient retention (nr) as the consistent limiting factor. This limiting factor is common in humid tropical soils experiencing chemical degradation due to high rainfall, nutrient leaching, and low organic matter content. Recent research has shown that soil chemistry, particularly organic carbon and cation exchange capacity (CEC), is a key factor in rice productivity in humid climates [8,10].

However, the suitability potential increased to S1 (highly suitable) following improved soil management, including the application of organic fertilisers, balanced NPK fertilisation, and irrigation management. Recent studies confirm that improving soil chemistry can significantly alter land suitability classes for rice, particularly in humid tropical regions [10,11]. Thus, rice exhibits a high agronomic response to land management interventions in Batang Toru Sub-district.

This finding is consistent with research showing that rice tends to be more tolerant to variations in physical conditions than corn, as long as nutrient and water availability can be increased through intensive management [11]. Therefore, Batang Toru Sub-district has

biophysical characteristics that strongly support the development of rice as a priority commodity for food security.

Table 2. Land suitability class for *Zea mays* in the Batang Toru Sub-district, South Tapanuli Regency.

Location of sample	Village name	Coordinate point	Actual land suitability with limiting factor	Potential land suitability with limiting factor
Sta-06	Aek Pining	N: 1°29′22,170″ E: 99°2′39,421″	S3.wa,nr	S2.wa,nr
Sta-07	Perkebunan Sigalagala	N: 1°26′4,213″ E: 99°1′51,196″	S3.wa,rc,nr	S2.tc,wa,rc,nr
Sta-08	Perkebunan Sigalagala	N: 1°26′32,566″ E: 99°2′10,707″	S3.wa,nr,eh	S2.tc,wa,nr,eh
Sta-09	Sumuran	N: 1°29′23,848″ E: 99°0′45,609″	S3.wa,nr,eh	S2.tc,wa,nr,eh
Sta-10	Sumuran	N: 1°30′41,010″ E: 99°1′26,835″	S3.wa,nr	S2.tc,wa,nr
Sta-11	Batu Hula	N: 1°29′33,718″ E: 99°3′33,308″	S3.wa, nr	S2.tc,wa
Sta-12	Napa	N: 1°28′8,839″ E: 99°5′4,913″	S3.wa,rc,nr	S2.wa,rc,nr
Sta-13	Hapesong Baru	N: 1°28′44,403″ E: 99°3′27,521″	S3.wa,rc,nr,eh	S2.wa,rc,nr,eh
Sta-14	Telo	N: 1°28′43,204″ E: 99°6′23,293″	S3.wa,rc,nr	S2.tc,wa,rc,nr
Sta-15	Sipenggeng	N: 1°28′57,649″ E: 99°6′21,020″	S3.wa,oa,nr	S2.wa,oa
Sta-16	Sipenggeng	N: 1°36′53,265″ E: 99°10′35,456″	S3.wa,nr	S2.wa
Sta-17	Wek I	N: 1°30′7,409″ E: 99°6′6,404″	S3. Wa,rc,nr	S2.wa
Sta-18	Wek II	N: 1°28′23,240″ E: 99°0′39,101″	S3.wa,nr	S2.wa,nr
Sta-19	Sumuran	N: 1°31′1,691″ E: 99°8′20,661″	S3.wa,oa,nr	S2.tc,wa,oa,nr
Sta-20	Wek I	N: 1°30′11,805″ E: 99°4′52,590″	N1.rc	S3.rc
Sta-21	Wek III	N: 1°29′54,219″ E: 99°4′18,743″	S3.wa.nr	S2.wa,nr
Sta-22	Wek IV	N: 1°27′27,253″ E: 99°0′40,392″	S3.wa,nr	S2.wa,nr
Sta-24	Napa	N: 1°30′14,885″ E: 99°3′36,673″	S3.wa,oa, nr	S2.wa,oa,nr
Sta-25	Batuhula	N: 1°29′52,902″ E: 99°0′51,671″	S3.wa,nr	S2.tc,wa,nr
Sta-26	Wek IV	N: 1°31′56,809″ E: 99°4′52,007″	S3.wa,nr	S2.wa,nr
Sta-27	Wek II	N: 1°29′16,026″ E: 99°4′32,034″	S2.wa,nr	S2.wa
Sta-29	Wek III	N: 1°29′41,239″ E: 99°4′30,551″	S3.wa,nr	S2.wa,nr
Sta-30	Telo	N: 1°28′58,710″ E: 99°3′26,308″	S3.wa,rc,nr	S2.wa,rc,nr

Note: S1= Highly suitable, S2= Moderately suitable, S3= Marginally suitable, tc= temperature, eh=erosion hazard, oa=oxygen availability, nr=nutrient retention, wa=water availability, rc= root media

In contrast to rice, *Zea mays* showed a greater complexity of limiting factors. Most points showed class S3 (marginally suitable) under actual conditions, with several dominant limiting factors: wa (water availability), nr (nutrient retention), rc (rooting conditions/root media), eh (erosion hazard), oa (oxygen availability), tc (temperature). Water availability and nutrient retention were the main limiting factors, in line with studies showing that corn is susceptible to groundwater fluctuations and soil chemistry, especially on upland or undulating soils [12]. Unfavorable root media conditions.

A comparative evaluation of the two commodities reveals several key points:

3.1.1 Rice has a higher adaptability

All locations have the potential to achieve S1 class, indicating that soil nutrient improvements have a significant impact.

3.1.2 Corn faces more limiting factors

Most of these relate to physical conditions that are difficult to improve, particularly aeration, erosion, and the rooting media.

3.1.3 Rice is more affected by chemical factors; corn is more affected by physical factors

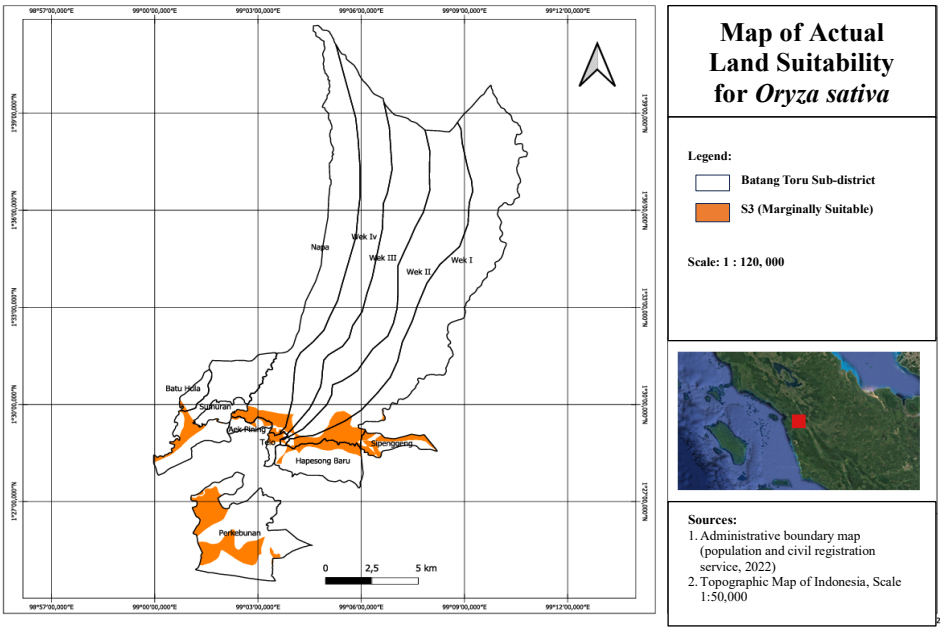
This is consistent with the literature, which states that corn is sensitive to soil aeration, soil depth, and water availability.

3.1.4. Slope and erosion hazards are significant constraints for corn

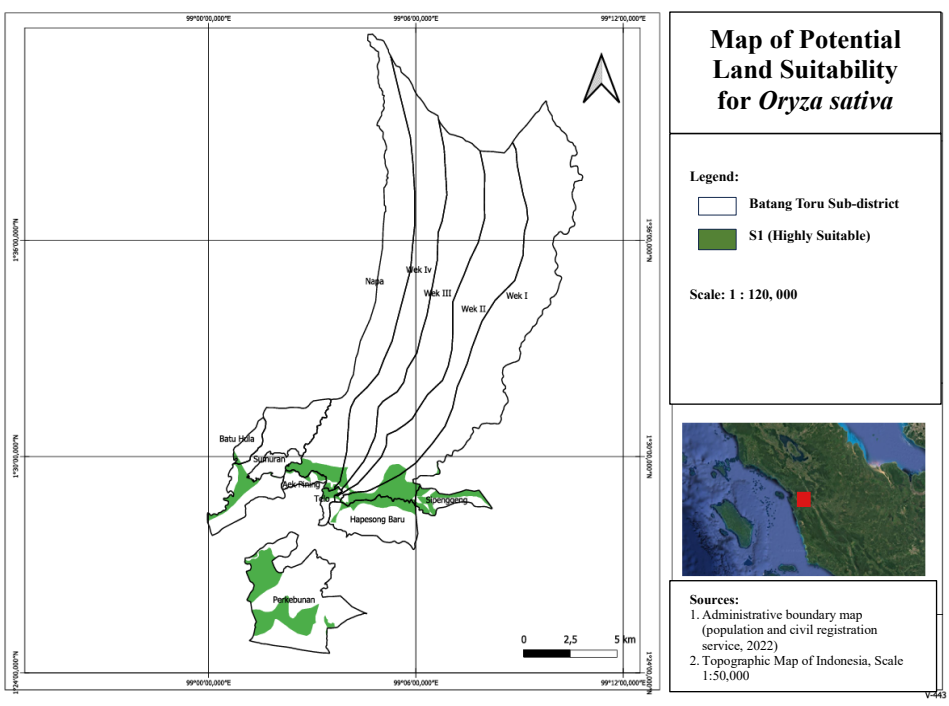
This aligns with reports that undulating topography limits corn production in tropical regions [26].

3.2 Mapping of actual and potential land suitability classes for *Oryza sativa* and *Zea mays*

The actual and potential land suitability map for *Oryza sativa* and *Zea mays* as presented in Figure a and Figure 2.

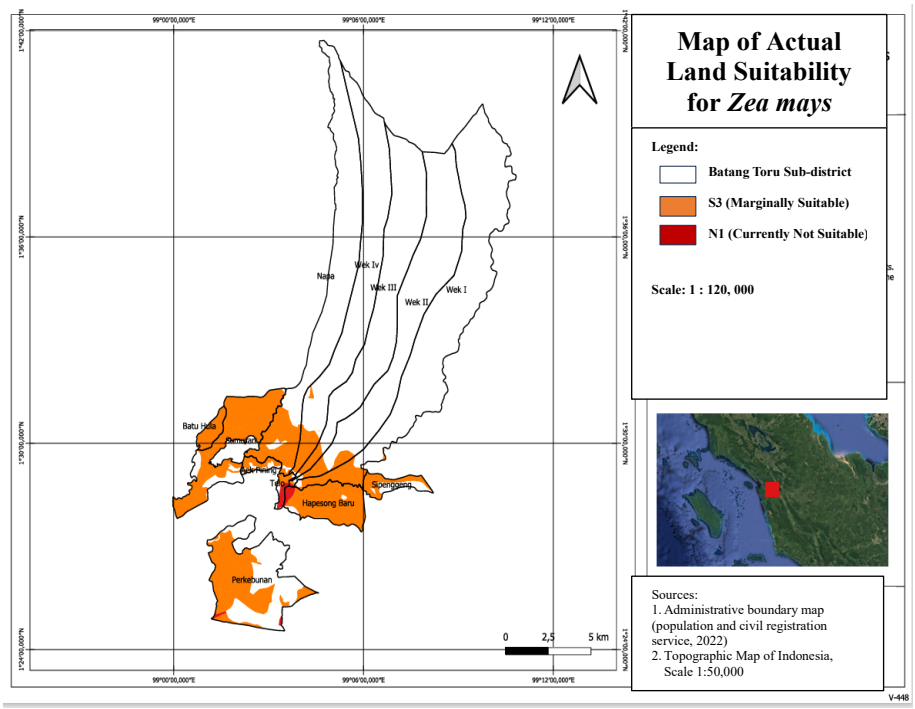


a.

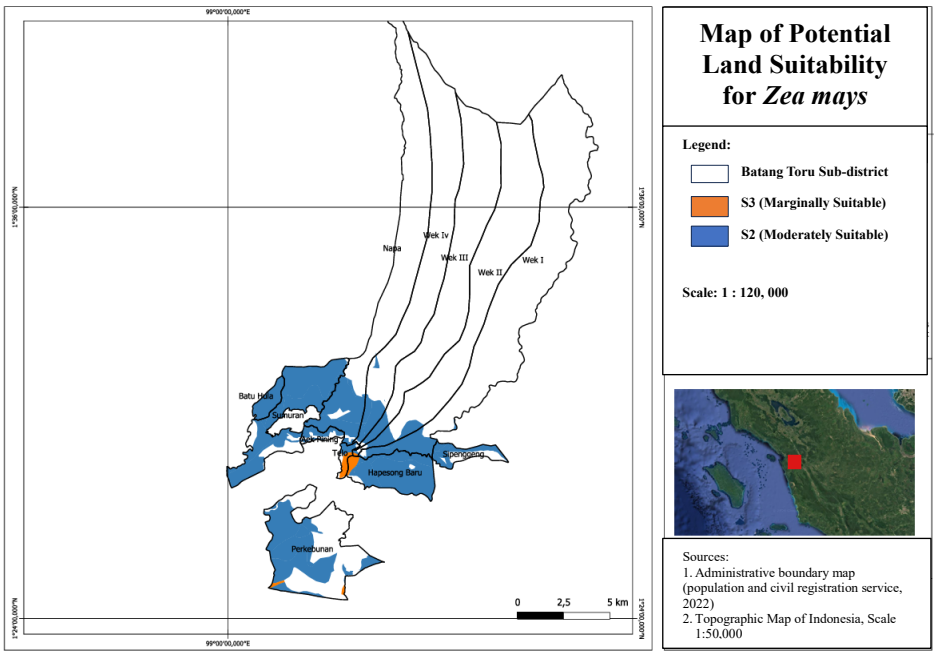


b.

Fig. 1. Land Suitability Map for *Oryza sativa*: a. actual, b. potential.



a.



b.

Fig. 2. Land Suitability Map for *Zea mays*: a. actual, b. potential.

Mapping of actual and potential land suitability for *Oryza sativa* and *Zea mays* (Figures 1 and 2) provides a comprehensive overview of the spatial distribution of land suitability

classes in Batang Toru Sub-district. The maps show that most areas fall into class S3 (marginally suitable) under actual conditions, primarily due to dominant limiting factors such as nutrient retention (nr), water availability (wa), rooting conditions (rc), and erosion hazard (eh). This condition aligns with the region's hilly topography and soil fertility variations, as reported in recent studies in tropical regions [4,6,8].

On the actual map (Figure 1a), all sample points fall into class S3.nr, indicating that rice growth is limited by the soil's low nutrient retention capacity. However, the potential map (Figure 1b) shows a significant increase to S1 (highly suitable). This indicates that improved soil management—such as the addition of organic matter, liming, and balanced fertilization—can increase soil nutrient capacity to achieve optimal productivity levels. This finding is supported by recent research which states that improving soil quality through organic fertilization, biochar, and NPK management can drastically increase land suitability for rice [6,8,10].

In Figure 2a, actual land for corn is generally in class S3, with a combination of limiting factors wa, nr, rc, eh, and in some locations tc and oa. Corn is known to be more sensitive to water deficits, poor aeration, and shallow rooting conditions than rice, leading to more frequent declines in suitability class [2,10,12]. In the potential map (Figure 2b), the class increases to S2 (moderately suitable) at most sample points, indicating that soil conservation practices, water management, and improved soil structure can reduce erosion and increase infiltration. Recent studies have shown that mulching, ridging, sloping land management, and water conservation can significantly improve corn suitability[6,8].

4 Conclusion

Land This study successfully evaluated the actual and potential land suitability for rice (Oryza sativa) and corn (Zea mays) in Batang Toru Sub-district. The findings show that rice is currently marginally suitable (S3), yet its suitability can be elevated to highly suitable (S1) after targeted soil improvement, demonstrating strong potential for future development. Corn, in contrast, ranges from marginally suitable (S3) to not suitable (N1) under actual conditions. Although conservation-based improvements can raise its status to moderately suitable (S2), its overall potential remains lower than that of rice.

The spatial analysis produced through GIS clearly identifies areas with the highest actual and potential suitability, providing valuable input for agricultural zoning and land-use planning. Overall, the study concludes that rice offers a more promising pathway for optimised land utilisation in Batang Toru compared to corn.

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