Research Article

Land Suitability Evaluation for Sugarcane Cultivation Based on Agroecological Zoning System in East Java, Indonesia

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ABSTRACT

Agroecological zoning system is essential to accelerate the production of plantation crops such as sugarcane. This is a tool that helps to identify the most suitable areas for growing specific crops based on the physical and biological characteristics of the land. The ideal conditions for sugarcane growth can be achieved from optimal planting land conditions and adequate climate and fertilization. Land use planning is key to the sustainability of plantation crops in Indonesia. In this study, we used land suitability evaluation for sugarcane cultivation using an agroecological zoning system. Multisource of suitability criteria was used from the thematic map that included the land use/land cover map, slope map, rainfall map, and soil type map as physical and biological characteristics of the land. On the land suitability map for sugarcane cultivation, the results are in the form of land area that was adjusted to the Food and Agriculture Organization indicators regarding land suitability class. We found that 23.20% of the area (11,149.49 km^2) was very suitable for sugarcane cultivation, 30.18% (14,499.67 km^2) was moderately suitable, 36.05% (17,321.71 km^2) was marginally suitable, and 10.55% (5,068.25 km^2) was not suitable for sugarcane plantation. In this study, it was found that around 1,114,949 ha of land in East Java had the potential to become sugarcane plantations based on the agroecological zoning system. This research recommended that the integrated approach of Geographic Information Systems (GIS) with satellite remote sensing vegetation datasets utilization might help to develop the site-specific management of sugarcane plantations.

Keywords: agroecological zone, land suitability, mapping, remote sensing, sugarcane.

Introduction

Sugarcane is one of the important industrial crops in Indonesia (Sulaiman et al., 2019). As an annual crop plantation commodity, sugarcane has been widely cultivated for a long time. The total area of sugarcane plantations in Indonesia in 2021 was approximately 2.42 million tons. In 2020, plantation crops were estimated to contribute around 560.2 thousand trillion rupiahs to the Indonesian GDP (Statista, 2022). According to BPS-Statistics Indonesia (2022), the provinces with the largest sugarcane plantations in Indonesia were North Sumatra, South Sumatra, Lampung, West Java, Central Java, Yogyakarta, East Java, South Sulawesi, and Gorontalo. From 1984 to 1985, Indonesia was one of the self-sufficient countries in sugar. However, due to population growth and the currency crisis, this success was not achieved. In Indonesia, the demand for raw sugar for food and beverages increases every year. In 2017, Indonesia consumed 6.32 million tons of sugar, with demand increasing by 6% in 2018 (Reuters, 2018). This great demand for sugar has created a huge gap between sugar production and demand. As a result, Indonesia became the world's largest sugar importer with 4.45 million tons from 2017 to 2018 (Ministry of Agriculture of Indonesia, 2017).

The planting area and varieties are significant factors in controlling cane production and productivity (Sulaiman et al., 2019). There are several strategies that can be used to increase sugarcane production without expanding the cultivation land (Machado et al., 2017). One of them is to determine the suitability of sugarcane plantations using an agroecological approach to emphasize the importance of maintaining soil health, which can help to improve the overall health and productivity of the crop. As a tropical plant, sugarcane needs a suitable climate for optimal growth. The main climatic factors that control sugarcane growth are rainfall, light, and temperature. Good sugarcane cultivation is highly dependent on crop quality, growing location, and farm management practices. Therefore, when cultivating sugarcane, it is necessary first to know the growing requirements for sugarcane and then look for areas with highly suitable cultivation areas (Fageria et al., 2011).

There is a lack of land suitability mapping based on the agroecological zoning (AEZ) system in Indonesia. The AEZ methodology employs a land resources inventory to evaluate all viable agricultural land-use options based on defined management conditions and input levels. It also quantifies the expected crop production for the relevant agroecological context. The land resources are characterized by factors such as climate, soil, and landform (Fischer et al., 2000). This can be useful in evaluating the suitability of land for growing sugarcane because different types of land have different potentials for supporting the growth of this crop. The significance of AEZ is especially relevant for small holder sugarcane farmers, who form a substantial part of Indonesia sugarcane industry. Small holders often operate on limited resources and may lack access to advanced agricultural inputs or techniques. For them, understanding land suitability based on AEZ can enhance productivity, helping them maximize yields within the ecological constraints of their land. This approach not only promotes efficient land use but also helps small holders minimize input costs by aligning farming practices with the land's natural capabilities. By adopting AEZ, small holders can improve their crop resilience, conserve soil health, and contribute more effectively to Indonesia sugarcane production, helping to bridge the supply-demand gap without the need for extensive land expansion (Nabati et al., 2020).

Regarding this, Indonesia land suitability surveys and mappings still follow conventional approaches which are time-consuming and costly (Sulaiman et al., 2019). More objectives and advanced decision-making processes are needed for the development of land suitability analysis (Al-Taani et al., 2017). A variety of multicriteria decision-making (MCDM) methods have been developed to help decision-makers solve their spatial problems with multiple criteria (Li & Chen, 2020; Ligmann-Zielinska & Jankowski, 2014; Worqlul et al., 2019). The analytic hierarchy process (AHP), as proposed by Saaty (1980), is a later development that has recently become increasingly popular (Flynn, 2019; Purnamasari et al., 2019; Ramamurthy et al., 2020). Remote sensing and geographic information systems (GIS) are widely used as effective and efficient methods for observing, measuring, and analyzing land suitability based on agroecological zoning (Prabhjyot-Kaur et al., 2024; Marwoto & Candra, 2007). These methods can be used to effectively and efficiently identify the sowing site for sugarcane production and improve decision-making ability approach regarding appropriate land use policies (Feizizadeh & Blaschke, 2014). The purpose of this study was to develop an initial approach for land suitability mapping for sugarcane cultivation in Indonesia based on the AEZ system to support the small holder sugarcane farmers by integrating MCDM methods, such as AHP, with remote sensing and GIS.

Materials and Methods

Study Area

This study was conducted in East Java Province, Indonesia, located between 111°0'–114°4' East longitude and 7°12'–8°48' South latitude. East Java is the largest province on Java Island, covering an area of 47,799.75 km² with a population of approximately 39,107,095 (Figure 1). The province is a major agricultural region, making it an ideal location for assessing land suitability for sugarcane cultivation.

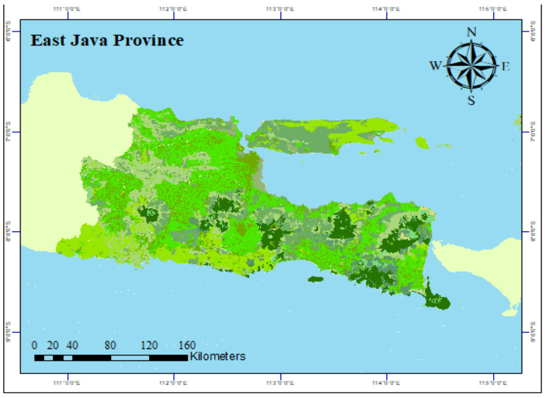

Fig. 1. The study area of East Java Province.

Data Collection and Processing

To ensure the accuracy of subject and geometric mapping and enhance the validity of the study results, geographical and climatic data for East Java were obtained from the Indonesian Geospatial Agency (Table 1). The data consisted of maps depicting geographic, geological, and climatic formations in vector format, with a scale of 1:50,000. These data were processed using ArcGIS 10.5 to derive the criteria for selecting suitable sites for sugarcane cultivation.

Table 1. List of data used in this study and their original sources.

Data	Scale	Source
Boundary map	1:50.000	Indonesian Geospatial Agency
Land use map 2013	1:50.000	Indonesian Geospatial Agency
Topography (slope) map	1:50.000	Indonesian Geospatial Agency
Rainfall map	1:50.000	Indonesian Geospatial Agency
Soil type map	1:50.000	Indonesian Geospatial Agency

Land Suitability Assessment Framework

The analysis of land suitability mapping for sugarcane cultivation employed a multistep process (Figure 2). The assessment, based on the agroecological zoning system, is a critical tool for ensuring effective and efficient use of natural resources. The objective of this assessment was to identify suitable areas based on environmental variables and classify them according to specific suitability rankings. Environmental variables used in this study included land cover, slope, rainfall, soil type, and vegetation. The criteria were selected based on their significant impact on sugarcane cultivation and formed the foundation of the evaluation process.

Table 2. Sugarcane agroecological zoning.

Class	Description
S1 (highly suitable)	Land having no or insignificant limitations to the given type of use. No specific management required; prefer use for cultivation
S2 (moderately suitable)	Land having minor limitations to the given type of use
S3 (marginally suitable)	Land having moderate limitations to the given type of use
N (not suitable)	Land having severe limitations that preclude the given type of use, but can be improved by specific management or have so severe limitations that are very difficult to be overcome

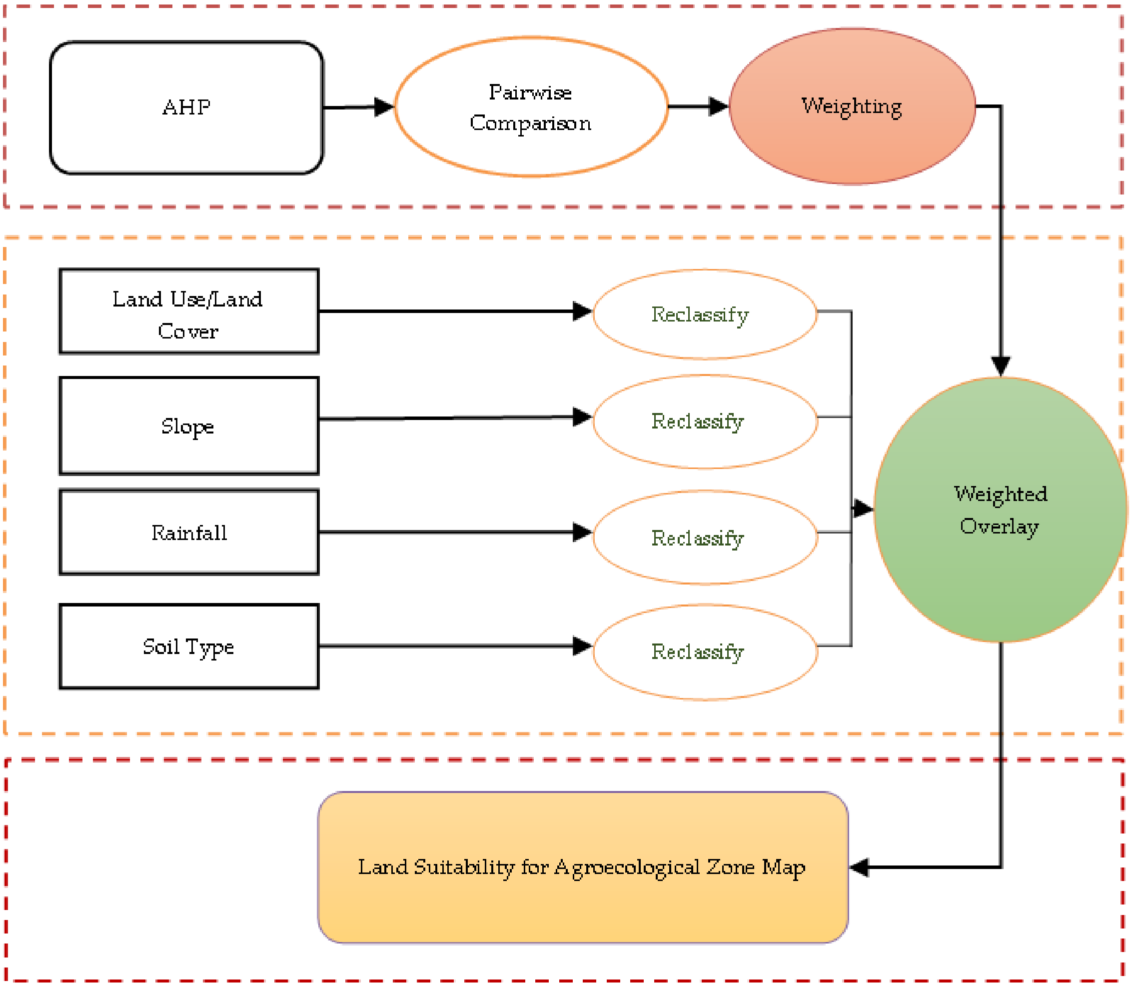

Fig. 2. An illustration of the proposed research framework.

Land suitability evaluation determines the potential of land for specific uses and classifies it into four general categories (FAO, 2007; Hegazy & Kaloop, 2015; Nguyen et al., 2020; Sys et al., 1991). The examination result of these criteria classifies into four general classes (Table 2).

Geospatial and Analytical Methods

The evaluation of agricultural suitability was conducted using GIS combined with AHP, an MCDM (Malczewski, 1999). GIS was employed to integrate spatial data, while AHP was used to prioritize the criteria based on their relative importance for sugarcane cultivation (Table 3). This integrated approach enabled the identification of the most suitable locations for sugarcane cultivation based on AEZ approach within East Java.

Table 3. The classification for sugarcane suitability assessment based on geospatial database (Malczewski, 1999).

Criteria	Suitability class	Sub-criteria
Land use and land cover (LULC)	S1	Class I
	S2	Class II
	S3	Class III
	N	Class IV
Slope (%)	S1	0–15
	S2	15–25
	S3	25–60
	N	>60
Rainfall (mm/year)	S1	1,000–1,500
	S2	1,500–2,000
	S3	2,000–2,500
	S4	2,500–3,000
Soil type	S1	*Typic Hapludults*
	S2	*Typic Epiaquands*
	S3	*Typic Endoaquepts*
	N	*Typic Eutrudepts*

Results and Discussion

East Java is the largest sugarcane-producing region in Indonesia, contributing an estimated 45.0% of the national sugarcane area and 47.24% of sugarcane production as of 2020 (BPS-Statistics Indonesia, 2022). Approximately 56.45% of the sugarcane area is cultivated by farmers, with the majority being small holders who owned less than 1 ha of land (BPS-Statistics Indonesia, 2022). While the region was a key contributor to sugar production, much of its agricultural land remained underutilized. This initial study identified 1,114,949 ha of potential sugarcane land, primarily concentrated in the southern region, where soil steepness was below 15%. The southern region's flat to moderately sloped terrain offered advantages for mechanized farming, reducing labor intensity and improving efficiency. Additionally, climatic conditions such as adequate rainfall and moderate temperatures further enhanced the suitability of this area for sugarcane cultivation.

Currently, sugarcane plantations in East Java occupied 203,566 ha, consisting of 184,211 ha of small holder plantations, 18,950 ha of state-owned plantations, and 656 ha of private plantations. These plantations were already located within areas deemed suitable for sugarcane cultivation based on agroecological zoning.

The suitability assessment criteria were used as layers of reclassified raster data, including land cover, land slope, soil type, and rainfall levels. All reclassified raster data were combined using a weighted overlay tool, with the weights derived from the AHP analysis. This method applied priority weighting criteria to produce a land suitability map for sugarcane cultivation.

Land suitability was classified into four categories (Table 2). Class S1 (very suitable) indicated the land did not have a significant or significant limiting factor for sustainable use. This land is a dry land with sufficient drainage. S2 class (suitable) included land that had limiting factors that can affect its productivity and required additional relatively light inputs, which could usually be handled by the farmers themselves. The limiting factors were large rainfall and high land slope. S3 class (according to marginal) was for the land that had heavily limiting factors that affected its productivity, required additional input, and high capital, so that there was a need for government or private intervention (irrigation). Meanwhile, Class N (not suitable) was for land that was not suitable because it had very heavily limiting factors and was difficult to overcome, such as soil erosion on steep slopes and high acidity in some areas.

The results of the AHP analysis indicated that land cover was the highest priority (44%), followed by rainfall (19%), land slope (19%), and soil type (14%) when determining suitable land for sugarcane seedlings. These weightings were used to create the land suitability map for sugarcane cultivation. The map classified the study area into four suitability categories based on FAO indicators. It was found that 23.20% (11,149.49 km²) of the study area was classified as very suitable for sugarcane cultivation, 30.18% (14,499.67 km²) as moderately suitable, 36.05% (17,321.71 km²) as marginally suitable, and 10.55% (5,068.25 km²) as unsuitable for sugarcane plantation (Figure 3; Table 4).

Since the land suitability for sugarcane seedlings was influenced by factors such as soil content, land use and cover, rainfall, and land slope (Jamil et al. 2018), in order to increase sugarcane production, it is essential to assess the level of land suitability for each land unit. In addition to identifying suitable areas for sugarcane cultivation, land suitability analysis can help farmers optimize land conditions to enhance production in targeted areas. Proper land management and utilization will ensure maximum yields for specific crops. A map of land units, used as a base map for sampling, was created by

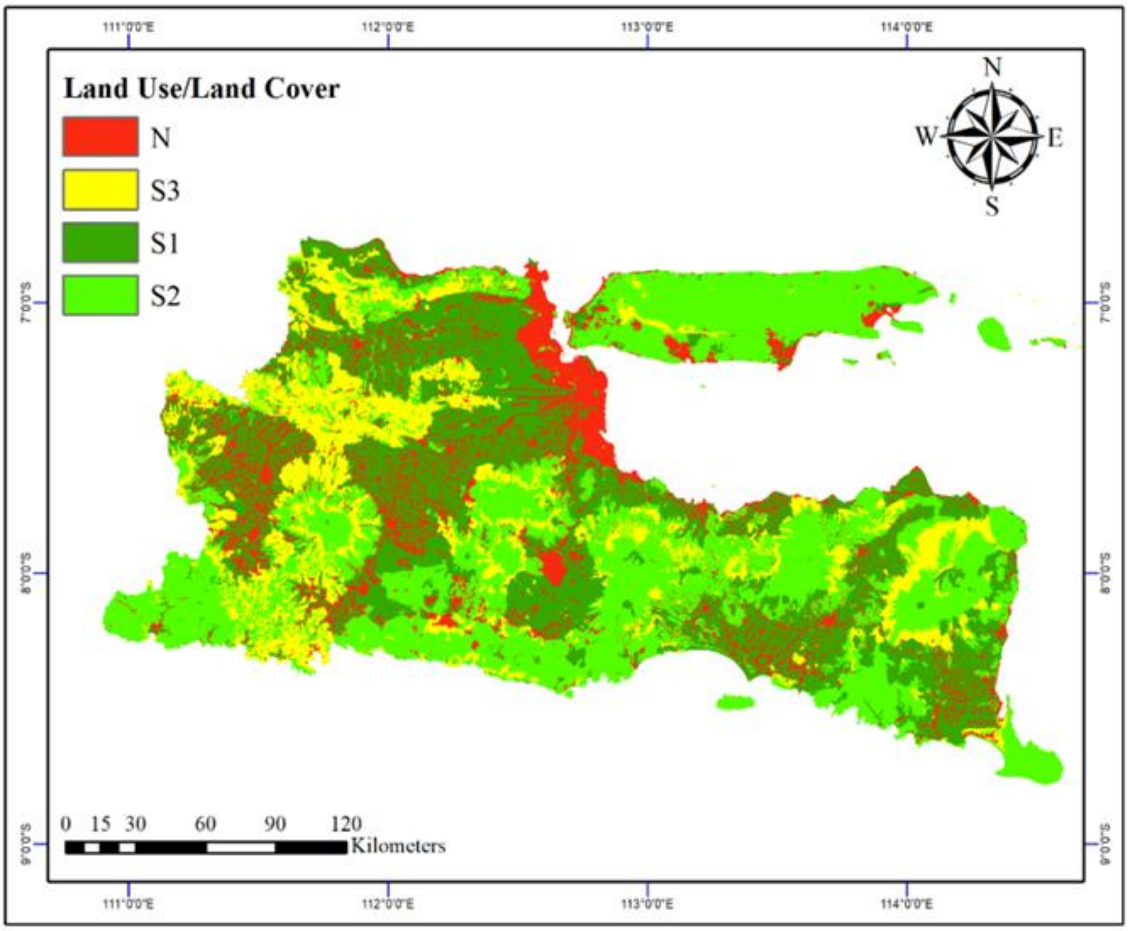

Fig. 3. Suitability land suitability map for sugarcane cultivation in East Java. S1 = very suitable, S2 = moderately suitable, S3 = marginally suitable, N = unsuitable.

overlaying soil maps, slope maps, rainfall maps, and land use maps.

These areas are primarily dry land with moderately drained soil. Good soil conditions for sugarcane seedlings are soils that are not too dry and not too wet, so irrigation and drainage must be considered (Gunarathna et al., 2018).

Tabel 4. Suitability classification and area distribution for sugarcane cultivation in East Java.

Suitability class	Area		
	%	km^2	ha
Highly suitable	23.20	11.149,49	1.114.949
Moderately suitable	30.18	14.499,67	1.449.967
Marginally suitable	36.05	17.321,71	1.732.171
Not suitable	10.55	5.068,25	506.825

Future yields of sugarcane plantations can be maximized through the application of several management practices (e.g., tillage and fertilization) (Silva-Olaya et al., 2017). In addition, the cultivation phase is very important. Cultivation is an essential step in determining the quality of sugarcane yields. One of the most important things in cultivation is the selection of a cultivation site/land. The cultivation location must have good drainage and be free from puddles. If the cultivation is carried out on dry land, the seedlings must have adequate and good irrigation and drainage system. On dry land, seedlings can be carried out if there is sufficient rainfall.

Conclusion

This initial research highlighted the role of land suitability assessment in optimizing sugarcane cultivation. Factors such as soil content, land use and land cover, rainfall, and land slope significantly influence the land suitability for sugarcane. By evaluating the suitability level of each land unit, this study identifies potential areas for sugarcane cultivation while also providing guidance for improving existing agricultural practices. More than 60% area of East Java was covered with marginally and moderately suitable land, while about 10% area was not suitable for sugarcane.

The findings emphasized that agroecological zoning could be an effective tool for supporting farmers in targeted areas. It enables them to implement strategies with minimal inputs to enhance productivity sustainably. These insights could inform decision-making processes, ensuring that interventions not only expand sugarcane production but also empower smallholder farmers to maximize yields on currently cultivated land. This approach promotes a balance between economic growth and environmental sustainability in sugarcane agriculture.

Conflict of Interest

We declare that we have no conflicts of interest, whether financial, personal, or otherwise, with any individuals or organizations connected to the subject matter presented in this manuscript.

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