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Multi-criteria decision analysis for optimal sugarcane land allocation in Merauke, South Papua, Indonesia

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[2]Center for Regional System Analysis, Planning and Development (CrestPent). Jl. Pajajaran, IPB Baranang Siang, Bogor 16710, West Java, Indonesia
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Abstract. *Rusdiana O, Kusdaryanto S, Muttaqien W, Machfud, Djaja I. 2025. Multi-criteria decision analysis for optimal sugarcane land allocation in Merauke, South Papua, Indonesia. Asian J Agric 9: 689-701.* Achieving sustainable sugarcane expansion requires integrating biophysical suitability with social and environmental considerations. This study applied a Multi-Criteria Decision Analysis (MCDA) using the Simple Additive Weighting (SAW) method to identify optimal areas for sugarcane cultivation in Merauke, South Papua, Indonesia. The analysis incorporates multiple criteria, including biophysical factors (climate, soil type, topography), land use policies (zoning, conservation areas), and social factors (land rights, indigenous communities' territories). Data were collected through field surveys, stakeholder interviews, and spatial analysis using Geographic Information Systems (GIS). The results indicate that approximately 80% of the study area is biophysically suitable for sugarcane cultivation. However, when considering land use policies, the available area reduces to 43.77% due to the presence of protected areas, forests, and risk-prone zones. After factoring in the rights of indigenous communities and areas of cultural significance, the land available for sugarcane cultivation shrinks further, leaving only 38.16% of the land as suitable for development. This highlights the trade-off between agricultural expansion and environmental conservation, as well as the importance of respecting indigenous land rights in land use planning. The study highlights the importance of combining geospatial analysis and stakeholder input for policymakers, land planners, and agricultural and forest developers to guide evidence-based, sustainable agricultural expansion in emerging regions.

Keywords: Forest area, indigenous rights, land suitability, multi-criteria decision analysis, sugarcane cultivation

Abbreviations: BBSDLP: Agricultural Land Resources Center, BIG: Geospatial Information Agency, BPS: Central Statistics Agency, BMKG: Meteorology, Climatology and Geophysics Agency, BRWA: Customary Territories Registration Agency, DEMNAS: National Digital Elevation Model, FPIC: Free, Prior, and Informed Consent, GIS: Geographic Information System, GRTT: Compensation for crops and plants, IPSDH: Directorate of Forest Resources Inventory and Monitoring, KLHK: Ministry of Environmental and Forestry, MCDA: Multi-Criteria Decision Analysis, MCDM: Multi-Criteria Decision Making, OAP: Papua Indigenous People, PSN: National Strategic Project, SAW: Simple Additive Weighting, SDGs: Sustainable Development Goals, SMCE: Spatial Multi-Criteria Evaluation

INTRODUCTION

Indonesia's sugar production remains heavily reliant on imports, despite a growing demand driven by consumption patterns in the food and beverage industries. In 2023, national sugar production was recorded at only 2.27 million tons, while the domestic demand was estimated at 7.3 million tons, resulting in a 70% dependency on imports (BPS 2024). This dependency is further exacerbated by the relatively low productivity of domestic sugarcane plantations (Sulaiman et al. 2023) and suboptimal sugar processing technologies. In response, the Indonesian government has set ambitious targets for self-sufficiency in sugar production by 2028 and industrial sugar self-sufficiency by 2030. Key to achieving these goals is the expansion of sugarcane plantations, particularly in regions like Merauke District, South Papua, which is part of the National Strategic Project (PSN) Cluster III (Peraturan Presiden 2023).

The development of sugarcane plantations in Merauke offers significant potential for enhancing national sugar production. However, land availability has become increasingly constrained. Between 2013 and 2019, Indonesia lost approximately 287,000 hectares of agricultural land due to conversion for urban and industrial development (IDEAS 2022). This highlights the urgent need for sustainable land optimization strategies that balance agricultural growth with environmental preservation. The sugarcane sector faces a critical challenge in addressing the environmental impacts associated with monoculture cultivation practices, which often lead to deforestation, biodiversity loss, and rising carbon emissions. As such, the dilemma facing Indonesia is how to increase agricultural productivity while maintaining ecological balance.

Despite the substantial potential for sugarcane cultivation, the development of plantations must be done with careful consideration of environmental and social factors. Previous studies (e.g., Verma et al. 2024; Rosa and Marin 2025) emphasize the ecological risks associated with monoculture practices and the importance of adopting sustainable farming practices. For example, countries like

Brazil and India have successfully enhanced sugarcane productivity through innovative breeding programs (Lu et al. 2024), offering valuable insights that could be applied to the Indonesian context to improve food security and agricultural sustainability.

This study aims to apply Multi-Criteria Decision Analysis (MCDA) using the Simple Additive Weighting (SAW) method to assess land suitability for sugarcane cultivation in Merauke. By integrating both biophysical and socio-political factors into the analysis, this research seeks to identify areas that are not only environmentally suitable for sugarcane farming but also compatible with existing land-use policies and sensitive to the needs and rights of indigenous populations. The results of this study will provide valuable insights for policymakers, land planners, and agricultural developers, assisting them in making evidence-based, sustainable decisions regarding agricultural expansion in emerging regions like Merauke.

This study contributes to existing research on land use optimization for sustainable agricultural development (Kennedy et al. 2016; Bayer et al. 2023; Romadhona et al. 2025) by emphasizing the integration of Multi-Criteria Decision Analysis (MCDA) in land use planning, which considers not only biophysical factors but also social and policy aspects (Naughton-Treves et al. 2005; Koczberski and Curry 2005). Utilizing the Simple Additive Weighting (SAW) method, this research assesses land suitability for sugarcane cultivation through a comprehensive framework that incorporates climate, soil, topography, land cover, and the rights and livelihoods of indigenous peoples an often overlooked dimension in land use planning. By addressing this critical gap, the study promotes a holistic approach that aligns ecological factors with spatial planning policies, ultimately aiming to provide actionable recommendations that support the United Nations' Sustainable Development Goals (SDGs), particularly in poverty alleviation (SDG 1), reduced inequalities (SDG 10), and sustainable ecosystems (SDG 15). This integrated approach offers a sustainable model for land allocation in Merauke, with implications for broader land management practices in other regions of Indonesia and similar tropical countries.

MATERIALS AND METHODS

Study area

This research was conducted in Merauke District, South Papua, Indonesia, which includes four sub-districts: Animha, Tanah Miring, Jagebob, and Sota. Geographically, the region is located between longitude 140° 18′ 28" E to 140° 18′ 30" E and latitude 7° 46′ 12" S to 7° 46′ 16" S or in the WGS 84 coordinate system, UTM Zone 54S (Figure 1). Merauke District has an area of 157,268.49 ha with a variety of land covers, including forests, savannas, and agricultural land. The area also has socio-economic challenges, such as Limited access to technology, agriculture, and dependence on the conventional agricultural sector. The research is to be carried out in May 2024.

Data types and sources

The data used in this study consisted of primary data and secondary data. Primary data was obtained through field surveys and in-depth interviews with informants consisting of local governments, indigenous peoples, and local farmers. Secondary data was obtained from satellite imagery, policy documents, as well as topographic and land cover maps published by relevant government agencies. The field survey was conducted in May 2024 in four sub-districts that were the focus of the research.

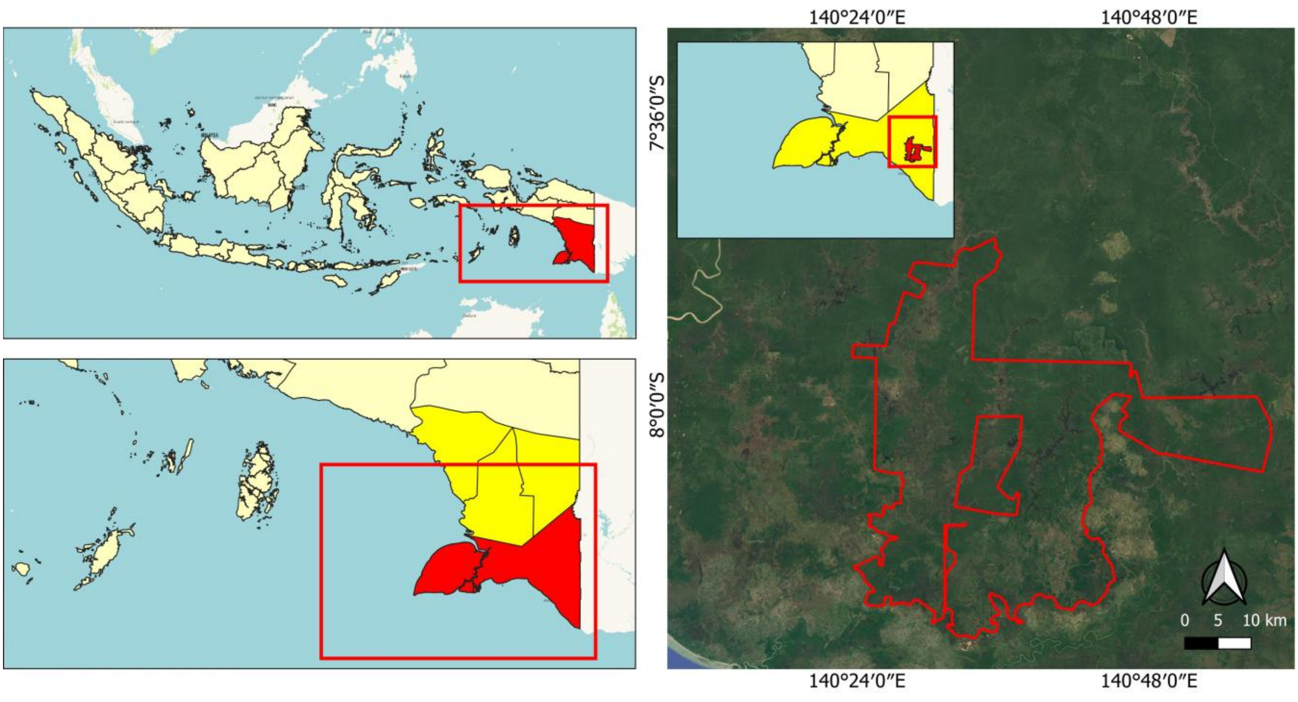


Figure 1. Research location in Animha, Tanah Miring, Jagebob, and Sota Sub-districts, Merauke District, South Papua, Indonesia

Data collection methods

The data collection procedure began with mapping the research area using satellite imagery to identify land cover and biophysical criteria. Subsequently, a field survey was conducted to verify the physical condition of the land and gather data from local communities and policymakers. In-depth interviews were conducted using semi-structured interview guidelines, with informants selected based on representative criteria from the government, indigenous peoples, and the local agricultural sector. The interview data were then analyzed using thematic analysis techniques to identify socio-economic and policy issues affecting the development of sugarcane plantations.

Analysis methods

This study used a combination of quantitative and qualitative approaches. A quantitative approach was used to conduct spatial analysis using Geographic Information System (GIS) software and the Simple Additive Weighting (SAW) method. A qualitative approach was used to obtain data related to spatial planning policies and social perspectives through in-depth interviews with local stakeholders, including indigenous peoples and local governments.

The SAW method was employed as the Multi-Criteria Decision Analysis (MCDA) technique. This method was chosen due to its effectiveness in incorporating multiple criteria and producing clear, weighted land suitability scores. The criteria for the analysis were grouped into three main categories: biophysical, spatial policy, and social and livelihood factors. Biophysical criteria included climate factors, such as rainfall and temperature ranges, soil characteristics like solum depth, and topographical features like slope and elevation. Spatial policy criteria involved land zoning regulations, protected areas, and conservation policies, while social and livelihood factors focused on indigenous peoples' rights to land and areas essential for their cultural and economic practices. The first step is to determine the criteria and weights for each parameter based on a literature review and input from stakeholders. Furthermore, data normalization is carried out to unify the measurement scale between different parameters. The results of this normalization are then used to calculate the preference value for each land alternative. A spatial overlay is then used to combine suitability maps of each aspect, resulting from the SAW process, to obtain a final map showing the optimal land for sugarcane plantation development.

In this study, the maps used are maps of spatial patterns, land cover, disaster risk, soil type, and rainfall issued by local governments and authorized ministries. Slope and elevation maps obtained from the National Digital Elevation Model (DEMNAS) image analysis using QGIS software (Belal et al. 2015). In addition, social data and the sustainable livelihoods of indigenous peoples are mapped from the results of a study conducted by USAID Lestari and the Customary Territories Registration Agency (BRWA 2024). In this study, standardization was carried out based on standards set with reference to certain criteria (Jakobsson and Giversen 2007; Mize 2012). In addition, the entire map was prepared with a uniform cell size and a georeferenced system.

Multi-criteria evaluation

The process of determining suitable land for sugarcane crop development took into account several assessed criteria. Spatial Multi-Criteria Evaluation (SMCE) in this study refers to the methodology described by Jamali (2010). Multi-Criteria Decision Making (MCDM) is one of the techniques used to choose the most optimal alternative by considering multiple criteria for a specific purpose (Rahardjo et al. 2000). The determination of criteria was based on strategic issues related to the SDGs, spatial planning policies, and land use suitability, and refers to literature reviews, relevant theories, and logical considerations.

Simple Additive Weight (SAW) method and overlay

Fishburn and MacCrimmon (Munthe 2013) stated that the SAW method is often referred to as the weighted addition method. The basic concept of the SAW method is to find the weighted sum of the suitability levels for each alternative across all attributes. In the application of land suitability for sugarcane plantation development using the SAW method, used set criteria, eligibility requirements (parameters), and weights were used. The steps of the SAW method are as follows:

Determining of land suitability criteria for sugarcane development

Land suitability in this study was assessed using three main categories of criteria. Biophysical criteria encompassed environmental and physical parameters such as rainfall, temperature, soil depth, land slope, and land cover. Spatial policy criteria involved regulatory and planning considerations, including agricultural zoning, protected areas, and disaster risk zones. Indigenous social and life criteria referred to local community dimensions such as customary territories, sustainable livelihoods, and sacred sites. The land suitability analysis was conducted through a stepwise raster overlay process in QGIS. In Stage 1, biophysical suitability was combined with spatial policy data to generate a preliminary suitability map. In Stage 2, this map was further refined by integrating social and livelihood constraints to produce the optimal land suitability map. The schematic workflow of this analytical process is presented in Figure 2.

Determining the reference weight

The weighting of each criterion was established through expert evaluations and paired comparisons conducted with professionals specializing in spatial planning, forestry, and agriculture. This method aimed to determine the relative importance of each criterion in accordance with the research objectives. Experts assessed each pair of criteria using a scale ranging from 1 to 9, where a value of 1 indicated equal importance, 3 suggested that the first criterion was slightly more important, 5 denoted moderate importance, 7 represented considerable importance, and 9 reflected that the first criterion was vastly more important than the second. Intermediate values of 2, 4, 6, and 8 were used to express nuanced levels of relative significance. The results were then synthesized into a paired comparison matrix based on this 1-9 scale, from which the final weights for each criterion were derived to reflect their proportional priorities within the overall land suitability assessment (Table 1).

Once the paired comparison matrix is compiled, the next step is to perform a consistency check using the Consistency Index (CI) and Consistency Ratio (CR) to ensure that the paired comparison matrix has adequate consistency. The steps of calculating CR are as follows:

i. Compute the eigenvector of the paired comparison matrix to get the criterion weight.
ii. Calculating the Consistency Index (CI) with the formula:

$$CI = \frac{\lambda \max - n}{n-1}$$

Where is the greatest eigenvalue and is the sum of the criteria.λ_"max" n

iii. Calculating the Consistency Ratio (CR) with the formula:

$$CR = \frac{CI}{RI}$$

Where is the Random Index which depends on the number of criteria (n). If the CR value is greater than 0.1, then the paired comparison matrix is considered inconsistent and needs to be corrected.

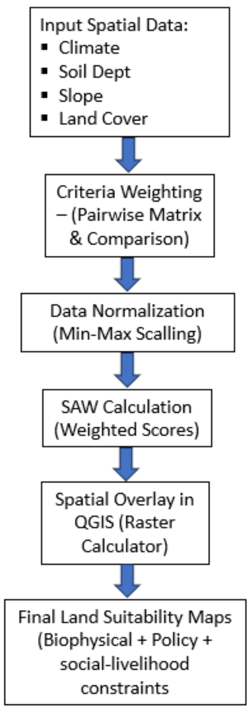


Figure 2. Analytical workflow of land suitability

Table 1. Pair comparison matrix

Criteria	Criteria A	Criteria B	Criteria C
Criteria A	1	3	1/5
Criteria B	1/3	1	1/7
Criteria C	5	7	1

Normalize the matrix.

Once the weights are determined, the data for each criterion is normalized using the following formula:

$$Rij = \frac{X_{ij} - \min(X_{ij})}{\max(X_{ij}) - \min(X_{ij})}$$

Where:

Rij: Normalized performance rating of alternative Ai on attribute Cij; i=1,2,..,m and j= 1,2,..,n

Xij: Value of each attribute column

max (xij): Maximum value of each attribute column

min (xij): Minimum value of each attribute column

Normalization matrix for biophysical conformity and spatial policy conformity aspects

$$X = \begin{Bmatrix} 1 & 1 & 1 & 1 \\ 0.5 & 0.5 & 0.5 & 0.5 \end{Bmatrix} \times \begin{Bmatrix} 0.25 \\ 0.25 \\ 0.25 \\ 0.25 \end{Bmatrix} = \begin{Bmatrix} 1 \\ 0.5 \end{Bmatrix}$$

Normalization matrix for social and livelihood fit aspects

$$X = \begin{Bmatrix} 1 & 1 \\ 0.5 & 0.5 \end{Bmatrix} \times \begin{Bmatrix} 0.5 \\ 0.5 \end{Bmatrix} = \begin{Bmatrix} 1 \\ 0.5 \end{Bmatrix}$$

Preference assessment

After the normalization process, the next step is to calculate the preference value for each alternative using the formula:

$$V_i = \sum_{j=1}^{n} W_j R_{ij}$$

Where:

Vj: Preference value of each alternative for j = 1,2,…..n

Wj: Preference weight of the decision-maker

Rij: Normalized performance rating of alternative Ai on attribute Cij; i = 1, 2,…n

Overlay spatial

After the results of the multi-criteria analysis are obtained, the final step is a spatial overlay of the land suitability map for each criterion. This spatial overlay allows mapping of the most suitable areas for sugarcane cultivation based on a combination of biophysical factors, spatial policies, and indigenous peoples' rights.

Validate results

To ensure the validity of the analysis results, field verification was carried out that compared the results of the spatial analysis with real conditions in the field. In addition, interviews with stakeholders and experts were conducted to evaluate the consistency of results and the relevance of policies to local conditions.

To verify that the filtering stage reflects an improvement in model or decision performance, it is necessary to relate these figures to evaluation metrics derived from the confusion metrics. The following are the steps to build a Confusion Metrics for each stage (Table 2).

Table 2. Confusion metrics for assessing the validity of results

	Predicted Positive	Predicted Negative
Actual Positive	True Positive (TP)	Fales Negative (FN)
Actual Negative	Fales Positive (FP)	True Negative (TN)

Accuracy = (TP+TN)/(TP+TN+FP+FN)
Precision = TP/(TP+FP)
Recall (Sensitivity) = TP/(TP+FN)

$$\text{F1 Score} = \frac{Precision\ x\ Recall}{Precision + Recall}$$

Application of ISO standards in GIS workflows

The analysis process using the Geographic Information System (GIS) follows the ISO 19100 standard, which includes the guidelines for the quality of geographic information. This ensures that the data used in this study meets high-quality standards in terms of accuracy and consistency. In addition, ISO 19115 is used to document geographic metadata, providing clear information regarding the origin and quality of the data used in the analysis. The maps generated during the overlay process use GIS software (such as QGIS) and follow the standard guidelines of ISO 19115 and ISO 19110, which provide a consistent framework for spatial data processing.

The SAW multi-criteria analysis method was used to determine the appropriate area for each aspect that aligns with the SDGs. This method is a weighted calculation technique that assigns a specific value to each criterion. By summing these weights, the method determines whether an alternative is suitable for a given decision. The results of spatial analysis using the SAW method will yield: (i) a map of sugarcane plantation suitability based on biophysical aspects; (ii) land suitability maps based on spatial policy; and (iii) land suitability maps considering the social aspects and livelihoods of indigenous peoples.

The next stage involves two filtration processes to obtain optimal land for sugarcane cultivation. First, the biophysical suitability map is overlaid with the spatial policy suitability map to obtain a map of suitable sugarcane plantation areas. Second, the sugarcane plantation suitability map is overlaid with the map of social suitability and indigenous peoples' livelihoods to create a map optimizing sugarcane plantation land use.

To ensure the validity of the analysis results, field validation was carried out by comparing the spatial analysis outcomes with observed field conditions. Additionally, interviewed with experts and policymakers were conducted to evaluate the consistency and relevance of the results to existing policies and practices. This validation process also incorporated feedback from indigenous peoples to ensure that the research outcomes are not only technically sound but also socio-economically relevant.

Overall, the combination of spatial analysis using SAW, spatial overlays, and a qualitative approach to capture social and policy dimensions provided a comprehensive view of the optimal land for sugarcane plantation development in Merauke District. This method enables the identification of areas that are not only physically suitable but also support social and ecological sustainability.

RESULTS AND DISCUSSION

Profile of the research area

This research was carried out in Merauke District, South Papua, which includes four sub-districts: Animha, Tanah Miring, Jagebob, and Sota, with a total area of 157,268.49 ha. The region has a flat topography topography (Table 3), an altitude of 27-71 meters above sea level (m a.s.l.), and an annual rainfall of ±1,869 mm that is suitable for sugarcane growth. The main soil types are Distric Cambisol (81.69%) and Eutric Cambisol (18.31%), both of which have a solum depth of >50 cm that supports sugarcane rooting.

Land cover is dominated by forests and savannas, while agricultural land is still limited. The main land use in the study area was dominated by forests and savannas, covering almost 52.38% of the total area, with the distribution as shown in Table 4.

In addition, based on data from the Agricultural Land Resources Center (BBSDLP 2016), the research area is divided into two main types of soil, namely Eutric Cambisol and District Cambisol (Table 5). The soil type of the Cambisol District covers about 81.69% of the total study area, which indicates soil with low fertility rates, which needs to be considered in the selection of locations for sugarcane plantation development (Koković et al. 2022).

Based on the characteristics of the land (Figure 3), the study location showed a fairly high annual rainfall, ranging from 1,800-2,000 mm per year. The study location shows a fairly high annual rainfall, according to Mopah Climatology Station data in 2023 ranging between 1,800-2,000 mm per year. This greatly supports the water needs of sugarcane plants, which require stable humidity throughout the year. In most areas, the soil solum depth exceeds 50 cm, with the soil types Eutric Cambisol and District Cambisol providing ideal conditions for the root growth of sugarcane plants (Koković et al. 2022). In addition, the mostly flat topography (slope <8%) favors the use of agricultural mechanization, which is an important factor for the efficiency of sugarcane production on a large scale. According to the status of forest areas, the study area is dominated by the status of Conversion Production Forest area by 65.21% (Table 6). Results of GIS overlay analysis of potential flood hazards using DEMNAS (Digital Elevation Model National), land use maps, river networks, and rainfall, the study area indicated to be flooded is 26.67% of the study area, which is a swamp area and riparian (Table 7). Spatially, spatial patterns, forest status, biodiversity, and flood risk are presented in Figure 4.

Table 3. Slope class of the study area (BBSDLP 2016)

Slope class	Area (ha)	%
0-3%	28,796.50	18.31
3-8%	128,471.99	81.69

Table 4. Land cover of the study area (IPSDH 2023)

Existing land cover	Area (ha)	%
Primary Dryland Forests	28,214.51	17.94
Secondary Dryland Forest	39,191.11	24.92
Primary Swamp Forest	11,229.85	7.14
Secondary Swamp Forest	8,642.09	5.50
Bushland	3,313.36	2.11
Swamp Bushes	19,654.69	12.50
Savannah / Grassland	30,695.17	19.52
Plantation	4.76	0.00
Dryland Agriculture	854.72	0.54
Mixed Dryland Agriculture	592.32	0.38
Paddy	24.13	0.02
Settlements	239.98	0.15
Bare land	1,593.34	1.01
Water Body	13,018.47	8.28
Total	157,268.49	100

Table 5. Soil type of the study area (BBSDLP 2016)

Soil type	Area (ha)	%
District Cambisol	128,471.99	81.69
Eutric Cambisol	28,796.50	18.31
Total	157,268.49	100

Table 6. The spatial pattern of Merauke District, South Papua, Indonesia, in the study area (RTRW Merauke District 2011)

Spatial patterns	Area (ha)	%
Local Protected Areas	9.22	0.01
Convertible Production Forest Areas	102,549.58	65.21
Permanent Production Forest Areas	22,523.81	14.32
Plantation Area	17,466.66	11.11
Food Crop Area	47.25	0.03
Horticultural Areas	12,339.94	7.85
Livestock Area	0.02	0.00001
Rural Settlement Areas	1,011.07	0.64
Urban Residential Areas	782.40	0.50
Water bodies	538.54	0.34
Total	157,268.49	100

Table 7. Flood risk

Disaster-prone	Area (ha)	%
Prone to flooding	41,950.60	26.67
Not prone to flooding	115,317.88	73.33
Total	157,268.49	100

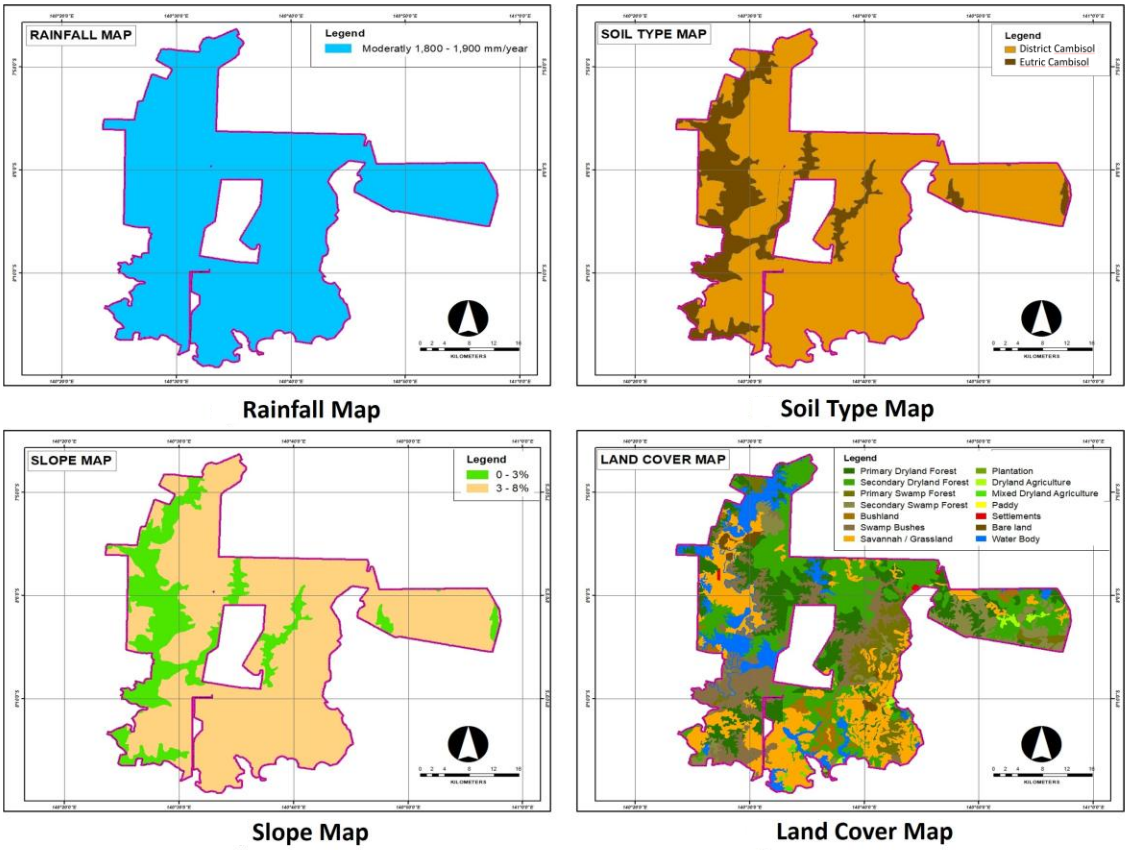


Figure 3. Map layers for the land characteristics of the study area. Source: BBSDLP (2016), BMKG (2023) and IPSDH (2023)

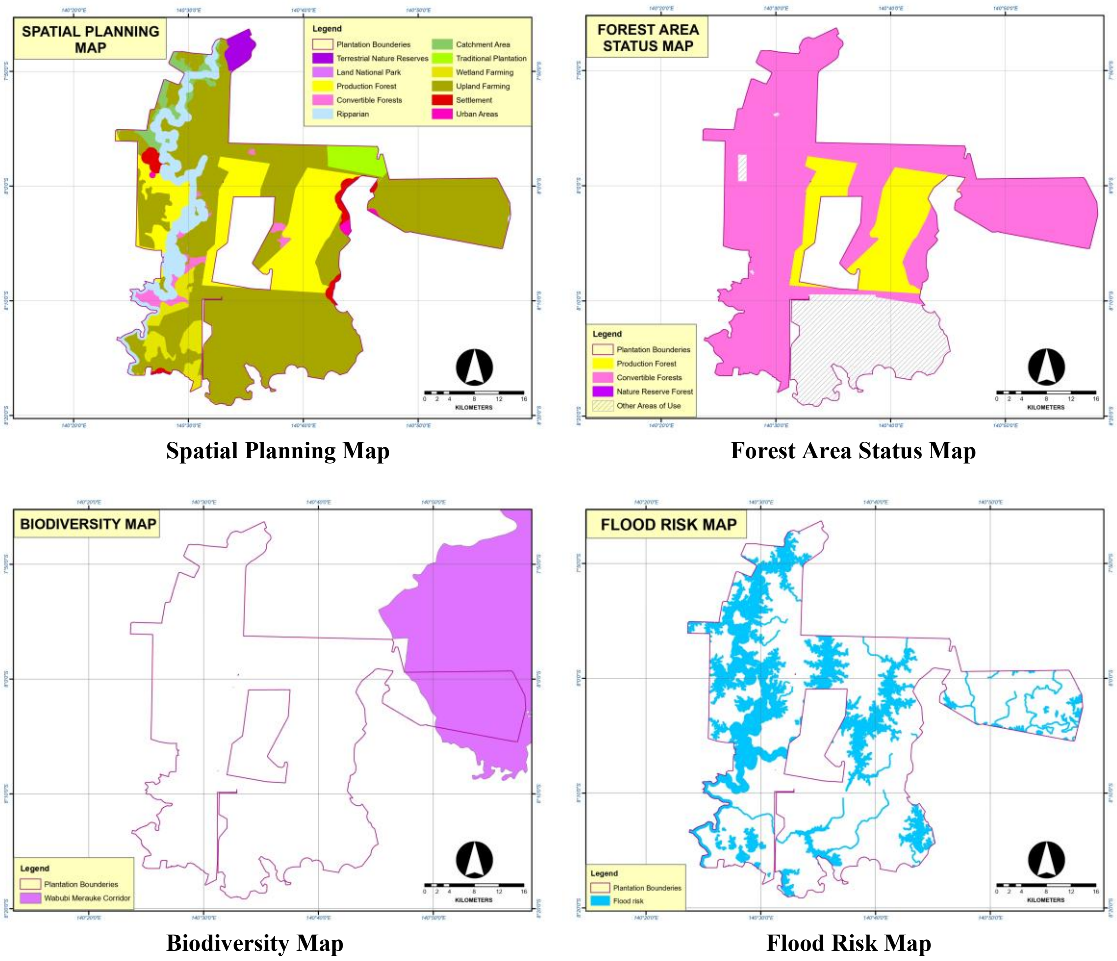


Figure 4. Map layers for spatial policy. Source: RTRW Merauke District (2011) and KLHK (2021)

The biodiversity that affects the study area is the corridor of protected animals (Gebrie et al. 2025), and based on data from the Ministry of Forestry, it is indicated that it covers an area of 9.95% of the study area. Based on biodiversity considerations, area that function as wildlife corridors must be protected. The status of corridors is presented in Table 8. Based on data from the Customary Territory Registration Agency (BRWA) in the study area, there is a customary territory of the Yei tribe covering an area of 22.86% of the study area (Table 9). In addition, there are also traditional community utilization areas and sacred places that the community believes cover an area of 6.52% of the study area (Table 10). Areas of importance to indigenous peoples, consisting of traditional use areas, sacred sites, and other customary territories, are presented spatially in Figure 5.

Table 8. Wildlife corridors status (KLHK 2021)

Corridors status	Area (ha)	%
Wildlife corridors	15,639.60	9.95
Non-wildlife corridors	141,628.89	90.05
Total	157,268.49	100

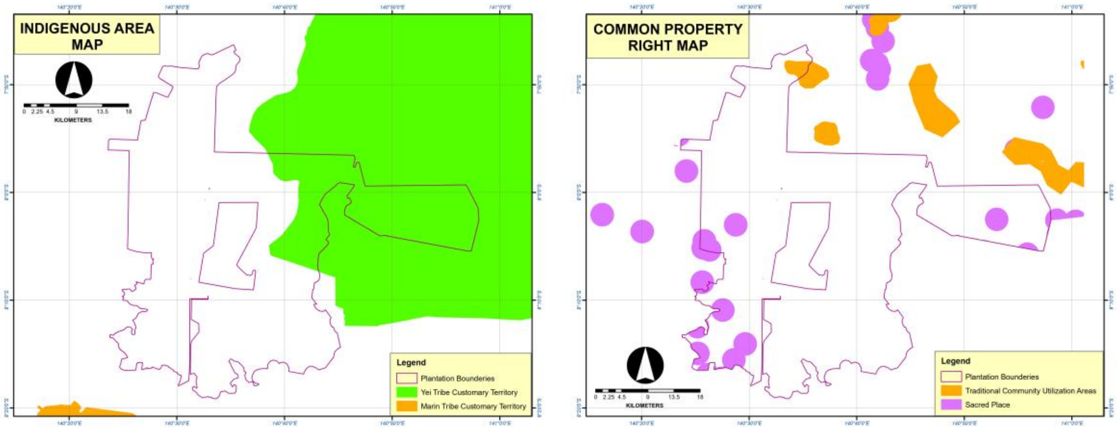
Table 9. Customary tribal registration area in the study area (BRWA 2024)

Customary Territory	Area (ha)	%
Yei Tribal Customary Territory	35,954	22.86
Non-Customary Territory	121,314.49	77.14
Total	157,268.49	100

Table 10. The area of life of indigenous peoples in the study area (RTRW Merauke District 2011)

Indigenous peoples' living area	Area (ha)	%
Traditional utilization area of the community	940.14	0.60
Sacred places	9,310.26	5.92
Non-common property right	147,018.09	93.48
Total	157,268.49	100

Source: RTRW Merauke District (2011)



Indigenous Area Map **Sustainable Livelihood Map**

Figure 5. Map layers for social and livelihood. Source: BRWA (2024)

Strategic issues

Strategic issues related to the Sustainable Development Goals serve as the foundation for determining the criteria to decide the optimal land allocation for sugarcane plantation development in the study area. The identification of sustainable development issues in Merauke District, based on a review of various related planning documents and FGDs with stakeholders, identified 33 sustainable development issues, detailed in Figure 6. The results of the screening process on these 33 issues, based on their impact in the following categories: (1) cross-sector, (2) cross-regional, (3) long-term, (4) stakeholders, and (5) cumulative impact, resulted in 7 strategic issues: (1) Biodiversity, (2) Land conversion, (3) Disaster risk (climate crisis, drought, floods, land and forest fires), (4) Licensing governance, (5) Waste issues (water and soil pollution), (6) Poverty (increasing poor population), and (7) Limited living space for indigenous peoples. The presence of indigenous peoples in protected areas can contribute to maintaining the integrity of tropical forests (Jocelyne et al. 2022). The relationship between these strategic issues and the Sustainable Development Goals is shown in Figure 6.

Figure 6 above illustrates that failure in one issue can hinder the achievement of many other SDGs, so that in regional development, a sectoral approach is not enough, but a cross-sectoral and cross-actor approach is needed. Ecological and social justice should be the main principles in sustainable development planning (Menton et al. 2020), and in particular in the context of optimizing land use for sugarcane plantations in the study area.

Optimization criteria

Based on strategic issues and the results of the screening process, 3 aspects were produced in the context of optimizing and the suitability of land use (Vera et al. 2020; Artikanur et al. 2023). The three aspects are (1) biophysical suitability, (2) spatial planning policies, and (3) social and livelihood aspects (Scoones 1998; Koczberski and Curry 2005; Naughton-Treves et al. 2005).

The aspect of land suitability consists of criteria (a) climate, (b) soil type, (c) topography, and (d) current land cover. Aspects related to spatial planning policies include criteria: (a) government policy space, (b) forest area space, (c) biodiversity, and (d) disaster risk areas. The aspects of social and livelihood criteria include (a) customary land and (b) sustainable livelihood. The flow chart of the SAW analysis process and the overlays used are presented in Figure 7. The screening process to decide the suitability and feasibility of land for the development of sugarcane plantations is based on criteria in each aspect, with the weight of each criterion as shown in Tables 11, 12, 13, 14, 15.

Land suitability analysis based on biophysical aspects

The results of the land suitability analysis based on biophysical aspects show that around 80% of the total research area, which is 125,819.15 ha, is suitable for the development of sugarcane plantations. The criteria used include the following climatic, soil, topography, and land cover conditions:

Climate: Land suitability based on rainfall between 800 mm and 5,000 mm per year indicates an optimal area for sugarcane plant growth (Silalertruksa and Gheewala 2018).

Soil type: Soil with a solum layer of more than 50 cm is considered suitable for sugarcane growth, while areas with shallower soil or rough texture are not recommended.

Topography: Land with a slope below 8% is considered ideal for mechanized systems in sugarcane farming.

Land cover: Land free of primary forests, swamps, and water bodies has a higher suitability value, while areas dominated by forest cover or water bodies are considered unsuitable. Lands with extreme conditions, such as very high rainfall or infertile soil types, do not fall into the optimal category for sugarcane plantations.

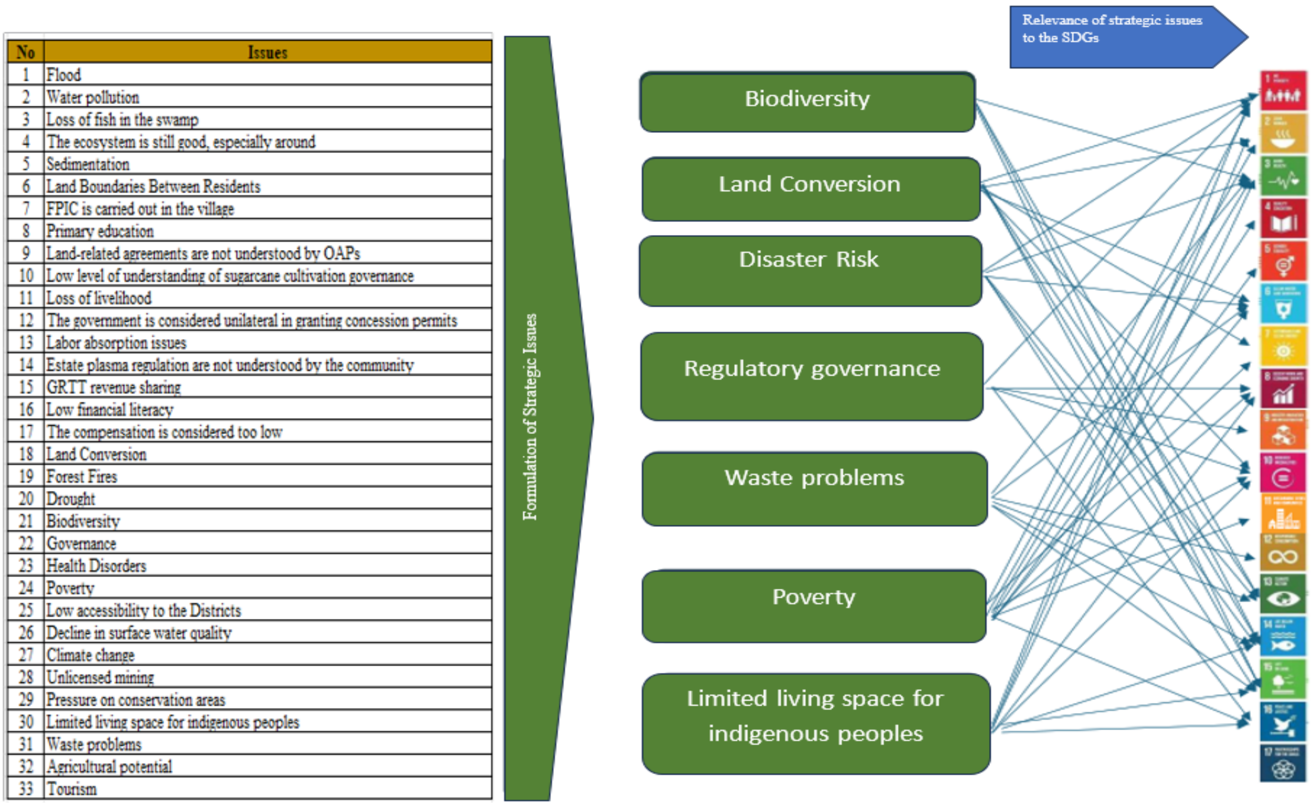


Figure 6. Diagram of the relationship of strategic issues to priority SDGs

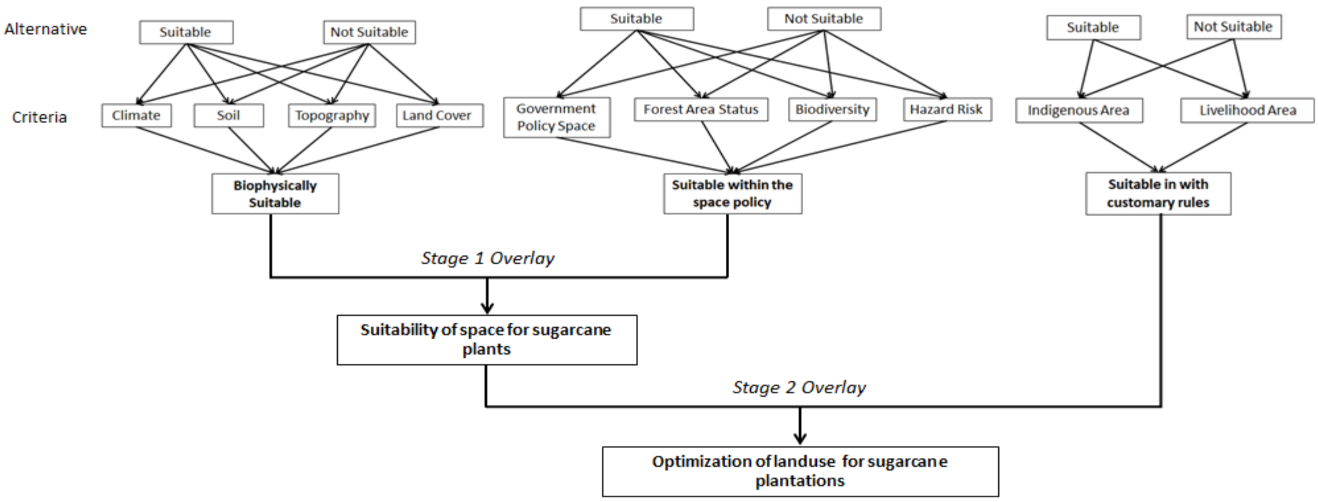


Figure 7. Diagram of the relationship of strategic issues to priority SDGs

Table 11. Biophysical aspects

Criteria	Weighted	Alternative	Score	Parametric
Climate	0.25	Suitable	2	1.000 - 5.000 mm/year
		Non-suitable	1	< 1.000 mm/year and > 5.000 mm/year
Soil Type	0.25	Suitable	2	Solum > 50 cm
		Non-suitable	1	Solum < 50 cm
Topography	0.25	Suitable	2	Slope < 30%
		Non-suitable	1	Slope > 30%
Land Cover	0.25	Suitable	2	Except for primary forests, swamps, settlements, and water bodies
		Non-suitable	1	Primary forests, swamps, settlements, and water bodies

Note: Source: Analysis results (2024)

Table 12. Spatial planning policy aspects

Criteria	Weighted	Alternative	Score	Parametric
Government policy space	0.25	Suitable	2	Cultivation areas
		Non-suitable	1	Protected areas
Forest area status	0.25	Suitable	2	Other use areas (APL)
		Non-suitable	1	Nature reserves and conservation forests
Biodiversity	0.25	Suitable	2	Outside the protected animal corridor area
		Non-suitable	1	The wildlife corridor area is protected
Hazard risk	0.25	Suitable	2	Areas outside flood risk
		Non-suitable	1	Flood risk

Note: Source: Analysis results (2024)

Table 13. Social and livelihood aspects

Criteria	Weighted	Alternative	Score	Parametric
Indigenous area	0.50	Suitable	2	Outside the customary area
		Non-suitable	1	Area of customary
Livelihood area	0.50	Suitable	2	Outside the livelihood area
		Non-suitable	1	Area of livelihood

Note: Source: Analysis results (2024)

Table 14. The compatibility rating of each alternative from each aspect is as follows.

Alternatives	Aspects		
	Land suitability (Biophysical)	Space policy compliance	Social and livelihood fit
Accordingly	1	1	1
Not accordingly	0.5	0.5	0.5

Note: Source: Analysis results (2024)

Table 15. Ranking of land suitability that applies to each aspect.

Alternatives	Value	Percentage	Ranking
Suitable	1	100%	1
Not suitable	0.5	50%	2

Note: Source: Analysis results (2024)

Land suitability analysis based on spatial planning policy

The second screening process is carried out by combining data on spatial planning policies, which include government regulations on the use of space for agriculture, conservation areas, and forest areas. Based on the existing policy in Merauke District, only areas outside protected areas and forest areas can be developed for sugarcane plantations. The results of this analysis show that of the 125,819.15 ha that are biophysically suitable, only 68,840.01 ha (43.77%) of the total research area) meet the spatial policy criteria that support use for agriculture, especially for the development of sugarcane plantations. These space policies include:

Agricultural zone: An area that is intended for agricultural activities and is not included in a protected area or forest area.

Forest areas: Primary and secondary forests, as well as conservation areas, are excluded from areas that can be used for plantations.

Along with the implementation of this policy, the area suitable for the development of sugarcane plantations has been significantly reduced, given the large number of areas protected by government regulations.

Analysis of land suitability based on social aspects and indigenous peoples' rights

In the last stage, screening is carried out based on social aspects and the rights of indigenous peoples. In Merauke District, there are areas managed by indigenous peoples, including areas used for sustainable livelihoods and sacred places considered important by indigenous tribes. The results of the analysis show that approximately 60,017.67 ha (38.16%) of areas that have met biophysical criteria and spatial policies should be excluded from sugarcane development plans to respect the rights of indigenous peoples, which include:

Customary land: Areas included in the customary territory or traditional areas of the Yei tribe (22.86% of the study area) are excluded from land planning.

Sustainable livelihoods: Areas that are important for the lives of indigenous peoples, such as sacred places and ancestral paths, cannot be used for plantations.

Scoones (1998) explained the concept of sustainable livelihood through the livelihood approach, which explores the history of thought about livelihood and its relationship with the study of poverty and welfare. This approach emphasizes the importance of assets owned by the community as capital to achieve welfare, face shocks such as natural disasters, and ensure the welfare of future generations. However, this concept has limitations, as expressed by de Haan (2012) and Natarajan et al. (2022). De Haan (2012) highlights that global processes often seize local space in an effort to achieve prosperity, so traditional livelihoods cannot meet global demands. Meanwhile, Natarajan et al. (2022) criticized the absence of power relations in many studies on sustainable livelihoods, especially in understanding the structural factors that drive poverty.

In the context of forest-dependent indigenous peoples, regional replanning often leads to access restrictions and even removal (Ungirwalu et al. 2021). Therefore, indigenous peoples' living space policies must consider their need for natural resources to support sustainable livelihoods. Taking into account the social aspects and rights of indigenous peoples, the area of land suitable for the development of sugarcane plantations in Merauke District is 60,017.67 ha, or around 38.16% of the total research area.

Optimal land

Based on the SAW analysis method and spatial overlay, land suitable for the development of sugarcane plantations is filtered through two stages, taking into account three main aspects. The first phase covers biophysical aspects and spatial policies, while the second phase involves screening the social aspects and livelihoods of indigenous peoples.

In the first stage, the results of biophysical land suitability screening based on climatic criteria, soil type, topography, and land cover showed that around 80% of the total study area (125,819.15 ha) had high suitability for sugarcane development (Figure 8.A). However, after considering spatial policies, the results of the analysis showed that only 43.77% of biophysically appropriate areas (68,840.01 ha) met the spatial policy criteria, such as agricultural zones and areas not protected by conservation policies or forest areas. Thus, spatial planning policies have a major effect on the reduction of the area that can be used for sugarcane plantations (Figure 8.B). These results highlight the significant impact of spatial planning policies in limiting the land available for plantations.

In the second stage (Figure 8.C), further screening taking into account the social aspects and rights of indigenous peoples shows that areas located within the customary territory of the Yei people or areas that are the source of sustainable livelihoods of indigenous peoples need to be excluded from sugarcane plantation development plans. Based on the map of customary territories and traditional use areas excluded from the program plan, there are approximately 60,017.67 ha that must be excluded. This makes the area suitable for the development of sugarcane plantations in the study area to 60,017.67 ha or about 38.16% of the total area studied (Figure 8).

The decrease in figures from 80% → 43.77% → 38.16% is not a decrease in performance, but rather an adjustment in threshold or classification which results in increased accuracy and consistency in field conditions. Validation with confusion metrics shows that the model is increasingly accurate and relevant, especially in the final stage. F1 Score as a combined metric shows that final screening is the most optimal stage to use in spatial decision making (Table 16).

This research highlights the importance of rights-based approaches in land use planning, which integrates aspects of biophysical, social, and spatial policies. Rights-based governance in land use planning emphasizes the integration of human rights principles into the management and management of land and natural resources. This approach aims to balance economic development with sustainability and social justice, particularly in the context of land grabbing and climate change (Marzo 2024).

Although the biophysical potential for sugarcane cultivation in Merauke is enormous, spatial planning policies and the protection of indigenous peoples' rights limit land use. The involvement of local communities in the decision-making process is also an important element for effective land governance (Bourgoin et al. 2013).

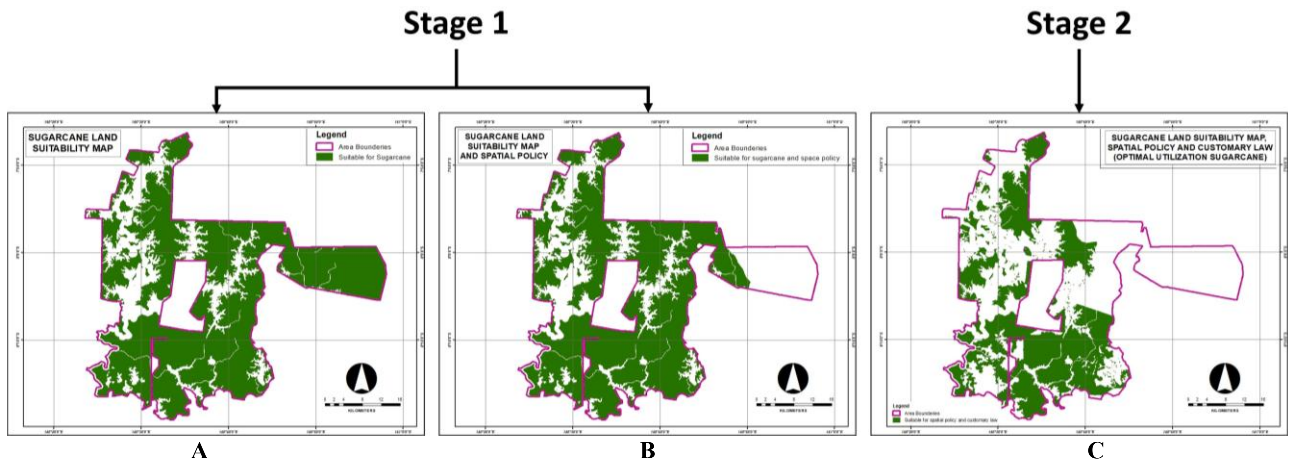


Figure 8. Multi-criteria analysis results map: A. Suitable sugarcane map, B. Suitable sugarcane and spatial policy, C. Optimal utilization sugarcane

Table 16. Comparison metrics between screenings

Screening	Accuracy	Precision	Recall	F1 score
Initial screening (80%)	20%	0.25	0.30	0.27
Middle screening (43.77%)	56.23%	0.60	0.65	0.62
Final screening (38.16%)	61.84%	0.70	0.72	0.71

It is therefore important to integrate inclusive and rights-based policies in land use planning in order to ensure that agricultural development is not only economically profitable but also ecologically and socially sustainable. In the context of regions with informal land tenure systems, a participatory approach can help clarify and secure land rights (Compton 2024). In addition. governance mechanisms must be able to balance the interests of private property owners, public policy goals, and community needs (Dougall et al. 2025).

This study shows that the development of sugarcane plantations in Merauke District must consider the balance between biophysically appropriate land potential and socio-ecological sustainability. Although most of the study areas have high biophysical suitability for sugarcane growth, spatial planning policies and indigenous peoples' rights limit land use for plantations.

It is important to note that spatial policies and management of indigenous territories must be respected to ensure social and ecological sustainability. This research also confirms the need for a rights-based governance approach in land use planning, which accommodates the interests of indigenous peoples and the sustainability of their livelihoods. Thus, the results of this study can guide in planning of the development of sugarcane plantations that are not only profitable in terms of production but also ensure community welfare and environmental sustainability.

Based on the results of the research. here are some suggestions that can be taken to support the sustainable development of sugarcane plantations in Merauke District:

Improvement of irrigation and drainage infrastructure: Considering that most of the research areas have the potential to be prone to flooding, there is a need for the development of effective drainage and irrigation systems. These systems should manage excess rainwater during the wet season and ensure adequate water supply during dry periods to support optimal sugarcane growth.

Protection of biodiversity: In the process of developing sugarcane plantations, it is important to maintain biodiversity around the developed land. Policies that support the protection of forest areas and the diversity of flora and fauna need to be enforced to reduce the negative impact on local ecosystems.

Indigenous peoples' rights-based approach: As a step to ensure social sustainability, this study suggests involving indigenous peoples in the land planning and management process. The implementation of rights-based governance principles in land use planning can help protect the rights of indigenous peoples and ensure that the development of sugarcane plantations does not harm their livelihoods. Local governments need to strengthen spatial planning policies to ensure that the expansion of sugarcane plantations does not damage areas of high conservation value or threaten the sustainability of indigenous peoples' lives. This can be done by drafting more detailed regulations on the use of space in accordance with the principles of the Sustainable Development Goals (SDGs) and strengthening the legal basis that recognizes and protects people's rights to land and natural resources in an inclusive manner.

Improvement of sustainable agriculture technology and practices: To increase the productivity of available land, investment in more efficient and environmentally friendly agricultural technologies is needed. The use of agricultural technologies that reduce dependence on chemicals and increase crop resilience to climate change can support the long-term sustainability of the sugarcane plantation sector.

Further research is needed to explore other land potentials that may not have been identified in this study. Extending research to other areas with similar biophysical and socio-economic conditions will improve adaptive planning and policy formulation. Future research should combine time-series datasets, participatory mapping, and scenario-based modeling to improve temporal accuracy, stakeholder representation, and long-term reliability in spatial suitability assessments.

In conclusion. this study demonstrates that integrating MCDA and GIS provides a robust framework for identifying optimal and sustainable sugarcane expansion zones in Merauke. South Papua. The combination of biophysical, spatial, and socio-economic criteria offers a holistic perspective that balances productivity, accessibility, and community welfare. The analysis showed that 80% of the regions studied had a high biophysical suitability for sugarcane cultivation. However, after considering spatial planning policies and indigenous peoples' rights. the eligible area shrank to 38.16%. This decline underscores the need for integration between agricultural productivity and socio-ecological sustainability in land use planning. A rights-based approach that respects the rights of indigenous peoples and ecological balance is essential to achieve long-term sustainability. Therefore. more inclusive and rights-based policies are needed to reduce social conflicts and increase agricultural yields sustainably. These findings are also relevant for land use planning in other tropical regions that face similar challenges. with the model developed as a reference for sustainable land management policies.

However. the study is limited by the temporal scope of the data and the exclusion of dynamic climatic and hydrological variables. which may influence long-term suitability. The weighting of social parameters was also based on stakeholder perception rather than longitudinal socio-economic datasets. which may affect replicability in different contexts. Future studies should incorporate climate models. temporal land-use monitoring. and economic optimization scenarios to enhance decision accuracy and scalability.

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