Oil palm suitability assessment in the northern region of Sarawak using Geographic Information System and Fuzzy Analytic Hierarchy Process approach

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Abstract**—**Oil palm plantation in Malaysia has been developed on a vast scale due to the tremendous need for crude palm oil. However, the accelerated development of oil palm plantations produced predicaments, such as monoculture cultivation, water quality deterioration, and loss of creatures' habitats to Malaysia, including Sarawak. The Sarawak government has appointed 2 million hectares of state's land for oil palm plantation, of which 1.2 million hectares have already been established. However, oil palm suitability assessment is lacking in Sarawak. Hence, it is important to assess oil palm plantation's suitability in an area with the likelihood of further expanding for oil palm plantation in Sarawak. The suitability assessment is aimed to promote the oil palm industry's sustainability. The research aims to conduct a land-use suitability assessment in a region with established oil palm plantations around Kabuloh, Miri, the Sarawak's Northern Region. A Geographic Information System was implemented to evaluate the suitability of oil palm cultivation in the study area. The assessment result showed that 78% of the study area is suitable for oil palm plantations. The developed oil palm suitability map could be utilized as a decision support tool to develop comprehensive planning for future oil palm expansion.

Keywords**—**oil palm, Geographic Information System, suitability assessment, sustainability, Sarawak

I. Introduction

The demand for palm oil is continuously rising due to growing food and biofuel demand [1]. The oil palm industry in Malaysia has also brought many benefits to the country. For instance, the oil palm is the major contributor to the agriculture sector's Gross Domestic Product (GDP) at 37.7% in 2019 [2]. Sarawak is one of the states that undergo massive plantation development. The state government has appointed 3 million hectares out of the 12.4 million hectares of the state's land for agricultural land-use [3]. A portion of Sarawak's primary forest had been converted into agricultural plantations [4]. Consequently, palm oil's development might transform the forest into a plantation area to fulfil the rising demand for palm oil [5]. In 2018, the oil palm trees occupied 1.56 million hectares of Sarawak land, equal to 27% of Malaysia's total planted area [6].

The rapid expansion of oil palm plantations has caused several problems. For example, the tropical forest is cleared and used intensively for the monoculture oil palm plantation. Monoculture plantation negatively impacts biodiversity by removing the habitats for various flora and fauna [7]. Moreover, oil palm plantation has expanded onto unsuitable areas such as peatland due to the limited availability of suitable areas, especially in Sarawak's northern region [8]. In Sarawak, 300,000 hectares of peatland has been converted to oil palm plantations in 2008 [9]. Therefore, sustainable agricultural land-use planning should be implemented to rectify the impacts of intensive oil palm cultivation. It is very significant to conduct land-use planning for sustainable oil palm expansion, which will benefit an economic return in the long term [10].

Land-use suitability assessment is a vital component of land-use planning. For this reason, the evaluation of the suitability of oil palm cultivation is necessary for sustainable development. Land-use suitability assessment is an approach to determine land potential over time based on specific land-use types, such as agricultural, urban, and environmental planning [11]. Stakeholders can implement the land-use suitability assessment to determine the land's potentials and limitations [12]. The land-use suitability assessment depends on the applicable criteria [13]. Various criteria should be considered to ensure the land is developed without deterioration [14]. Land characteristics and stakeholders' needs are the key applicable criteria in the analysis of land-use suitability assessment [15]. Land characteristics are affected by the physical environment, such as topography, soil, hydrology, and climate [16]. The involvement of multiple criteria with considering different weightage based on the degree of impact on the land's suitability is important in the analysis process [17]. The complicated relationship between the criteria causes difficulties to assess the land-use suitability precisely. The Geographic Information Systems (GIS) and integration of multiple criteria decision-making methods (MCDM) are the tools used to study the complicated relationship between the land criteria used in land-use suitability assessment [18]. The MCDM decision rule assists in the manipulation of various land criteria based on the relative importance of criteria to establish a relationship between them [19]. The relationship between the criteria will later be applied in production of land-use suitability map in GIS software.

This project is sponsored by the Sarawak Multimedia Authority (SMA) and Sarawak Digital Economy Corporation (SDEC) Berhad under the Sarawak State Government.

Since the Sarawak government plans to expand oil palm plantations [3], oil palm cultivation's suitability assessment is required for future expansion to ensure oil palm plantation sustainability. The objective of the research is to assess the suitability of oil palm cultivation in the Kabuloh region. The assessment was conducted using the GIS analysis tool with the integration of the MCDM approach. Consequently, the spatial analysis result provides information to achieve sustainable oil palm industry development and assists decision-makers in developing a strategic plan for the oil palm sector's future development.

II. Study Location

The study focused on Kabuloh and its surrounding area, between latitudes of 4° 3' N to 4° 10' N and longitudes of 113° 51' E to 114° 4' E. The study area covers approximately 28249 hectares of land that comprises 26 villages. In the study area, the elevation varies between 0 m and 197 m, and the slope gradient is between 0% and 38%. A high proportion of flatland, with poorly drained swamps, is located in the eastern zone, which has low altitude. The remaining part of the study area is covered by alluvium and red-yellow podzolic soil.

III. Methodology

The procedure of developing an oil palm suitability map is shown in Fig. 1. An area with active oil palm plantations was determined as the study area. Then, the applicable criteria of oil palm suitability assessment were determined. Subsequently, the weight of criteria was determined and followed by standardization of the criteria. Lastly, a weighted sum overlay analysis was conducted to develop the oil palm suitability map.

A. *Criteria Considered in the Oil Palm Suitability Assessment*

The criteria of Great Soil Group (GSG), agricultural land-use capability class (ALUCC), slope, and proximity to rivers and roads were chosen to assess the land's suitability for oil palm cultivation. These assessment criteria were determined depending on the literature review and secondary data availability in the study location. These criteria were later extracted from the spatial data. These spatial data were soil map, major agriculture commodities map, agricultural land-use capability map, river system map, and existing land cover map. Spatial data were mainly sourced from different local authorities: the Department of Agriculture Sarawak and the Department of Survey and Mapping Malaysia. A topography map in the study area was collected from the USGS EarthExplorer [20]. The criteria applied in the study are described as follows.

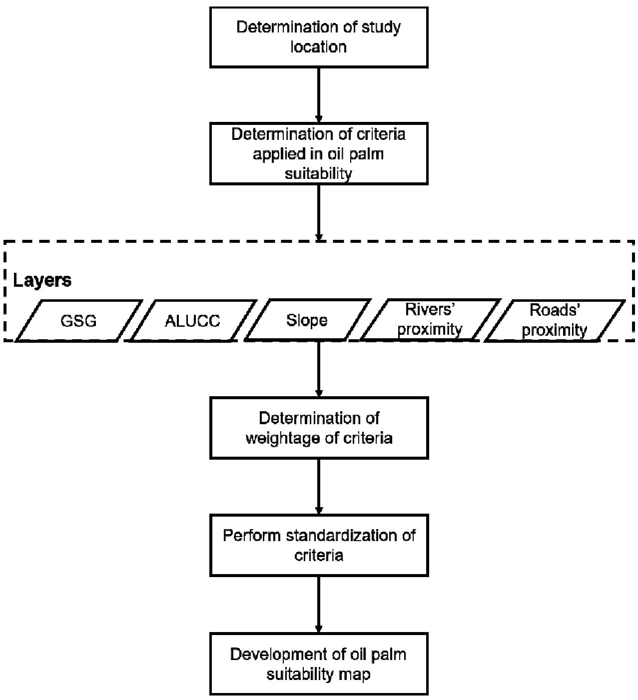

Fig. 1. Procedure of developing oil palm suitability map

1) *Great Soil Group*

Different soil types were classified to determine the soils' characteristics and behaviours. By knowing the characteristics of the soils, the soil performance was estimated for oil palm activities. The soil types are alluvial, red-yellow podzolic, gley, organic, podzol and arenaceous soil.

2) *Agricultural Land-use Capability Class*

The agricultural land-use capability classifies a particular soil's adequacy to cultivate different crops except those requiring particular administration [21]. Soils are classified into seven ALUCCs based on different factors. The factors considered are the limitations of the soils bringing to the crops, the risk of conducting agricultural activities on the soils and the ease of mechanization [22].

3) *Slope*

The land's slope varies based on the topography of land [23]. The slope gradient is a critical component of erosion control [24]. Additionally, the slope gradient negatively affects the soil properties and indirectly restricts crops' growth [23].

4) *Proximity to Rivers*

The river is essential to supply water for crop growth. Lack of sufficient water supply due to high evapotranspiration is a vital issue to the growth of crops. This issue can be resolved by irrigation [25]. However, there should be a buffer zone between the planting area and river to protect the riparian ecosystem from adverse environmental impacts [26].

5) *Proximity to Roads*

Crops should be planted near to road network to minimize transportation and other relevant costs. However, crops located at a certain distance away from roads are recommended to lower the traffic impact and allow for future road expansion [27].

B. *Determination of Weightage of Criteria*

The weightage assigned to each criterion will give a different result of land-use suitability analysis. Weightage value between 0 to 1 was inputted to each raster layer before overlay analysis is processed [28].

The weightage of each criterion is obtained through the Fuzzy Analytic Hierarchy Process (FAHP). The FAHP approach examines the weightage of various criteria by incorporating triangular fuzzy numbers (TFNs) [29]. The TFNs are applied for fuzzification of the pairwise comparison matrix. FAHP could compensate a portion of the assessment's vagueness when conducting multi-criteria analysis [30]. The Fuzzy logic method behind FAHP could achieve higher predictive accuracy [31]. Jamil *et al.* [32] conducted land suitability assessment for sugarcane cultivation in Bijnor district, India, using FAHP as the method to determine criteria weightage. Özkan *et al.* [33] implemented a similar approach to produce a suitability map for rice cultivation at Fener Village, Turkey.

The FAHP method and the geometric mean method were implemented to calculate the weightage of the criteria. A pairwise comparison matrix has been formed incorporated with the TFNs, as shown in TABLE I. The weightage of criteria was shown in TABLE II with the maximum eigenvalue (λ_{max}), consistency index (CI), random index (RI), and consistency ratio (CR).

With reference to TABLE II, the great soil group was given the highest weightage; meanwhile, the distance to infrastructure was given the lowest weightage. In short, the oil palm suitability was significantly affected by the Great soil group, and the distance to infrastructure will induce a smaller impact on the overall suitability assessment.

C. Standardization of Criteria

Standardization is the process to convert the assessment criteria of different extent and units into a standard range [34]. The assessment criteria were standardized through fuzzification using fuzzy linear membership functions (1).

The score of each sub-criteria was tabulated in TABLE III. The sub-criteria of the great soil group and the agricultural land-use capability class were scored in the range of 0-1 according to the scoring given in reference [35].

1) Fuzzification of Criteria

Fuzzification is the approach of modifying the assessment criteria into fuzzy membership values based on fuzzy membership functions. The output of the fuzzification process is commensurate values in the extent between 0 and 1. The boundary condition of each criterion to delineate the agricultural land-use suitability was tabulated in TABLE IV according to reference [21], [27], [36].

2) Fuzzy Linear Membership

Fuzzy linear membership alters the input criteria by allocating a membership value to every pixel through a fuzzy linear membership function. Membership values are fixed between 0 to 1. Value of 0 means no membership of the specified fuzzy set, while 1 implies full membership in the altered layer. The membership function was determined as below:

$$\mu(X) = \begin{cases} 0, & x \leq a \\ \frac{x-a}{b-a}, & a < x < b \\ 1, & x \geq b \end{cases} \tag{1}$$

where $\mu(X)$ is the membership value, a is the low bound, b is the high bound, and x is an intermediate value between a and b [37].

D. Oil Palm Suitability Map

After the criteria weights were assigned to each criterion layer in the Quantum GIS (QGIS) environment, an oil palm suitability map was produced through the weighted sum overlay analysis. The map was classified into five suitability classes of equal range according to the Food and Agriculture Organization (FAO) Framework's land suitability classification [16]. FAO Framework is a universal and scale-independent evaluation system to determine land suitability for specific use [38].

IV. Results and Discussions

A. Oil Palm Suitability

1) Highly Suitable

The oil palm suitability map with a resolution of 90

TABLE I. FUZZIFIED PAIR-WISE COMPARISON MATRIX OF CRITERIA

Criteria	Great soil group	Agricultur-al land use capability class	Slope	Proxi-mity to roads	Proxi-mity to rivers
Great soil group	1	(1, 2, 3)	(1, 2, 3)	(7, 8, 9)	(7, 8, 9)
Agricultural land use capability class	(1/3, 1/2, 1)	1	(2, 3, 4)	(5, 6, 7)	(5, 6, 7)
Slope	(1/3, 1/2, 1)	(1/4, 1/3, 1/2)	1	(3, 4, 5)	(3, 4, 5)
Proximity to roads	(1/9, 1/8, 1/7)	(1/7, 1/6, 1/5)	(1/5, 1/4, 1/3)	1	1
Proximity to rivers	(1/9, 1/8, 1/7)	(1/7, 1/6, 1/5)	(1/5, 1/4, 1/3)	1	1

TABLE II. WEIGHT OF CRITERIA

Criteria	Weight
Great soil group	0.423
Agricultural land use capability class	0.31
Slope	0.17
Proximity to roads	0.049
Proximity to rivers	0.049

λ_{MAX} = 5.102; CI = 0.026; RI = 1.11; CR = 0.023 $<$ 0.10

TABLE III. SCORE OF SUB-CRITERIA [20]

Great Soil Group	Score
Alluvial	1
Red-yellow Podzolic	0.7
Gley	0.5
Organic	0.4
Podzol	0.2
Arenaceous	0.1
Agricultural land use capability class	**Score**
Class 2	1
Class 3	0.8
Class 4	0.6
Class O4	0.4
Class 5	0.1
ClassO5	0.1

TABLE IV. BOUNDARY CONDITION OF CRTIERIA FOR DELINEATING OIL PALM SUITABILITY

Criteria	Low Fuzzy Membership Bound	High Fuzzy Membership Bound	Researcher
Great soil group	Arenaceous	Alluvial	[20]
Agricultural land use capability class	Class O5	Class 2	
Slope	25%	0%	
Proximity to roads	0m	50m	[27]
Proximity to rivers	0m	200m	[36]

m/pixel is presented in Fig. 2. The figure shows the distribution of oil palm suitability in the study area. As indicated in blue color in Fig. 2, approximately 6% (1,687 hectares) of the study area was categorized into the class "Highly suitable" for oil palm growth. The land classified into this class has alluvial soil, class 2 agricultural land-use capability, and gentle slope gradient (<8%). The area is also located close to the river and road.

2) Moderately Suitable

About 28% (8,092 hectares) of the study area was classified as moderately suitable land for oil palm cultivation, as indicated in green color in Fig. 2. The land classified into this class has alluvial soil and red-yellow podzolic soil that distributed evenly. The land has class 3 and class 4 agricultural capability. The land also has close proximity to the road and river. The land is found to have a moderate slope gradient (12%-20%), but mechanized farming is possible at this slope gradient [39].

3) Marginally Suitable

There was 43% (12,215 hectares) of the study area categorized as marginally suitable for oil palm growth, as indicated in yellow color in Fig. 2. The soil types found at this zone are gley soil, red-yellow podzolic soil, and arenaceous soil. The land in this category mostly has a moderate slope gradient (12%-24%). The land is near to rivers but far from trunk roads.

4) Currently Not Suitable

21% of the land (6,093 hectares) was classified as currently not suitable for oil palm cultivation, as indicated in orange color in Fig. 2. In this area, the soil type is mostly organic soil, and a minority is red-yellow podzolic soil and podzol. The organic soil (peat soil) is not suitable for cultivating oil palm [35]. Both gentle and steep slope gradient (0%-30%) can be found in this area. The land is located far from both rivers and trunk roads.

5) Permanently Not Suitable

It was identified that less than 1% (162 hectares) of the land were grouped as permanently not suitable for the growth of oil palm, as indicated in red color in Fig. 2. The type of soil found in the area is podzol. Both moderate and steep slope gradient is found in this area. A steep slope gradient (>25%) will cause severe erosion, which made this land not suitable for crop cultivation [24]. The land is located far from rivers and trunk roads.

Above all, a high proportion of land in Kabuloh and its surrounding area is suitable for oil palm cultivation. Seventy-eight percent of the land is ideal for growing oil palm. The land has gentle to moderate slope characteristics, favorable agricultural land-use capability, suitable soil type and located around the rivers and roads. By contrast, 22% of the land is unsuitable for oil palm cultivation. For instance, the land is having problematic soil type, such as deep peat soil (peat depth > 0.5m) that is not suitable for plantation if no further land improvement is conducted [35]. Another limitation of oil palm growth is the steep slope, which will cause severe soil erosion [24]. In short, oil palm cultivation is encouraged in a suitable area to ensure sustainable palm oil production and meet the rising palm oil demand with limited land resources.

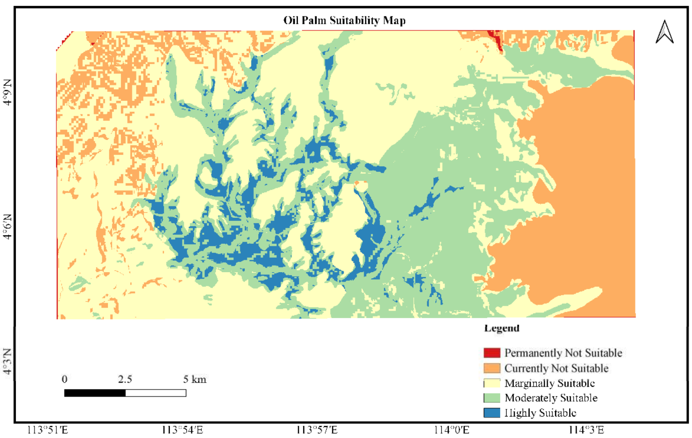

Fig. 2. Oil palm suitability map

V. Conclusion

The oil palm cultivation suitability is recommended to be conducted before future expansion to ensure oil palm plantation sustainability. Oil palm suitability assessment was conducted using GIS in the presence of multiple criteria, such as great soil group, agricultural land-use capability, slope, rivers' proximity, and roads' proximity. It was found that 78% of the land in Kabuloh and its surrounding area is suitable for oil palm cultivation. The major shortcoming of the unsuitable land is the slope, which will induce severe soil erosion. The unsuitable land also has deep peat soil, which will negatively impact oil palm growth if the land improvement is not performed before establishing plantation. The suitability map of oil palm cultivation could assist the government to develop a strategic plan for oil palm expansion and achieve sustainable agricultural development. The oil palm suitability map is recommended to be implemented as one of the decision support tools when planning for future oil palm expansion in Sarawak.

Acknowledgment

This research was supported by the Sarawak Multimedia Authority (SMA) and Sarawak Digital Economy Corporation (SDEC) Berhad under the Sarawak State Government. The authors wish to acknowledge Ms. Shariah Binti Umar from the Department of Agriculture Sarawak for providing kind support and assistance throughout our research.

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