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Spatially explicit land suitability assessment for wetland agroforestry using GIS, fuzzy logic, and multi-criteria analysis in tropical forest landscapes, West Sulawesi

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Abstract

Wetland ecosystems are increasingly recognized for their potential to support sustainable food production while maintaining critical ecosystem functions. However, their integration into tropical agricultural planning remains limited due to the lack of spatially explicit and methodologically robust frameworks capable of capturing the bio-physical complexity and hydrological dynamics of wetland landscapes. This study addresses this gap by assessing the potential of wetland-based agroforestry systems for sustainable food production using an integrated spatial analysis approach in Kalumpang District, Mamuju Regency, Indonesia. A mixed-method approach was employed, combining qualitative field observations and farmer interviews with quantitative spatial analysis using Geographic Information Systems (GIS). Wetland distribution was identified using fuzzy logic based on NDVI, NDWI, elevation, and slope, while land suitability was evaluated through Spatial Multi-Criteria Analysis (SMCA) incorporating weighted parameters such as soil properties, climate, topography, and flood risk. The results show that wetlands cover approximately 809.25 ha and exhibit high spatial heterogeneity. Land suitability analysis indicates that leafy vegetables and maize are predominantly classified as highly suitable (S1), whereas taro and cocoa are mainly moderately suitable (S2), reflecting differences in ecological adaptability. A zonation-based agroforestry model is further developed to align crop allocation with hydrological gradients, thereby optimizing land use allocation.
This study contributes a spatially explicit and integrative methodological framework that combines fuzzy logic and SMCA within a GIS environment to improve wetland suitability assessment for agroforestry planning in tropical landscapes.

Keywords : Wetland agroforestry, Land suitability analysis, Geographic Information Systems (GIS), Spatial multi-criteria analysis (SMCA), Sustainable food production

Introduction

Global food security remains a fundamental challenge amidst the simultaneous pressures of population growth, climate change, and land resource degradation (FAO et al. 2023). A production intensification-based approach alone is increasingly considered inadequate to ensure the sustainability of food systems, necessitating a transformation towards a landscape-based approach that simultaneously integrates ecological, social, and economic dimensions (Vira et al. 2015; Tan et al. 2020; Atapattu et al. 2024). In this context, agroforestry is increasingly recognized as a key strategy in supporting sustainable food production systems through the integration of trees, crops, and/or livestock in a single land unit that can increase productivity while maintaining ecosystem function.

Among various landscape types, wetlands are a strategic resource that remains underutilized in agricultural planning, particularly in tropical regions. Globally, wetlands play a crucial role in providing ecosystem services such as hydrological regulation, carbon storage, soil quality improvement, and biodiversity conservation (Gordon et al. 2010; Davidson et al. 2018; Gardner and Finlayson 2018). Furthermore, the integration of agroforestry into wetland ecosystems has the potential to improve food security and community livelihoods through production diversification and increased stability of agricultural systems (Muchane et al. 2020; Afentina et al. 2021; Khatun and Palit 2023). However, poorly managed wetland utilization, particularly through intensive drainage practices

and land conversion, can lead to ecosystem degradation, increased carbon emissions, and biodiversity loss (Verhoeven and Setter 2009; Evers et al. 2016; van Dam et al. 2025).

In Indonesia, the potential of wetlands to support sustainable food production remains underutilized. Despite wetlands covering over 20 million hectares, most agricultural planning still focuses on dryland areas and conventional irrigation systems (Nurtyawan and Hendarna 2020; Syahza 2022). This condition is also evident in Mamuju Regency, West Sulawesi, where communities living around forested landscapes still rely heavily on local resources, including wetlands, to meet household food needs (Utami A 2022). However, wetlands in this region have generally not been systematically evaluated using an evidence-based approach capable of capturing the spatial complexity of biophysical and hydrological dynamics. (Karim et al. 2023).

The development of wetland-based agroforestry systems requires accurate and integrated spatial information to support informed decision-making. Geographic Information Systems (GIS) have been widely used in land suitability evaluation by integrating various parameters such as soil, topography, climate, and hydrology (Todorovic and Steduto 2003; Wotlolan et al. 2021; Soraya et al. 2022). However, most previous approaches are still deterministic and less able to represent high spatial uncertainty in wetland ecosystems (Lee et al. 2019; Zarei et al. 2021). Fuzzy logic-based approaches offer a more adaptive alternative in capturing variations in environmental conditions, while integration with Spatial Multi-Criteria Analysis (SMCA) enables more comprehensive and decision-based land suitability assessments (Hassanzadeh et al. 2019; Feilhauer et al. 2020).

Although various studies have highlighted the potential of agroforestry in improving the sustainability of agricultural systems, most research still focuses on single-parameter-based land suitability evaluation or deterministic approaches that are unable to accommodate the spatial complexity and hydrological dynamics of tropical wetland ecosystems. Furthermore, there are not many studies that explicitly integrate fuzzy logic approaches with Spatial Multi-Criteria Analysis (SMCA) within a GIS-based framework to evaluate agroforestry land suitability in tropical wetland environments.

Furthermore, studies linking the results of biophysical land suitability evaluations with the development of hydrological gradient-based agroforestry zoning models are still very limited, especially in local-scale tropical forest landscapes. This limitation indicates that there is still a gap between spatial-based land suitability analysis and practical implementation in the form of adaptive agroforestry planning based on specific environmental conditions.

Therefore, this study aims to assess the potential of wetland-based agroforestry to support sustainable food production through an integrated GIS-based land evaluation approach. Specifically, this study combines fuzzy logic analysis, Spatial Multi-Criteria Analysis (SMCA), and spatial overlay techniques to identify wetland distribution and evaluate land suitability for selected agricultural commodities in tropical forest landscapes.

The main contribution of this research lies in the development of a methodological framework that integrates fuzzy logic and SMCA in a GIS environment to produce spatially explicit and adaptive land suitability evaluations to wetland dynamics, as well as the proposal of a hydrological gradient-based agroforestry zoning model as an implementative approach to optimize commodity allocation and minimize environmental risks. This approach is expected to be used as a basis for decision-making in sustainable agroforestry planning and strengthening food security in tropical regions.

Materials and Methods

Study Area and Site Selection

This research was conducted in Kalumpang District, Mamuju Regency, West Sulawesi, Indonesia, a tropical forest landscape with naturally occurring wetlands that have not been optimally utilized in modern agricultural systems. This area also demonstrates a high level of community dependence on local resources to meet household food needs (Utami A 2022).

The selection of the research location was based on several methodological considerations relevant to the research objectives. First, the Kalumpang area has complex biophysical characteristics, characterized by the presence of freshwater swamp-type wetlands scattered across various topographic conditions. This condition makes Kalumpang a suitable representative for testing a spatial-based land suitability evaluation approach that integrates hydrological, topographic, and biophysical parameters, as used in this study (Calvin et al. 2024; Ruba et al. 2025).

Second, the area is located within a tropical forest landscape with relatively limited human intervention, providing suitable conditions for assessing the potential of wetland-based agroforestry without the distortions of intensive land-use change. This is crucial in the context of developing agroforestry systems that maintain ecosystem function while increasing land productivity, as

emphasized in landscape-based approaches (Tan et al. 2020; Atapattu et al. 2024).

Third, land use practices by the community in this region are still adaptive to environmental conditions and are carried out traditionally, thus providing a relevant empirical context for integrating qualitative and quantitative approaches within the mixed-method framework used in this study. (Yusriadi et al. 2024).

Fourth, to date, the Kalumpang region has not been extensively evaluated using a Geographic Information System (GIS)-based approach that integrates fuzzy logic and Spatial Multi-Criteria Analysis (SMCA) for explicit wetland suitability assessment. This limitation indicates a research gap in the development of a spatially based land evaluation framework capable of representing the uncertainty and dynamics of tropical wetland hydrology (Hassanzadeh et al. 2019; Feilhauer et al. 2020).

The selection of Kalumpang District was based not only on data availability and accessibility, but also on its relevance as a representative case study for testing and developing an integrated GIS-based land suitability evaluation approach. The results of this study are expected to have a high degree of transferability to other tropical regions with comparable biophysical and socio-economic characteristics.

Spatial Analysis and Modeling Framework

Spatial overlay analysis was conducted by integrating actual land use maps, land suitability maps, and forest area boundary data using ArcGIS software to produce a spatial land availability assessment (Nugraha 2018; Amelia et al. 2024).

This process is strengthened through land suitability modeling using the Model Builder extension, which has been widely applied in GIS-based land evaluation studies, particularly in wetland ecosystems (Killa 2021; Zamaya et al. 2021). Methods for determining wetland distribution are presented in:

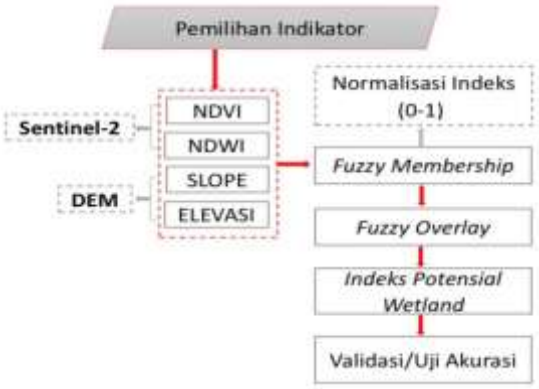


Fig. 1 Method for Determining the Distribution of Wetlands

Fuzzy Logic Analysis

Fuzzy logic analysis is used to classify wetland areas by considering spatial uncertainty related to hydrological dynamics and vegetation characteristics. This approach allows for a more realistic representation of environmental conditions than deterministic classification methods (Nugraha 2018; Lanya et al. 2019). The main variables used include the Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), elevation, and slope.

Sentinel-2 Level-2A images were obtained from the Copernicus Open Access Hub and processed to extract the relevant spectral bands, namely Band 3 (Green), Band 4 (Red), and Band 8 (Near-Infrared) (Ghorbanzadeh et al. 2020; Verhegghen et al. 2022). NDWI is used to detect the presence of surface water, while NDVI is used to assess vegetation cover. Digital Elevation Model (DEM) data is used to obtain land elevation and slope information.

Each variable was converted into a fuzzy membership value using the Fuzzy Small function, assuming that lower values better represent wetland conditions (Rahmawaty 2020; Adar et al. 2024). All fuzzy membership layers were then integrated using the fuzzy overlay method with an operator that produces the minimum value of each parameter, so that only areas that meet all criteria are classified as wetlands. (Rizaldi et al. 2022; Mahardika et al. 2023).

Fuzzy Analysis Procedure (ArcGIS)

The analysis stages using ArcMap are carried out as follows:

1. Collection of atmospherically corrected Sentinel-2 Level-2A imagery from the Copernicus Open Access Hub, then band extraction was performed:
   - Band 03 (Green)
   - Band 04 (Red)
   - Band 08 (Near-Infrared)
2. Spectral index calculation using Raster Calculator:
   - NDWI (Normalized Difference Water Index) is used to detect the presence of surface water.
   - NDVI (Normalized Difference Vegetation Index) is used to assess vegetation cover.
   - DEM (Digital Elevation Model) is used to obtain elevation and slope data.
3. Transform each parameter into a fuzzy membership function and integrate using fuzzy overlay.

Model Validation

Validation of the classification results was carried out through field surveys and accuracy tests using a confusion matrix (Feilhauer et al. 2020; Halabisky et al. 2023). This process was performed using the Combine Tool in ArcMap to compare the fuzzy classification results with field reference data.

Table 1 Confusion Matrix Categories

Category	Description
TP	True Positive – detected as a match and is indeed correct
TN	True Negative – detected as non-compliant and is indeed correct
FP	False Positive – detected as a match but actually does not match
FN	False Negative – not detected as a match but actually is a match

Table 2 Raster Merge Result Values

Ground Check	Fuzzy Results	Category	Amount
1	1	TP	721
1	0	FN	33,780
0	1	FP	306,915
0	0	TN	16,908,831

Classification accuracy was evaluated using overall accuracy (OA) and the kappa coefficient. Overall accuracy is calculated as:

$$OA = \frac{TP + TN}{TP + TN + FP + FN} \times 100 \quad (1)$$

Meanwhile, the kappa coefficient is used to measure the level of agreement between the classification results and the reference data after controlling for the possibility of random fit. The overall accuracy and kappa values in this study indicate the model's reliability in identifying wetland distribution.

Spatial Multi-Criteria Analysis (SMCA)

Land suitability evaluation was conducted using Spatial Multi-Criteria Analysis (SMCA) by integrating various biophysical and environmental parameters (Hassanzadeh et al. 2019). The analysis stages include determining objectives, selecting criteria, determining weights, and integrating them through spatial overlay.

Land Suitability Criteria

The criteria used include soil texture, soil pH, organic carbon content, annual rainfall, average temperature, slope, and flood hazard (Singha and Swain 2016; AbdelRahman et al. 2022; Suab et al. 2024).

Table 3 Land Suitability Analysis Criteria

No	Criteria	Unit	Influence
1	Soil texture	Qualitative	Positive
2	Soil pH	Scale	Positive
3	Organic Carbon	%	Positive
4	Rainfall	mm/year	Positive
5	Average temperature	°C	Positive
6	Slope	%	Negative
7	Flood hazard	Qualitative	Negative

Weighting Using AHP

The weight of each criterion is determined using the Analytical Hierarchy Process (AHP) method through pairwise comparison to capture the relative importance of each parameter based on expert assessment (Natsagdorj et al. 2020).

Table 4 Weighting of Land Suitability Indicators

Criteria	Weight (%)
Rainfall	20
Temperature	15
Soil pH	10
Soil texture	15
Slope	15
Organic C	10
Flooding hazard	15

The consistency of the comparison matrix is tested using the Consistency Ratio (CR), where a CR value < 0.10 indicates that the weights used are consistent and methodologically acceptable.

Land Suitability Calculation

The land suitability score is calculated using the weighted linear combination (WLC) method with the equation:

$$N = \sum_{i=1}^{n} (S_i \times B_i) \quad (2)$$

where: N is the land suitability score, Si is the standard score of each criterion, Bi is the criterion weight, and n is the number of criteria (Taufik et al. 2018; Nurkholis et al. 2020).

Land Suitability Classification and Output

The analysis results are classified into land suitability classes S1 (very suitable), S2 (moderately suitable), and S3 (marginally suitable) based on national land evaluation guidelines (Ritung et al. 2011; Molla et al. 2020; Ezz and Abdel-wahab 2025).

The analysis output is in the form of a land suitability map showing the spatial distribution of areas suitable for the development of taro, corn, leafy vegetables and cocoa commodities in wetland environments.

Results

Spatial Distribution of Wetlands

The results of a Geographic Information System (GIS)-based analysis that integrates the Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), elevation, and slope show that wetlands in Kalumpang District are spread across various land use categories, including production forests, limited production forests, protected forests, national park areas, convertible production forests, and other land use areas (Other Land Use/OLU). The analysis focused on wetlands located in OLU, production forests, and convertible production forests.

The total identified wetland area reached 809.25 ha and was spread across 12 villages (Table 5). The largest wetland area was in Tumonga Village (546.03 ha), followed by Sandapang Village (93.04 ha) and Kondobulo Village (45.93 ha), while the smallest area was in Lasa Village (1.18 ha) and Polio Village (2.05 ha). Field verification identified the dominant wetland type as freshwater swamp.

Table 5 Wetland distribution area in Kalumpang District.

Village	Area (Ha)
Batumacada	5.00
Kalumpang	24.18
Karama	25.43
Karataun	21.86
Kondobulo	45.93
Lasa	1.18
Limbong	19.07
Makkaliki	13.90
Polio	2.05
Sandapang	93.04
Siraun	11.57
Tumonga	546.03
Total	809.25

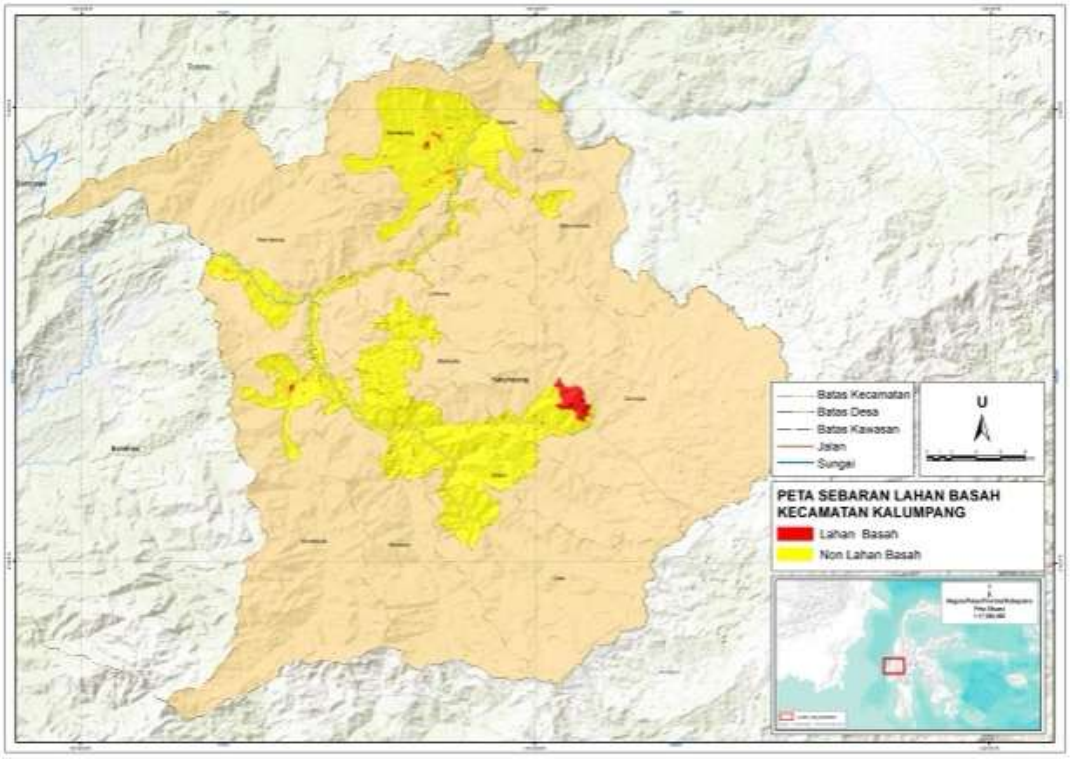


Fig. 2 Map of Wetland Distribution in Kalumpang District, Mamuju Regency

Utilization of Local Plants

The results of field observations and interviews show that wetlands are used for several agricultural and plantation commodities, including taro (*Colocasia esculenta*), corn (*Zea mays*), leafy vegetables (spinach), and cocoa (*Theobroma cacao*).

Biophysical Conditions of Land

The analysis results show that rainfall, temperature, slope, soil characteristics, and flood hazard vary across the study area. The average temperature ranges from 27–34 °C. The slope ranges from 16–30% in most areas. Soil texture ranges from fairly fine to fairly coarse with a relatively high organic carbon content. Most areas are classified as low flood hazard (F0).

Land Suitability for Taro Plants

The overlay analysis results show that land suitability for taro is dominated by class S2. The total land area in class S2 reached 640.25 ha, while class S3 reached 150.64 ha, and class S1 was 6.84 ha (Table 6). The distribution of land suitability varies between villages, with the largest area being in Tumonga Village.

Table 6 Actual Potential Land Suitability for Taro Plants across all villages in Kalumpang District

Village	N	S1	S2	S3	Total
Batumacada			3.28	1.71	4.98
Kalumpang		0.77	0.46	22.88	24.11
Karama	6.02	0.40	16.30	2.71	25.43
Karataun			12.53	9.32	21.85
Kondobulo			42.12	3.81	45.93
Lasa		0.12	1.06		1.18
Limbong		0.99	11.24	6.78	19.01
Makkaliki		2.12	10:32	1.46	13.90
Polio		1.84	0.22		2.05
Sandapang	4.82		42.49	45.72	93.04
Siraun		0.42	11.13		11.55
Tumonga		0.18	489.09	56.26	545.53
Total	10.84	6.84	640.25	150.64	808.57

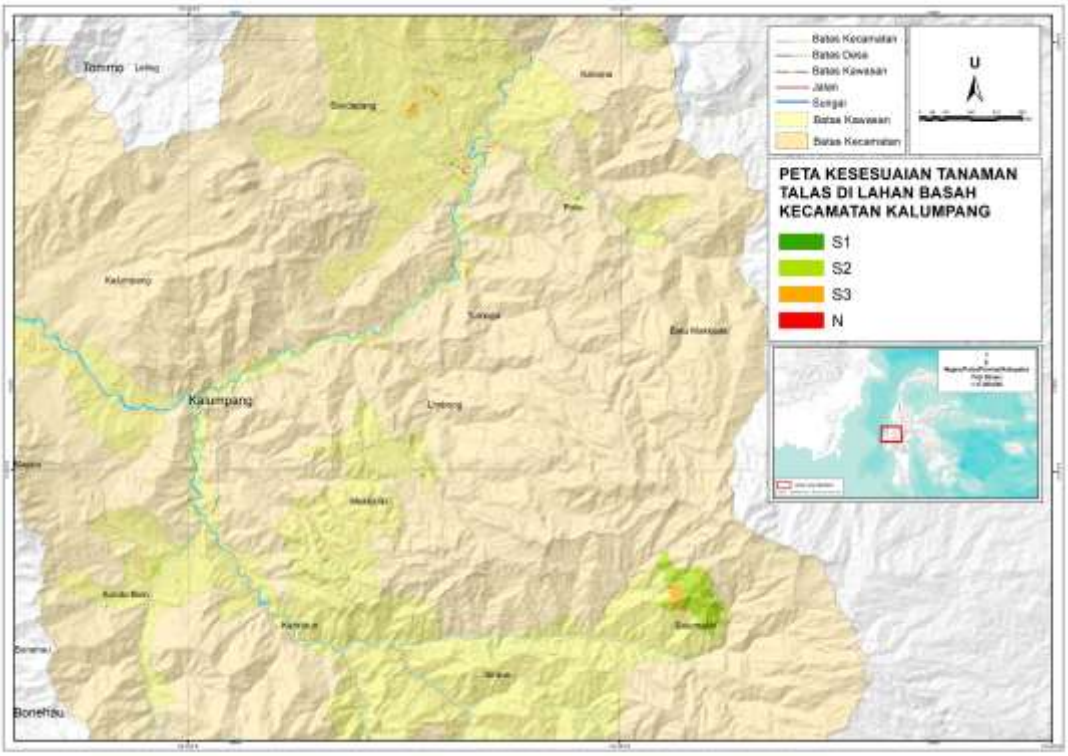


Fig. 3 Maps of Actual Potential of Taro Plants

Land Suitability for Corn Plants

Land suitability for corn is dominated by classes S1 and S2. The total land area in class S1 reaches 275.35 ha, class S2 reaches 415.51 ha, and class S3 is 104.81 ha (Table 7). The distribution of suitability classes shows variation between villages, with the largest concentration of land area in Tumonga Village.

Table 7 Actual Land Suitability Potential for Corn Plants in all villages in Kalumpang District

Village	N	S1	S2	S3	Total
Batumacada		2.91	0.57	1.51	4.98
Kalumpang		0.77	12.45	10.89	24.11
Karama	6.16	2.65	2.40	14.22	25.43
Karataun		1.36	20.49		21.85
Kondobulo		0.95	43.72	1.26	45.93
Lasa		0.80	0.38		1.18

Limbong		2.28	14.13	2.61	19.01
Makkaliki		6.20	7.70		13.90
Polio		1.93	0.12		2.05
Sandapang	6.74		14.72	71.58	93.04
Siraun		6.15	5.41		11.55
Tumonga		249.36	293.43	2.75	545.53
Total	12.90	275.35	415.51	104.81	808.57

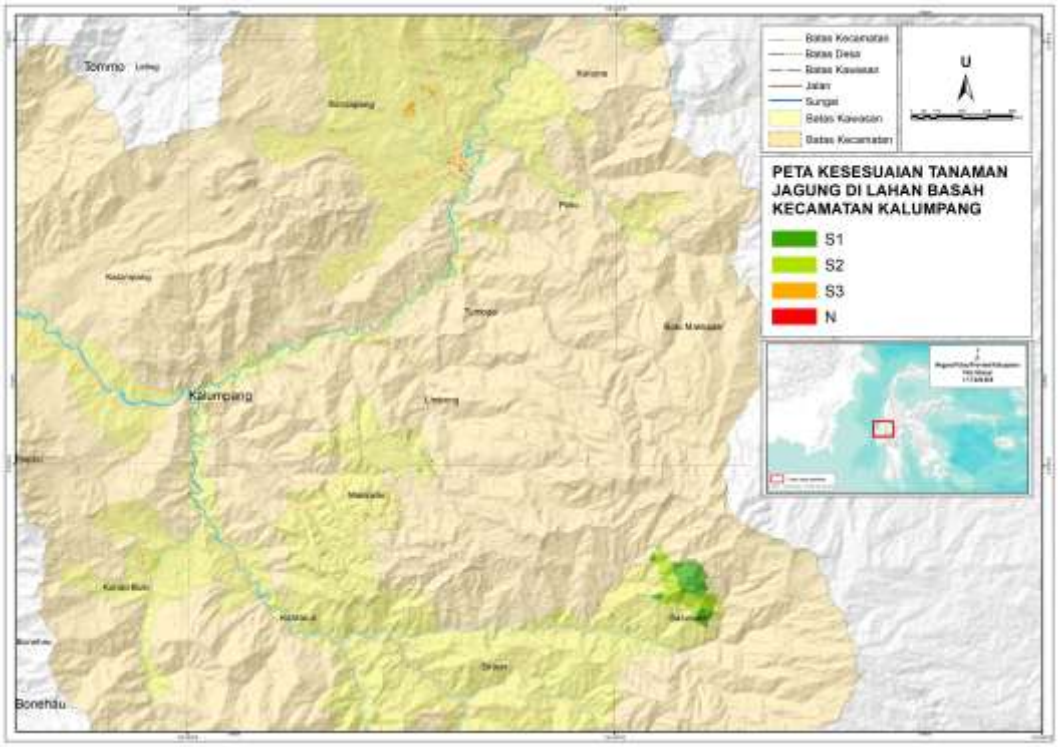


Fig. 4 Map of Actual Potential of Corn Plants

Land Suitability for Spinach Plants

The analysis results show that land suitability for spinach is dominated by class S1. The total land area in class S1 reached 272.92 ha, class S2 386.81 ha, and class S3 134.70 ha (Table 8). Land suitability is distributed throughout the village, with variations in area within each class.

Table 8. Actual Land Suitability Potential for Spinach Plants in all villages in Kalumpang District

Village	N	S1	S2	S3	Total
Batumacada		2.11	1.37	1.51	4.98
Kalumpang	0.12	0.16	11.11	12.71	24.11
Karama	7.28	2.65	2.40	13.09	25.43
Karataun		1.36	19.67	0.81	21.85
Kondobulo		0.02	16.28	29.64	45.93
Lasa		0.80	0.38		1.18
Limbong		2.28	14.13	2.61	19.01
Makkaliki		6.20	7.70		13.90
Polio		1.84	0.22		2.05
Sandapang	6.74		14.72	71.58	93.04
Siraun		6.15	5.41		11.55
Tumonga		249.36	293.43	2.75	545.53
Total	14.14	272.92	386.81	134.70	808.57

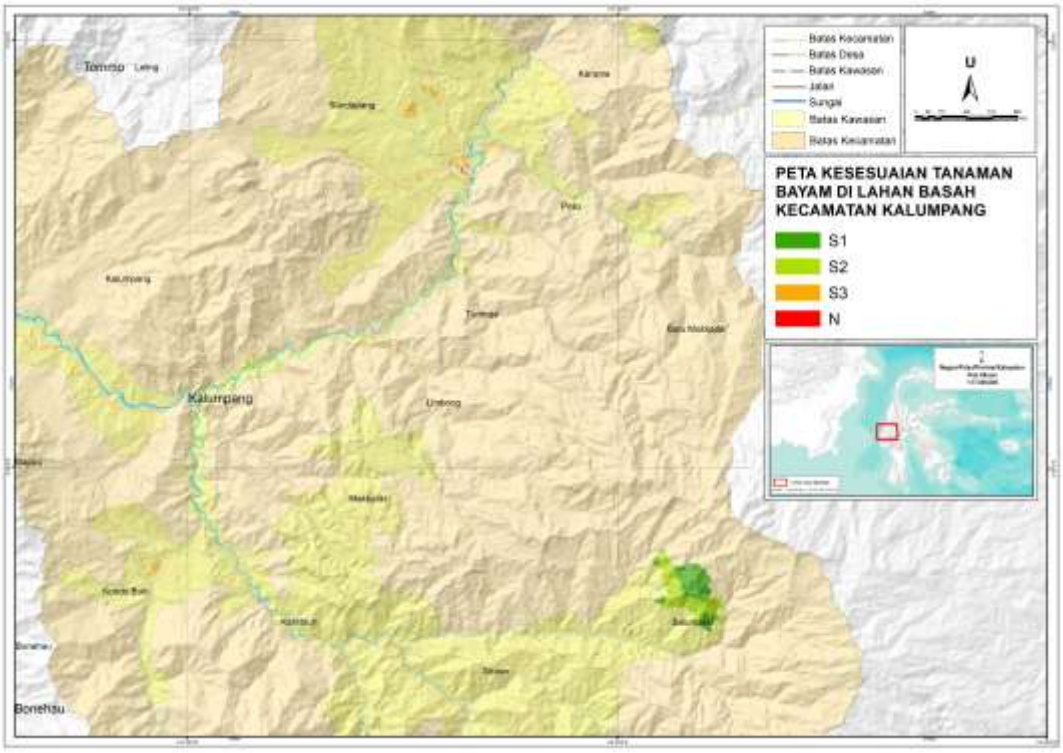


Fig. 5 Maps of Actual Potential of Spinach Plants

Land Suitability for Cocoa Plants

Land suitability for cocoa is dominated by class S2, with an area of 400.92 ha. Class S1 covers 292.96 ha, and class S3 covers 100.66 ha (Table 9). The distribution of land suitability varies between villages, with the largest concentration in Tumonga Village.

Table 9. Actual Potential Land Suitability for Cocoa Plants across all villages in Kalumpang District

Village	N	S1	S2	S3	Total
Batumacada		2.91	1.35	0.73	4.98
Kalumpang		0.77	12.37	10.97	24.11
Karama	7.28	3.17	2.26	12.72	25.43
Karataun		7.00	14.85		21.85
Kondobulo		2.65	42.02	1.26	45.93
Lasa		0.80	0.38		1.18
Limbong		5.06	11.70	2.25	19.01
Makkaliki		12.44	1.46		13.90
Polio		2.05			2.05
Sandapang	6.74	0.59	15.71	69.99	93.04
Siraun		6.17	5.38		11.55
Tumonga		249.36	293.43	2.75	545.53
Total	14.02	292.96	400.92	100.66	808.57

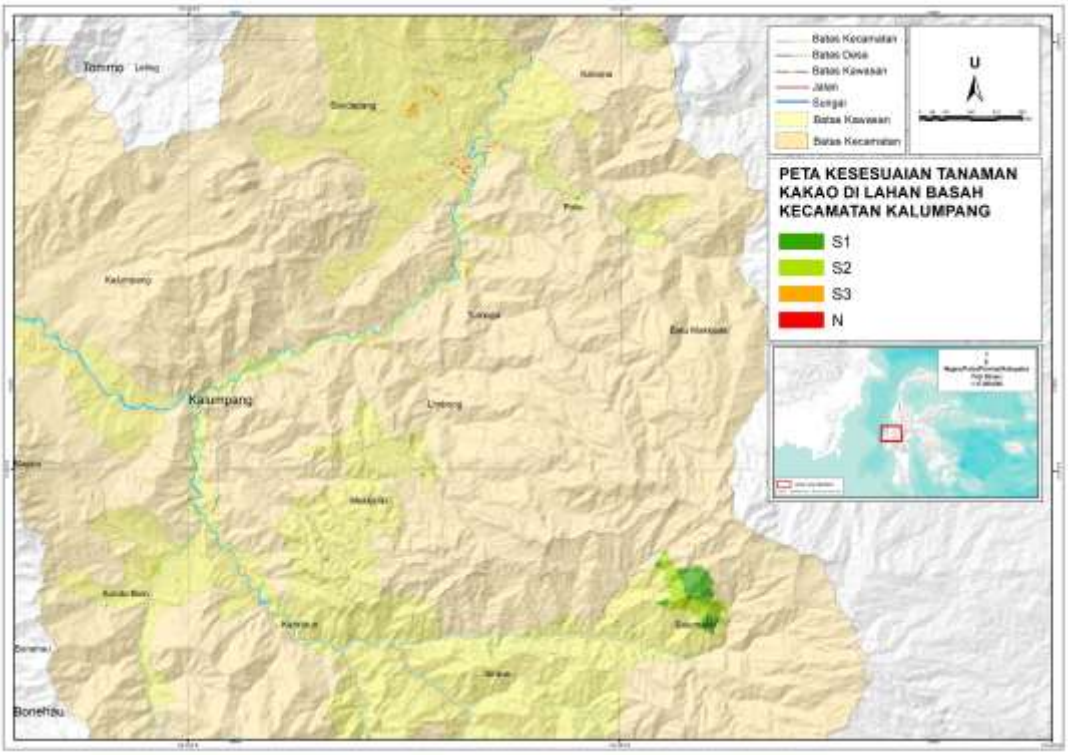


Fig. 6 Map of Actual Potential of Cocoa Plants

Wetland Agroforestry Zoning

The results of the integration of land suitability analysis and field data resulted in the division of the region into four zones based on hydrological gradients and elevation, namely the wetland core zone, buffer zone, transition zone, and highland zone.

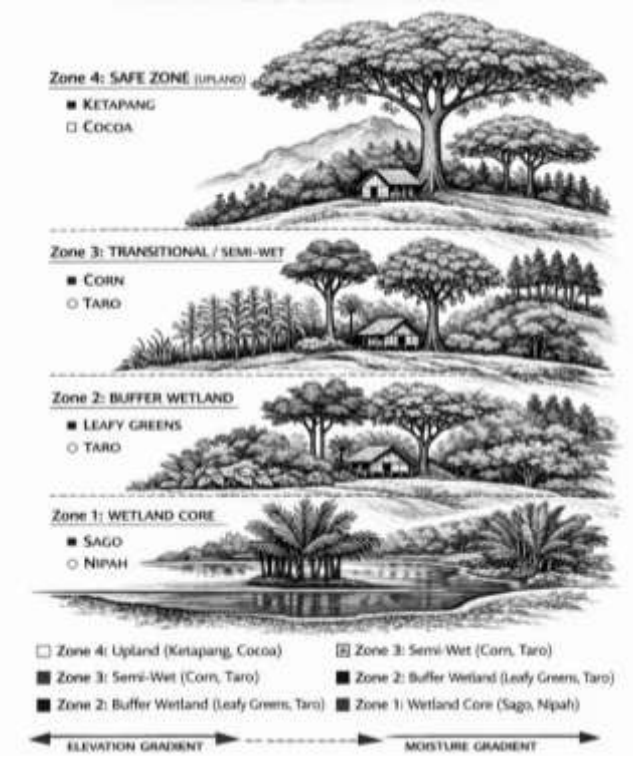


Fig. 7 Wetland Agroforestry Zoning

Discussion

Integration of Spatial Methods in Revealing Wetland Dynamics

The results of this study indicate that the integration of Geographic Information Systems (GIS) with NDVI, NDWI, and topographic parameters is able to identify the spatial distribution of wetlands with a high level of detail. This finding is consistent with previous studies showing that the combination of spectral indices and biophysical variables is effective in representing hydrological characteristics in wetland landscapes (Nugraha 2018; Lanya et al. 2019; Ghorbanzadeh et al. 2020).

However, compared with conventional deterministic classification-based approaches, the results of this study indicate that the application of fuzzy logic provides greater flexibility in capturing spatial uncertainty, particularly in transition areas between wetlands and non-wetlands. This finding extends the results of previous studies, which generally used a binary classification approach, making it less able to represent continuous environmental gradient conditions (Feilhauer et al. 2020; Zarei et al. 2021).

Thus, the integration of GIS–fuzzy–SMCA in this study is not only applicable, but also provides a methodological contribution in developing a more adaptive land suitability evaluation approach to the complexity of tropical wetland ecosystems.

The Ecological Role of Wetlands in Sustainable Food Systems

The dominance of freshwater swamp-type wetlands identified indicates that the study area serves important ecological functions, particularly in hydrological regulation and carbon storage. This finding aligns with global literature that places wetlands as a key component in maintaining ecosystem stability and supporting ecosystem services that contribute to food systems (Davidson et al. 2018; Gardner and Finlayson 2018).

In the context of the relationship between ecosystems and food production, the results of this study support the concept of the water–food–ecosystem nexus which emphasizes that the sustainability of food production is highly dependent on the integrity of ecological functions (Gordon et al. 2010). However, unlike some studies that emphasize wetland exploitation through production intensification, the results of this study indicate that a zoning-based approach and agroforestry integration are more appropriate in maintaining a balance between production and conservation (Tan et al. 2020; Atapattu et al. 2024).

Local Adaptation and Diversification in Response to Environmental Variability

Land use patterns among local communities indicate that the selection of commodities such as taro, corn, and leafy vegetables represents an adaptation to the biophysical conditions of wetlands. This finding is consistent with previous research showing that local knowledge plays a crucial role in determining land use strategies in dynamic environments (Nadeem et al. 2021; Adebo 2023).

However, the results of this study also show that the distribution of land suitability does not fully align with actual practices on the ground. This discrepancy indicates a gap between farmer preferences and the biophysical potential of the land, which has rarely been addressed in previous studies. In this context, a spatial-based approach such as the one used in this study can provide additional information to support evidence-based decision-making.

In addition, the identified commodity diversification shows consistency with global findings that agroforestry and mixed farming systems can increase production stability and household economic resilience (Plieninger et al. 2020; Khatun and Palit 2023). The integration of various commodities is also related to efficient resource utilization and increased resilience to environmental stress (Vira et al. 2015; Muchane et al. 2020).

Biophysical Limitations and the Role of Multi-Criteria Approaches

The results of the study indicate that rainfall and slope are the main limiting factors in land suitability. This confirms that land suitability is multidimensional and cannot be explained by a single parameter. This finding is consistent with land evaluation studies that emphasize the importance of a multi-criteria approach to integrating various biophysical factors (Hassanzadeh et al. 2019).

However, it should be noted that the SMCA approach used in this study relies heavily on the determination of criteria weights through AHP, which is inherently subjective. This indicates conceptual limitations in the model used, particularly in representing the complexity of interactions between environmental variables. Furthermore, the use of spatial data at a specific resolution can also affect the level of detail in the analysis results.

Nevertheless, findings regarding high organic carbon content and low flood risk indicate that the biophysical conditions of the study area have relevant characteristics for the development of

agroforestry systems (Trettin et al. 2020; Novia 2021).

Land Suitability Zoning as an Adaptive Approach

Differences in land suitability levels between commodities indicate that a zoning-based approach provides a more systematic framework for land management than a uniform approach. The results showed that corn and leafy vegetables had a broader distribution of suitability, while taro and cocoa showed a more specific distribution.

This finding is in line with the concept of landscape-based agroforestry which emphasizes the importance of space allocation based on biophysical characteristics (Hassanzadeh et al. 2019). However, unlike several previous studies that only stopped at land suitability mapping, this study developed a zoning model that links land suitability to hydrological gradients.

This approach provides a conceptual contribution to the development of wetland-based agroforestry systems, particularly in the context of tropical landscapes with high environmental variability.

Agroforestry Zoning Model as a Methodological Contribution

The resulting agroforestry zoning model shows that commodity distribution can be adjusted according to hydrological and elevation gradients. The wetland core zone, buffer zone, transition zone, and upland zone exhibit distinct characteristics in terms of land suitability.

Unlike conventional approaches, which tend to be static, the zoning model in this study is dynamic because it takes into account spatial variations in environmental conditions. This strengthens the argument that integrating spatial approaches with agroforestry can reduce the trade-off between food production and ecosystem conservation (Tan et al. 2020; Zarei et al. 2021).

Thus, the main contribution of this research is not only on the empirical aspect, but also on the development of a methodological framework that links land suitability analysis with the implementation of zoning-based agroforestry.

Implications for Spatial-Based Planning

The findings of this study indicate that wetlands have the potential to be developed into food production systems integrated with ecological functions. However, implementing this approach requires the integration of spatial information, biophysical conditions, and local practices.

In contrast to general policy approaches, the results of this study provide a more specific spatial basis for land-use planning. In this context, wetland management requires considering the balance between utilization and conservation, particularly by avoiding intensive drainage practices that could potentially damage the ecosystem (Evers et al. 2016; Das 2025).

In addition, the successful implementation of agroforestry systems also depends on institutional factors and community capacity, which are important aspects in developing sustainable agricultural systems (Doherty et al. 2019).

Research Limitations

This study has several limitations that require consideration in interpreting the results and developing further research. The approach used in this study is based on static spatial data (cross-sectional), so it is unable to capture the temporal dynamics of wetland ecosystems, particularly seasonal variations in hydrological conditions. Temporal variability in rainfall and groundwater level fluctuations have the potential to influence wetland distribution and land suitability, but have not been fully accommodated in the model used.

The use of fuzzy logic and Spatial Multi-Criteria Analysis (SMCA) methods relies heavily on parameter selection and criterion weighting. Although the weighting was performed using the Analytical Hierarchy Process (AHP) approach, this process still contains elements of subjectivity that can influence the evaluation results. Furthermore, this approach has the potential to result in uncertainty propagation, where uncertainty in each input parameter can accumulate in the final land suitability modeling results.

The spatial data resolution used, particularly Sentinel-2 imagery and Digital Elevation Models (DEMs), is limited in capturing micro-topographic variations and small-scale hydrological conditions. This limitation can introduce spatial bias, particularly in areas with high heterogeneity, thus affecting the accuracy of wetland boundary delineation.

Model validation was conducted through field surveys with limited spatial coverage. This could potentially result in the validation results not fully representing the full range of land conditions in the study area, particularly in areas that are difficult to access, which could impact the reliability of the classification results.

This research places more emphasis on the biophysical aspects of land suitability, so it has not comprehensively integrated socio-economic factors, such as market access, farmer preferences, and institutional capacity, which also play a role in the implementation of agroforestry systems at the local level.

Despite these limitations, the approach used in this study still provides a systematic and integrated spatial analysis framework for evaluating wetland-based land suitability. Therefore, future research is recommended to develop a more comprehensive approach by integrating multi-seasonal temporal data, higher spatial resolution, and socio-economic analysis to improve the model's accuracy and applicability in sustainable agroforestry planning.

Conclusion

This study shows that wetlands in Kalumpang District have significant spatial potential for the development of land-suitability-based agroforestry systems to support sustainable food production. The integration of Geographic Information Systems (GIS), fuzzy logic, and Spatial Multi-Criteria Analysis (SMCA) enables explicit, multi-parameter identification of wetland distribution and land suitability evaluation.

The analysis indicates that land suitability is heterogeneous and location-specific, with variations in distribution across different commodities spatially. This pattern underscores the importance of a zoning-based approach over a uniform land-use approach in the context of wetland landscapes.

The main contribution of this research lies in the development of a methodological framework that integrates fuzzy logic and SMCA within a GIS environment to generate land suitability evaluations that adapt to the biophysical dynamics of wetlands. Furthermore, this study proposes a hydrological gradient-based agroforestry zoning model that links land suitability evaluation results to spatial commodity allocation.

These findings broaden the generally deterministic approach to land evaluation to be more contextual and uncertainty-based, and provide an analytical basis for the development of agroforestry systems in tropical wetland landscapes.

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Data availability. The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request

Authors' contribution: All authors reviewed the manuscript. WUA provided the map and the corresponding author, MAL, for the final inspection of the manuscript and the second corresponding author

Ethics declarations

Declarations

The authors declare no competing interests.

Conflict of interest

No potential conflict of interest was reported by the author(s).

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