Department of Civil and Construction Engineering

Faculty of Engineering and Science

Digitizing the Map of Agricultural Plantation Areas in a Southern Region of Miri for Sustainable Agricultural Land Use Planning

Erik Ngoi Yiew Tuang

0000-0003-1767-1778

This thesis is presented for the Degree of

Master of Philosophy

of

Curtin University

August 2021

Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature:

Date: 24th August 2021

Acknowledgements

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

I wish to express my appreciation to my principal supervisor, Dr Tay Ai Chen, for her assistance at every stage of the study period and her patience and motivation to guide me when the road was tough.

Besides, I would like to extend my sincere thanks to the thesis committee members, A/Prof Dr Tony Hadibarata, Ir Dr Vera Loo Hui, and Ir Dr Sung Aun Naa, for their constructive comments and suggestions.

Furthermore, I am deeply grateful to my parents, who have been supportive throughout the study period.

I am also thankful to GOD for providing me with the grace and wisdom to complete this journey.

My sincere thanks also go to Ms Shariah Binti Umar and Mr Frankie Lanying from the Department of Agriculture Sarawak for assisting with the research.

I would like to give my special regards to the Faculty of Engineering and Science and Curtin Malaysia Graduate School for their administrative support throughout the study period.

Abstract

Agricultural land use in Malaysia is expanding massively due to the high demand for agricultural products. However, the rapid expansion of agricultural land use brings challenges, such Malaysia, including Sarawak. Sarawak government assigned 3 million hectares of the state's land for agricultural land use. Currently, sustainable agricultural land use planning is lacking in Sarawak. Hence, it is imperative to assess the suitability of agricultural land use in an area with active agricultural activities in Sarawak, determine the potential impact of existing agricultural activities, and provide recommendations for future agricultural land use.

A study was conducted in an area with active agricultural activity in a southern region of Miri, namely Kabuloh. The agricultural land use suitability in the Kabuloh region and surrounding area was assessed using a Geographic Information System combined with the Fuzzy Analytic Hierarchy Process (FAHP). The weightage of each criterion was determined by the FAHP method before the agricultural land use suitability was conducted in the GIS environment. Then, the suitability map was overlaid with the existing land cover to determine the current condition of agricultural land use. Next, the landscape features were overlaid with the existing land cover to determine the potential threats of existing agricultural land use. After that, mitigation strategies were determined to rectify the potential threats. Finally, a future agricultural land use plan was produced to enhance the sustainability of agricultural land use in the study location.

According to the agricultural land use suitability map, 5% of the area is highly suitable, followed by moderately suitable (42%) and marginally suitable (33%) for agricultural land use. In addition, 19% and 1% of the study area constitutes currently and permanently not suitable areas for agricultural land use, respectively. The unsuitable area has either a steep slope or unsuitable soil characteristics for cultivation. The overlay of the suitability map and existing land cover suggests that a portion of the existing oil palm plantation is developed in the unsuitable zone. Hence, the oil palm plantation's potential threats were determined by spatially overlaying the plantation layer on the landscape features. A portion of the plantation was found to be established by deforestation and peatland conversion. Additionally, the oil palm plantation is developed in two water catchment areas. Several rivers are found to flow through the existing plantation area. Besides, the establishment of the oil palm plantations could negatively impact the survival of protected flora and fauna in the study location due to habitat loss.

Moreover, there are several villages located in the study location. All villages are located near (<10km) the oil palm plantation. The villagers could be experiencing different socio-economic impacts depending on their social groups, such as plantation workers and smallholders. Potential socio-economic impacts experienced by these social groups were discussed based on the outcome of past studies. For example, the plantation workers and smallholders could generate more income in various ways. The workers can receive several types of allowance from the company. Moreover, the children of plantation workers could access better education.

On the other hand, the plantation workers' family could experience higher daily expenses when they need to buy more food from the market after the forest was converted into an oil palm plantation. In addition, the smallholders could face higher instability of livelihood due to market price high volatility.

After the analysis of potential impacts, several conservation strategies were proposed to rectify the potential negative consequences. The recommended conservation strategies were conservation of forest and peatland, improved fertilizer and hydrological practices, promotion of structural diversity and complexity in the plantation, and agroforestry zone establishment around the plantation. Three economic crops, sago, paddy, and coconut, were recommended to promote crop diversity in the study location. The suitability assessment of these economic crops was conducted and visualized in three different suitability maps. Lastly, a future agricultural land use map was produced to ensure future agricultural land use sustainability. The study location was divided into four different zones; namely, protected zone, peatland rehabilitation zone, buffer zone and agriculture zone

Kabuloh and the surrounding area has a high potential for large-scale agricultural activities on the premise of sustainable agricultural land use planning. The research produced a future agricultural land use map that considers the need for environmental conservation and socio-economic development. The sustainability of agricultural development at the study location can be enhanced by mitigating the identified potential negative impacts. After mitigating the negative impacts, the recommended economic crops can be cultivated in the recommended agriculture zone shown in the future agricultural land use plan to boost the local socio-economic development. The successful deployment of the future agricultural land use map in the Kabuloh region could further enhance the mapping to a wider area of Miri.

Table of Contents

List of Figures

List of Tables

Acronyms

λ_{max}	Principle Eigenvalue of Matrix
AHP	Analytic Hierarchy Process
ALUCC	Agricultural Land Use Capability Class
APOC	American Palm Oil Council
CI	Consistency Index
CO_2	Carbon Dioxide
CR	Consistency Ratio
CR	Critically Endangered
EFB	Empty Fruit Bunches
EN	Endangered
FAHP	Fuzzy Analytic Hierarchy Process
FAO	Food and Agriculture Organization
FELCRA	Federal Land Consolidation and Rehabilitation Authority
FRIM	Forest Research Institute Malaysia
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GIS	Geographic Information Systems
GSG	Great Soil Group
IUCN	International Union for Conservation of Nature
IVA	Ideal Vector Approach
LC	Least Concern
MCDM	Multiple Criteria Decision-making Methods
NT	Near Threatened
PGIS	Participatory Geographic Information System
POME	Palm Oil Mill Effluent
QGIS	Quantum Geographic Information Systems
RI	Random Index
SI	Semantic Import
TFNs	Triangular Fuzzy Numbers
USGS	United States Geological Survey
VU	Vulnerable
WLC	Weighted Linear Combination

Chapter 1 Introduction

The land is one of the natural resources explored and developed to meet human needs to carry out various daily activities (Nguyen 2017). Due to the rapid population growth, the demand for agricultural products is continuously rising to meet the increase of food demand and nutrient needs (Aizen and Harder 2009). Consequently, the need for agricultural development might transform land use, especially from a forest, into a plantation area (Lambin and Meyfroidt 2011). Land use planning is required to meet the current needs without sacrificing future generations' needs (Marrewijk 2003). Rational land use planning is vital to achieving sustainable development (De Wit and Verheye 2009). Without a proper land use study on agricultural development, some areas are converted into plantation areas, unsuitable for crop growth with their soils and surrounding environment (Miettinen, Shi, and Liew 2016). It is crucial to conduct land use planning to ensure that the land is planned for sustainable agricultural land use, which will benefit an economic return in the long term (Aznar-Sánchez et al. 2019). Several types of information should be considered throughout the land use planning process, such as people's needs, landscape features, and existing land use with the help of technology. The land use planning process is progressive and repetitive and should be revised when new information is available (FAO 1993).

1.1 Challenges Faced by Current Agricultural Land Use

The agricultural land use in Malaysia has undeniably brought many benefits to the country. For instance, the agricultural land ensures sufficient food production for the growing population and is a vital economic activity in Malaysia (Noor, Mardzuki, and Mamat 2018). However, the rapid expansion of agricultural land use has caused several problems. For example, land biodiversity was negatively impacted when tropical forests were cleared and used intensively for monoculture agricultural plantations (Tang and Al Qahtani 2020). In addition, continuous land clearing due to plantation expansion jeopardized local animals' lives, especially orangutans in Malaysia (Nantha and Tisdell 2009). A hundred thousand orangutans in Borneo were sacrificed because their habitats were destroyed due to the booming oil palm plantation industry (Beech 2019). Besides wildlife, there were several environmental issues raised by the environmental activists, such as forest degradation (Lord and Clay 2006), higher carbon dioxide emission from the annual fire used for land clearing (Purnomo et al. 2018), and peat draining (Miettinen et al. 2012). Above all, conservation strategies should be implemented to rectify the impact brought by the agricultural land use expansion.

The problems faced by the region with active agriculture activities show a need to assess the existing agricultural land use. The assessment is purposed to determine the suitability of the land used for agricultural activities. The suitability of agricultural activities can be affected by the physical environment, such as topography, soil, hydrology, and climate (FAO 1976). The Land and Water Development Division of the Food and Agriculture Organization (FAO), an international agency that aims to enhance food security, had made substantial advances to develop the assessment tools to evaluate agricultural land use suitability, such as the FAO

Framework (Verheye 2002). Evaluating the suitability of agricultural land use is necessary for the sustainable development of Malaysia's agriculture industry.

Sarawak is one of the states that undergo massive plantation development since the government have appointed 3 million hectares out of the 12.4 million hectares of state's land for agricultural land use (Chua 2019). Part of Sarawak's primary forest had been converted into agricultural plantations (Ichikawa 2007). For instance, oil palm trees occupy 1.56 million ha of Sarawak land, equal to 27% of Malaysia's total planted area (Wong 2018). Oil palm plantation had expanded onto unsuitable area such as peatland due to limited availability of suitable area, especially in the southern region of Miri, such as the Kabuloh region (Cramb and McCarthy 2016). There was 300,000 ha of peatland converted to oil palm plantations in 2008 (Wetlands International 2010). The peatland could have different agricultural land use potential instead of planting oil palm tree. Hence, it is crucial to assess the current agricultural land use and recommend future agricultural land use plan in a region with active plantation activities in Sarawak.

1.2 Land Use Suitability Assessment

Before developing a land use plan, the land use suitability must be assessed (Mokarram and Aminzadeh 2010). Land use suitability assessment is an approach to determine land potential over time based on specific land use type, such as agricultural, urban and environmental planning (Ramamurthy, Reddy, and Kumar 2020). Analysis of land use suitability helps stakeholders determine the level of land suitability for a particular type of use (Kenate 2017). In the analysis of land use suitability, land characteristics and stakeholders' needs are the key variables to be considered (Amiri and Shariff 2012). The involvement of different criteria has a different degree of impact on the land's suitability (Al-shalabi et al. 2006). Original properties of land, socio-economic condition, and environmental criteria are the assessment criteria to ensure the land is developed without deterioration (Bandyopadhyay et al. 2009). Hence, land use suitability depends on multiple criteria to assure land use sustainability (Malczewski 2004; McDowell et al. 2018). The assessment outcome can be used as a tool to guide the stakeholders to develop the land optimally.

The choosing of applicable criteria and the method implemented to assess the criteria could vary the output of land use suitability assessment (Feizizadeh and Blaschke 2013; Baidya et al. 2014; McDowell et al. 2018). The complicated relationship between the criteria could cause difficulties to assess the land use suitability precisely. Integration of multiple criteria decision-making methods (MCDM) and Geographic Information Systems (GIS) could help decision-makers to understand the complicated relationship between the criteria used in land use suitability assessment (Memarbashi et al. 2017). Therefore, it is appropriate to combine GIS and MCDM techniques to integrate the complex land characteristics during the agricultural land use suitability assessment.

1.3 Problem Statement

Agricultural activities play a significant role in the development of Malaysia. The agricultural products ensure the self-sufficiency of food production within the country. Meanwhile, Malaysia is the world's second-largest exporter of palm oil (Lam et al. 2009). The accelerated agricultural expansion has provoked numerous undesirable consequences, such as forest degradation (Lord and Clay 2006), loss of flora and fauna habitats (Nantha and Tisdell 2009), peat subsidence (Miettinen et al. 2012), and monoculture biodiversity (Tang and Al Qahtani 2020). Furthermore, a vast amount of peatland in Sarawak was converted into plantations to meet agricultural product's growing demand (Wetlands International 2010). The problems caused by accelerated agricultural expansion has increased the urgency to perform agricultural land use planning in the region with intense agricultural activities.

Similar to other developing regions, Kabuloh is dealing with active plantation development. Existing agricultural land use at Kabuloh could positively and negatively impact the sustainability of agriculture development. Consequently, agricultural land use planning is indispensable for sustainable agriculture production. However, there is lacking agricultural land use planning in the Kabuloh region. Hence, it is imperative to implement a suitability assessment of current agricultural land use and recommend future agricultural land use in Kabuloh, a region with active plantation activities in Sarawak.

1.4 Research Objectives

The research aims to examine the existing agricultural land use and suggest sustainable agricultural land use planning in the Kabuloh region, south of Miri, by map overlay analysis. The objectives of the research are:

- to assess the suitability of agricultural land use in the Kabuloh region;
- to assess existing agricultural land use to facilitate strategic planning in the Kabuloh region; and
- to produce a digitized agricultural land use plan in the Kabuloh region to enhance agricultural sustainability for future planning.

1.5 Research Scope

The research will deliver a prototype of digitized maps with detailed land use zoning for future agricultural land use in the Kabuloh region and the surrounding area. The Kabuloh region was chosen as it is an existing agricultural site and has an active agricultural plantation that has the potential to be developed as a sustainable agricultural land for the long term. The study area covers from latitudes of 4° 3' N to 4° 10' N and longitudes of 113° 51' E to 114° 4' E. The secondary data were collected from the Department of Survey and Mapping Malaysia, Department of Agriculture Sarawak, United States Geological Survey Earthexplorer, Forest Research Institute Malaysia, International Union for Conservation of Nature, Department of Irrigation and Drainage Sarawak, and Center for International Forestry Research. The data is limited to agricultural areas (locality and crop types), ownership of plantation area, agricultural land use capability, existing land cover map, topography features, soil types, hydrological system, road system, habitat existence of protected flora and fauna, human settlement area and land cover trajectory. The Geographic Information System (GIS) was used to assess existing agricultural land use and digitize the maps. The Fuzzy Analytic Hierarchy Process was used to determine the weightage of various assessment criteria. The criteria were later standardized by the Fuzzy Linear Membership function before analysis was conducted.

The secondary data obtained was integrated into a map system to produce the suitability map of agricultural land use and future agricultural land use map. The impact of the existing agricultural land use on the environmental and socio-economic aspects around the Kabuloh region was analyzed qualitatively. The environmental aspects were analyzed qualitatively by studying the historical land cover, hydrology system, peatland area, protected flora and fauna, and slope. The ownership of plantation area, proximity of the land to infrastructure and human settlement areas were analyzed using the digitized map to study the social aspects of agricultural land use. The analysis was aimed to ensure human welfare enhancement and environmental protection. Besides, the crops with high economic value for future agricultural land use were recommended to balance the environmental protection and socio-economic performance at the study location. However, the suggested crops and existing agricultural land use should not induce negative environmental and social impacts on the study area. Mitigation strategies were recommended to rectify the potential negative impacts of existing agricultural land use. Finally, a future agricultural land use plan encompassing the study location’s environmental and socio-economic characteristics was produced to propose sustainable agricultural land use planning.

1.6 Research Questions

The research questions of this study are:

i) What is the suitability of agricultural land use in the Kabuloh region?

ii) What is the potential impact of existing agricultural land use on the environment and the local society by map overlay analysis?

ii) What is the recommended future agricultural land use in the Kabuloh region by map overlay analysis?

1.7 Research Significance

The research outcomes can identify the potential impact of existing agricultural land use on the study area’s environment and society. The spatial information could help to achieve sustainable agricultural development of the Kabuloh and the surrounding area. Sustainable agricultural development should be practiced to mitigate the threats caused by the existing agricultural land use. The agricultural land use in the Kabuloh region can be designed effectively by looking into the economic return, people’s needs, and valuable environment conservation. Additionally, the result could help the decision-makers develop a strategic plan for the agriculture sector's future development. For instance, the research outcome can be applied to enhance Sarawak's agriculture sector's productivity and efficiency, as mentioned in the Sarawak Digital Economic 2018-2022. Additionally, successful implementation of the agricultural land use map in the Kabuloh region can further expand the mapping to a broader area of Miri. More similar studies could be conducted in the region with intensive agricultural activities in Malaysia's other regions. Furthermore, the studies could enhance the overall sustainability of Malaysia's agriculture industry.

Chapter 2 Literature Review

Impacts induced by the expansion of oil palm plantations are reviewed at the beginning of this chapter, as explained in **Section 2.1**. Since the expansion of oil palm plantation had converted a massive amount of land into agricultural land, it shows a need to assess the agricultural land use suitability to determine the oil palm plantation developed on suitable agricultural land, as reviewed in **Section 2.2**. The Geographic Information System (GIS) is an application system that can integrate multiple land characteristics and human preferences to analyse agricultural land use suitability. The theories and usefulness of GIS are reviewed in **Section 2.3**. The influence of assessment criteria on the assessment outcome and how to standardize criterion are reviewed in **Section 2.4** to understand the flow to process the criteria. Lastly, the agricultural land use suitability assessments conducted in Malaysia are reviewed in **Section 2.5** to update the current development of agricultural land use suitability assessment in Malaysia. The literature review is summarized, and the research gaps are stated at the end of this chapter in **Section 2.6**.

2.1 Impact of Plantation Expansion on Environment and Society

Continuous plantation expansion caused several environmental issues in the past based on literature. According to past researches, the oil palm plantation caused negative impacts on the forest's biodiversity. For instance, it was found that oil palm plantation only preserves 17%-21% of the species richness after primary and logged forests were converted based on surveys of forest butterflies at Sabah's plantation area (Koh and Wilcove 2008). In addition, Fitzherbert et al. (2008) reported that oil palm plantation caused a reduction of 85% of primary forest species, especially the species with specialized diets. Mercer, Mercer, and Sayok (2013) discovered that rivers around oil palm plantations contain lower abundance, richness, and diversity of invertebrate species than rivers around the rainforest. This scenario was due to damage to riverbank habitats and exposure to pesticides fighting Rhinoceros beetle.

Additionally, oil palm plantation is the primary driver of deforestation. 8.12 Mha tree cover was lost, and the principal driver is commodity-driven deforestation (Global Forest Watch 2020). Koh and Wilcove (2008) found that 55%-59% of oil palm expansion caused forest conversion during 1990-2005. Meanwhile, Wahid et al. (2010) revealed that 27.4% of peatland in Malaysia had been converted into oil palm plantation in 2009. The area of converted peatland is very likely going uptrend due to rapid oil palm plantation expansion. Peatland conversion also caused deterioration of water quality at the river flow through the oil palm plantation. Gandaseca et al. (2014) assessed the water catchment area's water quality heavily planted with oil palm. They found that the river contained a high biochemical oxygen demand and a low level of dissolved oxygen. Chellaiah and Yule (2018) realized that rivers flowed through oil palm plantation in Borneo had a higher concentration of phosphorus and potassium than rivers flowed through native forests. Leaching of fertilizer from oil palm plantation could be the reason for the high concentration of phosphorus and potassium.

On the other hand, the rapid development of the oil palm sector delivers benefits to society. The oil palm sector substantially contributes to the employment market by offering 437,696 job opportunities in 2019 (Department of Statistics Malaysia 2019). Public listed oil palm companies declare to engage actively in corporate social responsibility (CSR) activities. The company provided food aid, healthcare access, and education programs to support the community's needs (Sime Darby Plantation Berhad 2020). In 2018, Malaysia's agriculture sector's Gross Domestic Product (GDP) was RM 99.5 billion. Oil palm contributed 37.9% of the agriculture sector's GDP, making it the most significant contributor (Department of Statistics Malaysia 2020). Oil palm also has the highest oil yield as compared to soybean, sunflower, and rapeseed. The oil yield of oil palm is 3.72t/ha/year, while the other three crops produce less than 1t/ha/year (Shimizu and Desrochers 2012).

2.2 The Need for Agricultural Land Use Suitability Assessment

In this day and age, there is an increasing demand for agricultural land. The increasing demand for agricultural land creates competition with other land use, such as urban, forest reserve, industrial, and recreation land use. The intensity of land competition is risen due to the global population growth, developing demand for foodstuffs, and place from the burgeoning community (Tilman et al. 2011). The most suitable land for agricultural land use is limited, and less appropriate land is continuously employed as agricultural land (Verheye 2008). Agricultural land development is frequently seen as one of the causes of environmental issues; however, it can become a fundamental environmental component if thoughtfully controlled (Loehr 2012).

Well-grounded and precise agricultural land use suitability assessment is urgent as the land is a finite asset. Agricultural land use suitability assessment aids decision-maker and stakeholder to utilize the rare land resources competently. Decision-makers can estimate appropriateness for agricultural land use based on the assessment result (Maddahi et al. 2014). Agricultural land use suitability of various countries could differ based on numerous determinants, such as land properties, socio-economic conditions, governmental limitations, and human's necessities (FAO 1985). Dent and Young (1981) mentioned that the concept of agricultural land use suitability assessment remains the same since the early time that the landowners decided on suitable crops to plant on the particular land. Besides, the landowners determine suitable crop to grow based on the local season. Landowners learned about land suitability through the experience delivered from several generations and failures.

Agricultural land use suitability assessment is a vital component of agricultural land use planning (Ritung et al. 2007; AbdelRahman, Shalaby, and Essa 2018). The assessment is a fundamental stage for introducing the appropriate land use judgment. A scientifically regulated system is implemented throughout the agricultural land use suitability assessment to predict particular land performance for agricultural land use. The decision-maker can implement the outcomes to guide the stakeholders to determine an optimum land use (Ritung et al. 2007). The desire for optimum land use indicates that balance must be accomplished between environmental factors, social-economic requirements, and human needs. The achievement of equilibrium is never straightforward so that the actualization of agricultural development plans requires cooperation from diverse perspectives, such as social, economic, and environmental (Sys, Ranst, and Debaveye 1991). Hence, agricultural land use suitability assessment is imperative to be realized to identify the latent performance of land.

2.3 Application of Geographic Information System in Agricultural Land Use Suitability Assessment

Geographic Information System (GIS) is a commonly used tool for land use suitability assessment. Various land characteristics such as soil, climate and topography can be integrated and analyzed by using GIS. GIS helps users combine multiple complex datasets into a single new dataset and present thematic maps (Longley and Goodchild 2020). One of the widely adopted GIS software is Quantum GIS (QGIS). QGIS is an open-source geographic information system software application that comprises viewing, editing, and analysing geospatial data. GIS can be used in agricultural land use suitability assessment to identify suitable areas for intense agriculture development without sacrificing sustainable development (Barakat et al. 2017; Ennaji et al. 2018).

GIS-based land use suitability assessment has its origins from the implementations of hand-drawn overlay techniques applied by landscape architects from America within the late nineteenth and early twentieth century (Malczewski 2004). McHarg (1969) improved the overlay techniques by introducing a manual overlay cartographic process. The process is extensively accepted to become the predecessor of the classic overlay approaches in GIS. According to Collins, Steiner, and Rushman (2001), the development later continued with computer-assisted overlay mapping, then multi-criteria evaluation, and lastly, artificial intelligence methods.

The computer-assisted overlay mapping method in the GIS environment significantly improved the land use suitability assessment (Tomlin 2012). The method has been widely implemented to assess land use suitability in Boolean operations and weighted linear combination (WLC). The method is simple to execute within the GIS environment and easily understandable (Malczewski 2004). However, Hopkins (1977) determined that the Boolean operations and WLC method were used without sufficient understanding of the assumptions made to the weights assigned to the criterion maps, and the assessment results become doubtful. Both methods oversimplified the intricacy of the land use planning issues (Malczewski 2000). Incorporating MCDM methods into the GIS environment can improve the shortcoming (Malczewski 2004).

The ability of GIS to handle a wide variety of spatial data from various places attracts researchers to integrate GIS with MCDM methods (Chen, Yu, and Khan 2010). Integration of GIS and MCDM is always found in the study of land use suitability to incorporate multiple land characteristics during the decision-making process (Jamil, Sahana, and Sajjad 2018).

Integration of GIS and MCDM is a procedure that joins the different spatial data into resultant data (Malczewski 2004). The MCDM methods facilitate the decision-making process by defining the relationship between the multiple criteria and output map (Mendas and Delali 2012).

The application of the MCDM method in the GIS system can be viewed as a procedure that integrates and modifies several criterion maps into a single suitability map in land use suitability assessment. The MCDM decision rules establish the connection between the criterion maps (input) and the suitability map (output). The decision rules entail applying spatial data, the priorities of the decision-makers, and manipulating the data and priorities as stated by prescribed decision rules (Malczewski 1999). Two classes of multi-criteria decision rules are available in the GIS environment to assess land use suitability. There are multiobjective approaches and multiattribute approaches. Multiobjective approaches require alternatives to be generated by solving a multiobjective mathematical programming problem. Alternatively, multiattribute approaches assume the alternatives are given directly (Malczewski 2004). The multiattribute approaches were applied to determine weightage of criteria since it has been widely incorporated within the GIS environment.

Several MCDM decision rules have been employed in the GIS system for assessing land use suitability. One popular method in generating pairwise comparisons is the Analytic Hierarchy Process (AHP) approach (Chang, Parvathinathan, and Breeden 2008). The approach is a decision-making instrument to solve a complex decision-making problem (Saaty 1990). It can be implemented to derive the weights of the assessment criteria (Malczewski 2004). However, several deficiencies exist to implement the MCDM methods in the GIS environment (Zhou and Civco 1996). The input to the GIS-multicriteria assessment processes usually contains inaccuracy, ambiguity, and imprecision, yet the decision-maker typically assumes the input is precise and accurate.

An approach to improving MCDM methods' shortcomings in the GIS environment is to apply fuzzy logic methods (Malczewski 2004). The fuzzy logic method can define a set without clear limits of items belonging to a given factor in the GIS environment (Zadeh 1965). A fuzzy factor is a factor whose items may possess degrees of belonging between 0 and 1, contrary to the traditional set where each item only can be assigned either 0 or 1 as the degree of belonging. The fuzzy logic method offers a system for interpreting uncertainty in the sense of partial truth and vagueness (Malczewski 2004).

The combination of the fuzzy logic method and MCDM approach in GIS-based land use suitability assessment produces the Fuzzy AHP (FAHP) method (Malczewski 2004). FAHP method is an AHP method that examines multiple criteria associated with fuzzy numbers. FAHP overcomes the weakness of AHP, which is the ambiguity from the use of the crisp numbers (Mikhailov and Tsvetinov 2004). Hence, FAHP could compensate a certain degree of the assessment's vagueness when dealing with the multi-criteria analysis (Erensal, Öncan, and Demircan 2006).

The MCDM and fuzzy logic method had been utilized in several GIS-based land use suitability studies (Banai 1993; Jiang and Eastman 2000). Banai (1993) studied the application of the AHP method to fuzzify the land use suitability analysis criteria in the GIS environment. Keshavarzi et al. (2010) applied fuzzy set theory in their research to reclassify the continuous variation of land characteristics and determine land suitability for irrigated wheat cultivation in Iran. Prakash (2003) determined that FAHP method has better performance to address uncertainty compared to other MCDM methods, namely AHP and Ideal Vector Approach (IVA). Furthermore, Qiu et al. (2014) concluded that the fuzzy logic method attains higher predictive accuracy than the Boolean approach and Weighted Linear Combination method. In short, the fuzzy membership functions able to produce more informative land suitability maps.

2.4 Criteria Used to Assess Agricultural Land Use Suitability

Criteria are the determining factors in agricultural land use suitability assessment (Akpoti, Kabo-bah, and Zwart 2019). Decision-maker uses these tools to evaluate the environmental system and make a critical decision. The criteria are deduced from various aspects, such as biophysical, socio-economic, and management practice (Walker 2002). The criteria source can be observed through field visit, remote sensing, or secondary data reproduction (Meyer et al. 1992). The criteria that were commonly used in previous studies are shown in **Table 2.1**.

Criteria involved in the land use suitability assessment are associated with different significance levels (Akinci, Özalp, and Turgut 2013). The higher value of the criterion's weightage indicates greater importance of the land use suitability criterion (Romeijn et al. 2016). For instance, the decision-maker gives soil characteristics of land higher weightage in the land suitability analysis than criteria related to distance to infrastructure (Keshavarzi et al. 2010; Dadhich, Patel, and Kalubarme 2017; Pilevar et al. 2020). The significance level of each criterion should be determined before the suitability assessment is continued.

The criteria have come with a different range of values which is not standardized. The most implemented approach to standardize the criteria is the linear transformation method (Malczewski 2004). However, the value could be changed or misrepresented by the linear transformation process. Standardization of the criteria in either a monotonous ascending or descending manner causes the misrepresentation of value (Radočaj et al. 2020). Some attempt had been made to deal with this issue by implementing the Fuzzy logic methods. Standardization by using Fuzzy logic methods is based on the implementation of fuzzy membership functions. Fuzzy membership functions come with the possibility of numerically representing the criteria to a 0 to 1 scale based on various functional forms such as Gaussian, sigmoid, inverted sigmoid, and linear functions (Ustaoglu and Aydınoglu 2020). Fuzzy standardization results in a more accurate standardization output than the linear transformation method (Radočaj et al. 2020).

Table 2.1: Criteria of land use suitability analysis from past studies

Criterion \ Study	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	**Total**
Slope	/	/	/	/	/	/	/		/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/		26
Great soil group	/	/	/	/	/	/	/	/	/			/	/			/				/						/	/		15
River		/						/	/	/	/			/		/	/	/	/		/	/	/	/			/	/	16
Road proximity			/	/				/	/	/	/				/		/	/	/		/	/	/	/	/	/	/	/	18
Land use capability																/												/	2

Source: Table reproduced from Akpoti, Kabo-bah, and Zwart (2019, 203)

Notes: 1. Van Ranst et al. (1996) **2.** Kalogirou (2002) **3.** Qin and Jixian (2002) **4.** Mas et al. (2004) **5.** De la Rosa et al. (2004) **6.** D’haeze et al. (2005) **7.** Sicat, Carranza, and Nidumolu (2005) **8.** Baja, Chapman, and Dragovich (2007) **9.** Cengiz and Akbulak (2009) **10.** Gumma et al. (2009) **11.** Reshmidevi, Eldho, and Jana (2009) **12.** Bandyopadhyay et al. (2009) **13.** Baniya, Böehme, and Baniya (2009) **14.** Yu et al. (2011) **15.** Mendas and Delali (2012) **16.** Akinci, Özalp, and Turgut (2013) **17.** Masoud et al. (2013) **18.** Deng et al. (2014) **19.** Chandio et al. (2014) **20.** Albaji et al. (2014) **21.** Passuello et al. (2014) **22.** Austin et al. (2015) **23.** Romano et al. (2015) **24.** Zabihi et al. (2015) **25.** Nguyen et al. (2015) **26.** Mishra, Deep, and Choudhary (2015) **27.** Yalew et al. (2016) **28.** Tercan and Dereli (2020)

2.5 Agricultural Land Use Suitability Assessment in Malaysia

Past researchers conducted the agricultural land use suitability assessment in Malaysia from 2005 to 2018. Howell et al. (2005) assessed a rubber smallholding in northwest Pahang, Peninsular Malaysia. The research was mainly focused on the soil characteristics of the study area. The study area's main limitations were the high water table level, soil texture, uprooting, and slope. The limitations were recommended to be corrected via drainage, the establishment of a cover crop, or terracing.

Arshad (2015) evaluated the suitability of various soil series for oil palm cultivation in the district of Temerloh and Kuantan, Pahang. Eleven types of soil series were studied to determine oil palm cultivation's suitability in the study area. The study was conducted using the combined limitation and parametric approach to evaluate soil series suitability for oil palm growth. Two types of soil series were found highly suitable. Seven types of soil series were found moderately suitable, and the remaining types of soil series were marginally suitable for planting oil palm trees.

Agricultural land use suitability assessment was conducted by Olaniyi, Abdullah, and Ramli (2015) in different districts of Selangor. Suitability assessments of cultivating paddy, oil palm, rubber, and coconut were conducted in the study area. The authors considered environmental and socio-economic criteria to evaluate agricultural land use suitability. The authors applied GIS and MCDM methods to analyze agricultural land use suitability. The results showed that the most suitable paddy, coconut, and oil palm cultivation zones were Kuala Langat and Sabak Bernam districts. Klang and Petaling districts were only suitable for growing rubber. The authors foresaw potential environmental threats in Kuala Langat and Sabak Bernam districts since the districts were suitable for a more diverse variety of crops.

Ahmed et al. (2016) analyzed the agricultural land-use suitability for rubber crops in Seremban, Malaysia. The study area's soil texture, rainfall index, elevation and slope were assessed to determine rubber cultivation's suitability in the study area. The authors incorporated GIS and MCDM approaches to facilitate the analysis of data. The results showed that Senawang, Rantau, and Mambau were highly suitable, Labu and Nilai were moderately suitable, while Mantin, Lenggeng, and Pantai were not suitable for rubber cultivation. The authors foresaw potential land degradation in the area unsuitable for rubber's growth.

Suhairi, Jahanshiri, and Nizar (2018) conducted agricultural land use suitability assessment for the Bambara groundnut cultivation in entire Peninsular Malaysia. Soil, climate, land use, and topography criteria were applied to assess the Bambara groundnut cultivation's suitability. GIS and MCDM method were utilized in this study to analyze the data. The outcome of the research determined that Semenyih was highly suitable for growing the Bambara groundnut.

Based on the literature review, there is no agricultural land use suitability assessment developed to determine the suitability of agricultural land use in the southern region of Miri to improve the agricultural land use sustainability in Sarawak. Besides that, there is a lack of study that recommends future agricultural land use in the southern region of Miri to promote agricultural land use sustainability in Sarawak. In terms of geographical location, the past studies were conducted in Peninsular Malaysia, while no study conducted in East Malaysia, particularly in Sarawak, was determined.

2.6 Summary of Literature Review

Agricultural activities have positively and negatively impacted the environment and society within and around the agricultural land. Meanwhile, a portion of agricultural activities was developed in the unsuitable zone that brought environmental and social issues. Improper planning of agriculture activities expansion will diminish the sustainability of agricultural land use. Hence, agricultural land use suitability assessment is imperative to be conducted to promote sustainable agricultural land use planning. Integration of GIS and MCDM is an applicable method that has not been conducted in East Malaysia to assess agricultural land use suitability. Sarawak, a state with active agriculture plantations, lacks agricultural land use planing, although a significant portion of the land is designated for agricultural land use. The impact of the existing agricultural land use on the environment and society remains unclear in Sarawak’s active plantation region based on past researchers. Hence, it is urgent to assess the agricultural land use suitability and impact of existing agricultural land use on the environment and society in a region of Sarawak that active with agricultural activities. Conservation strategies should be recommended if any potential threat is determined.

Chapter 3 Methodology

This chapter describes the procedure to assess agricultural land use suitability and potential threats of existing agricultural land use in the Kabuloh region and the surrounding area. The approach applied to recommend future agricultural land use is described at the end of this chapter. The flow of the research methodology is summarized in **Figure 3.1**. The background of the study area is introduced briefly in **Section 3.1**. After that, the criteria considered in the quantitative agricultural land use suitability assessment are described in **Section 3.2**. Then, the processes involved to determine the weight of each criterion are explained in **Section 3.3**. Subsequently, **Section 3.4** describes the process of standardization of criteria. Later, the process to produce the agricultural land use suitability map is introduced in **Section 3.5**. The process involved to assess the potential threat of existing agricultural land use is presented in **Section 3.6**. Suitability assessment of suggested crops for future agricultural land use is described in **Section 3.7**. The suggested crops can be planned for future agricultural land use to enhance the sustainability of agricultural land use. Lastly, the rationale behind the zoning of future agricultural land use is explained in **Section 3.8**.

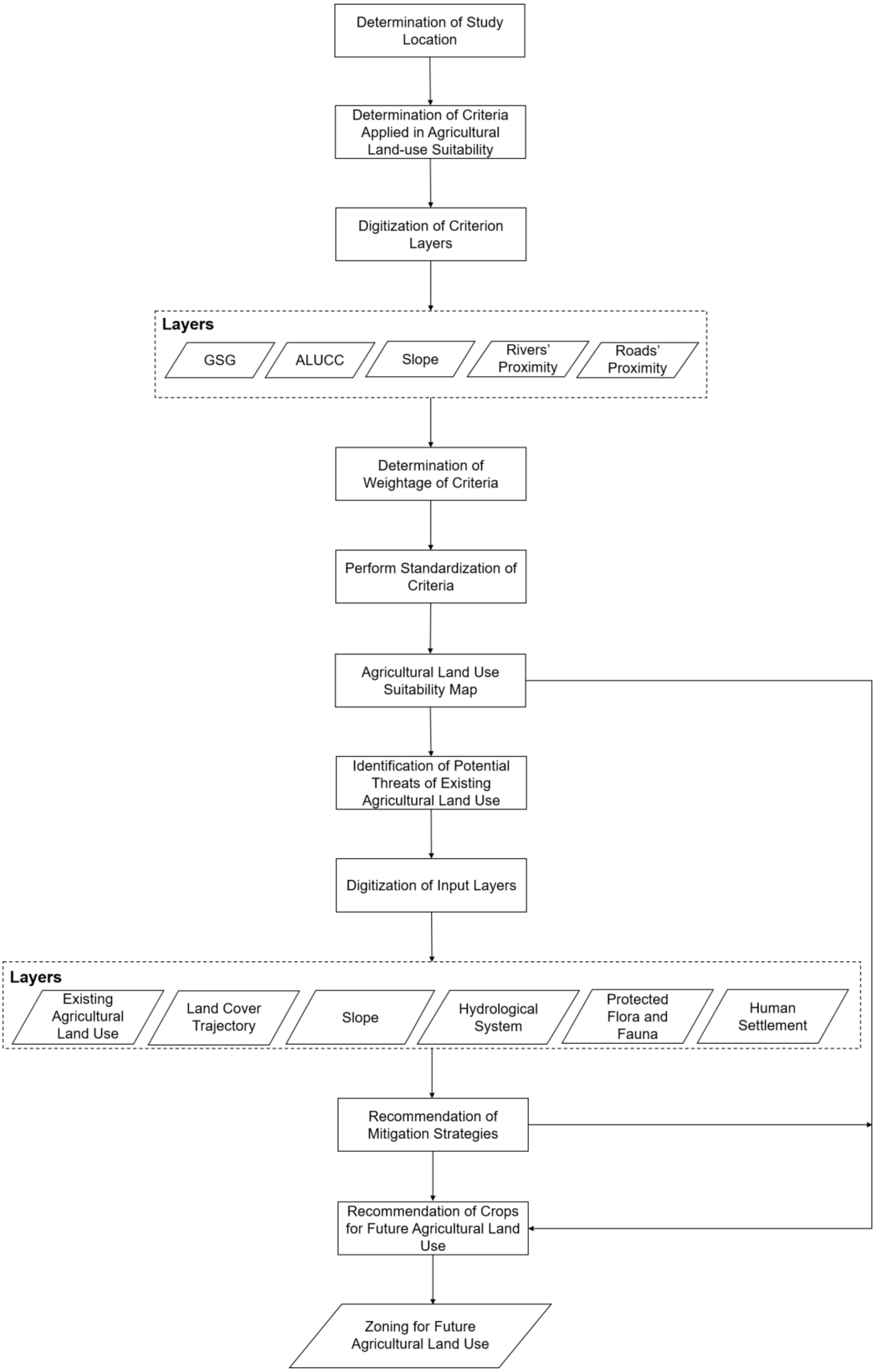

Figure 3.1: Research methodology

3.1 Determination of Study Location

The study focused on a southern region of Miri, East Malaysia, as shown in **Figure 3.2**. The study area was centred at Kabuloh and spread over Miri and Marudi. The study area lies between latitudes of 4° 3' N to 4° 10' N and longitudes of 113° 51' E to 114° 4' E and covers approximately 28368.43 ha of land that comprises 26 villages. In the study area, the elevation varies between 0 m and 197 m. The slope percentage is between 0% and 38% in the study area, and a high proportion is a flatland, with poorly drained swamps located at the eastern zone of the study area, which has low altitude. The remaining part of the study area is covered by coastal and riverine alluvium.

Meanwhile, the mean annual rainfall at the study area varies from 2247 – 3499mm (Arumugam 2016). The temperature in the study area is ranged from 23 – 32 ˚C (Arumugam 2016). The study area experiences a tropical climate symbolized by southwest and northeast monsoons (Arumugam 2016). Oil palm is the cultigen contributing substantially to the local villages' livelihoods because a vast amount of land is under oil palm cultivation. Oil palm plantation (11372.57 ha) covers 40% of the study area, while the primary forest (11260.28 ha) covers 39.7% and only a minority of land planted with paddy (234 ha), as shown in **Figure 3.3**.

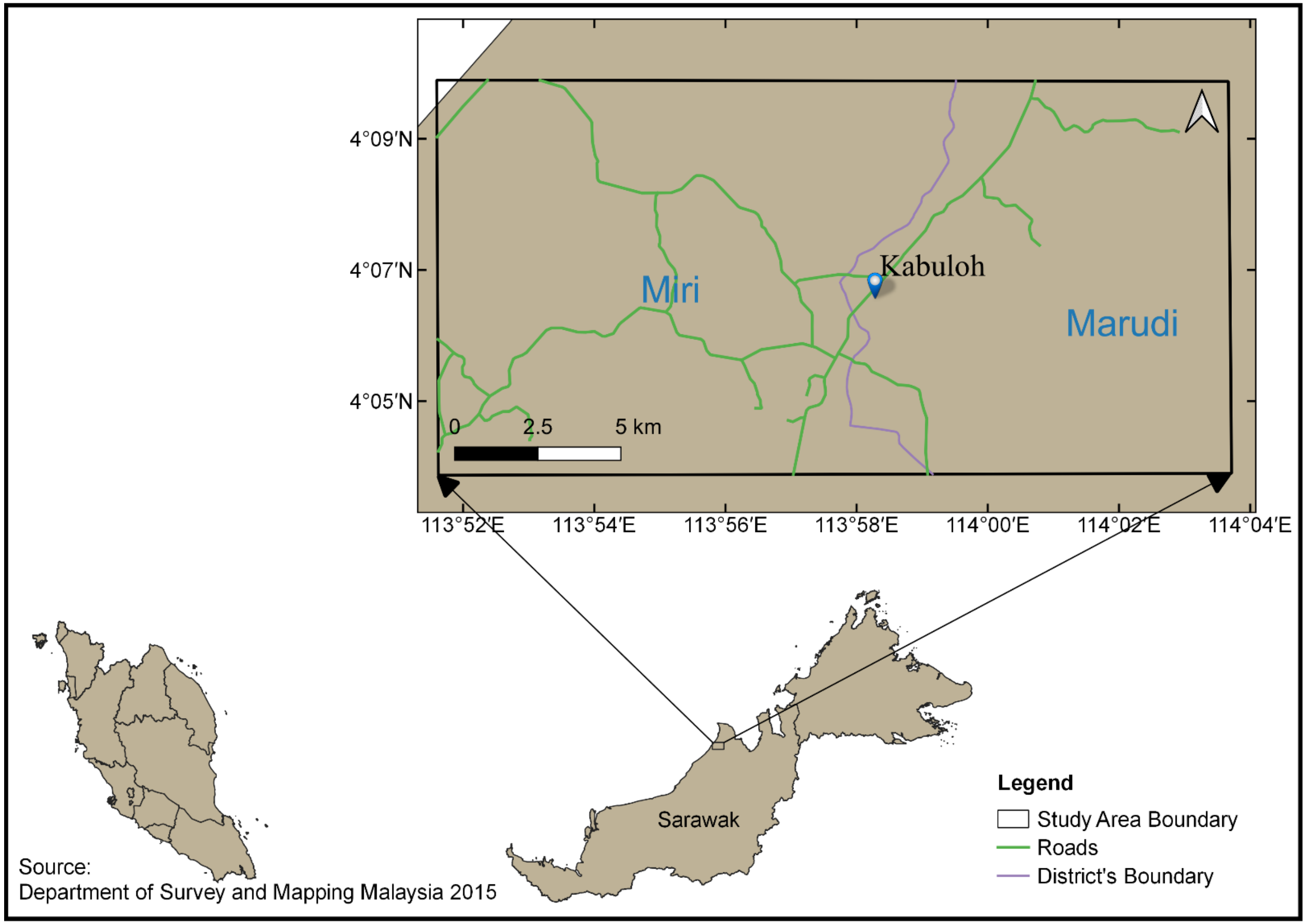

Figure 3.2: Location map of study area

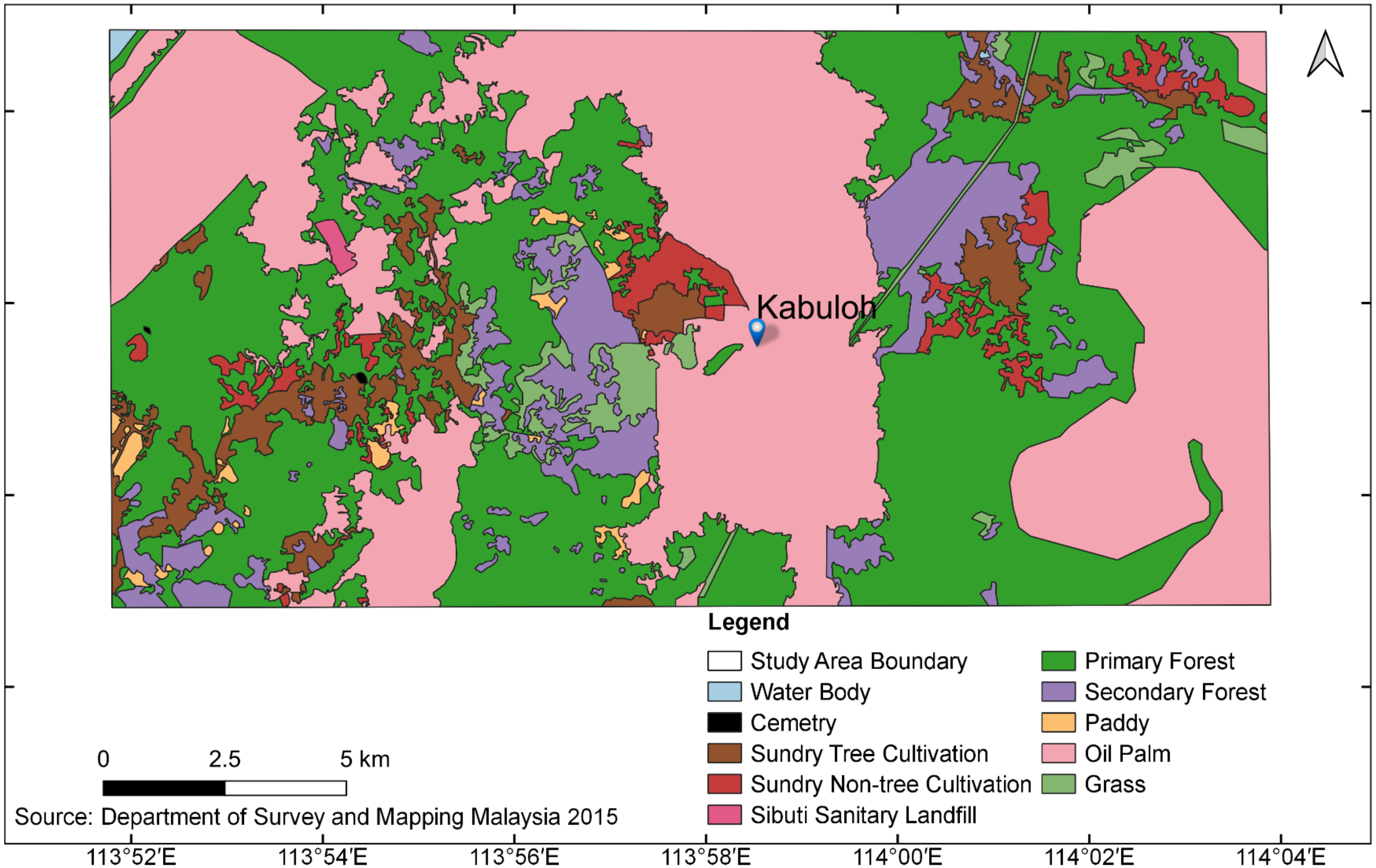

Figure 3.3: Existing land cover map

3.2 Determination of Criteria Applied in Agricultural Land Use Suitability Assessment

The criteria of great soil group (GSG), agricultural land use capability class, slope, and proximity to rivers and roads were chosen to assess the land's suitability in the study area for agricultural purposes. These criteria were applied in similar studies conducted at other locations (Cengiz and Akbulak 2009; Akinci, Özalp, and Turgut 2013; Yalew et al. 2016). Spatial data were mainly sourced from the Department of Agriculture Sarawak and the Department of Survey and Mapping Malaysia. These spatial data were soil map, agriculture land use capability map, major agriculture commodities map, river system map, and existing land cover map. Although the soil map was published in 1982, it was used because it is the latest version obtained in 2020 from the Department of Agriculture. Additionally, several hundred to thousand years are taken to form new soil types, and eventually, lead to the change of "Great soil group" and "Agriculture land use capability class" (Weil and Brady 2017). Therefore, the characteristic of soil formation supports the validity of the soil map and agriculture land use capability map. The slope map in the study area was sourced from the United States Geological Survey (USGS) Earthexplorer. All the spatial data used for agricultural land use suitability assessment and their sources are summarized in **Table 3.1**. The criteria applied in this study are justified in the **Sections 3.2.1 - 3.2.5**. After the applicable criteria were determined, the criterion layers were digitized from the hardcopy or photo into vector and raster layers. The digitization process was performed by using Quantum Geographic Information Systems (QGIS).

Table 3.1: Source of spatial data used for agricultural land use suitability assessment

Spatial data	Resolution (m/pixel)	Source of data
Great soil group	15	Department of Agriculture Sarawak 1982b
Agriculture land use capability class	15	Department of Agriculture Sarawak 1982a
Major agriculture commodities map	-	Department of Agriculture Sarawak 2019a
River system	15	Department of Agriculture Sarawak 1982b
Existing land cover map	-	Department of Survey and Mapping Malaysia 2015
Slope	90	USGS Earthexplorer 2010

3.2.1 Great Soil Group

Different soil types were classified, as shown in **Figure 3.4**, to determine the soils' conditions and behaviours. By knowing the characteristics of the soils, the soil performance can be estimated for agricultural activities. Hence, it is significant to know the major soil type in the study area when evaluating agricultural land use's suitability. The study area's primary soil type is red-yellow podzolic soil (Department of Agriculture Sarawak 1982b). In the east of the study area, organic soil is available (Department of Agriculture Sarawak 1982b). Along the area in which different rivers flow, alluvial soils can be found due to the accumulation of the sediments carried by the rivers' flows (Akinci, Özalp, and Turgut 2013).

3.2.2 Agricultural Land Use Capability Class

The agricultural land use capability class (ALUCC), as shown in **Figure 3.5**, classifies a particular soil's adequacy to cultivate different crops except those needing particular administration (Akinci, Özalp, and Turgut 2013). Soils are classified into seven classes in the development of ALUCCs. ALUCCs are classified based on the limitation they bring to the crops to be planted on the soils, the risk of conducting agricultural activities on the soils and the ease of mechanization (Department of Agriculture Sarawak 1982a). The description of each class is tabulated in **Table 3.2**. Different ALUCCs are spread evenly on the study area's land except for the Class 1 ALUCC (Department of Agriculture Sarawak 1982a).

3.2.3 Slope

The topography of the area changes the development of soils (Binkley and Fisher 2013). An increment of slope decreases the soil layer's thickness and soil fertility (Atalay 2006 as quoted by Akinci, Özalp, and Turgut 2013, 75). Additionally, slope degree is the critical component of erosion control (Koulouri and Giourga 2007). Slope negatively affects the soil properties and indirectly restricts crops' growth (Binkley and Fisher 2013). A steeper slope causes a more significant nutrient loss due to erosion (Guerra et al. 2017). Meanwhile, slope brings difficulties to the ease of mechanization on the land, such as soil tillage, drainage, and irrigation (Akinci, Özalp, and Turgut 2013). Most of the study area land has a gentle slope between 0% and 6% (Soil Science Division Staff 2017), as shown in **Figure 3.6**.

3.2.4 Proximity of Land to Rivers

Lack of sufficient water supply due to high evapotranspiration could be a vital issue to crop growth. This issue can be resolved by irrigation (Zabihi et al. 2015). However, there should be a buffer zone from the planting area to protect the riparian ecosystem from adverse environmental impacts (Lorion and Kennedy 2009). The proximity of land to the rivers of the study area was presented in **Figure 3.7**.

3.2.5 Proximity to Land to Roads

Crops should be planted near to road network to minimize transportation and other relevant costs. However, it should be located at a distance away from roads to lower the traffic impact and allow future road expansion (Tercan and Dereli 2020). The road network and plantation existence have a strong positive correlation (Zabihi et al. 2015). The proximity of land to the roads of the study area is presented in **Figure 3.8**.

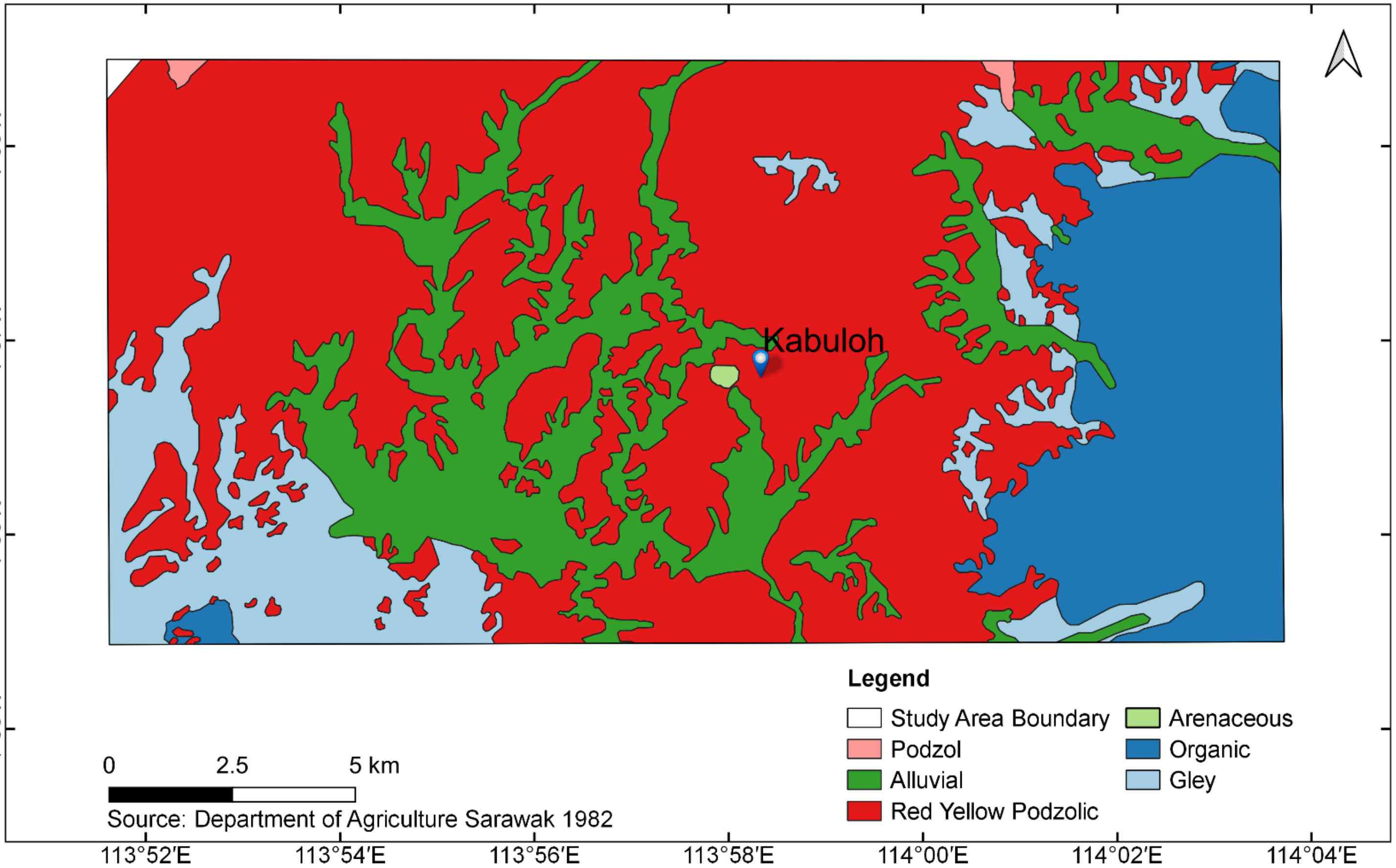

Figure 3.4: Great soil group

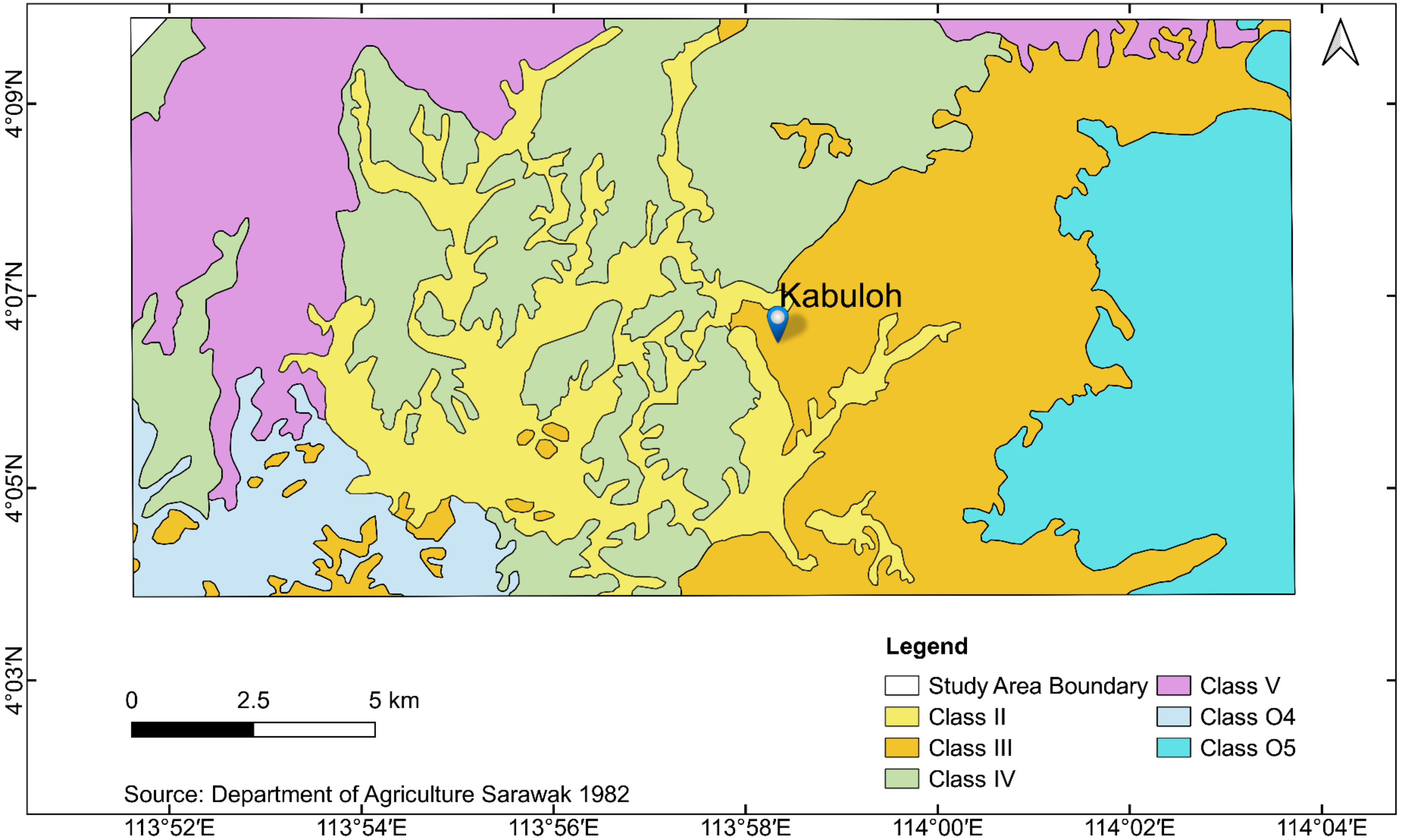

Figure 3.5: Agriculture land use capability class

Table 3.2: Description of agricultural land use capability classes

Class	Description
Class I	Lands are come with no constraint or one minor constraint to grow the crop.
Class II	Lands have two or more minor constraints that limit the range of crops and involves moderate conservation practices. The soils are deep with good to imperfect drainage. The topography of lands is moderately sloping to rolling. The frequency of flooding is less and of short duration.
Class III	Lands have two or three moderate limitations in which the range of crops and the degree of possible mechanization are limited. These limitations might significantly obstruct farm operation, narrow the choice of crops, and increase the need for fertilizer.
Class IV	Lands are having limitations in that it is only can be planted with a few types of the crop, but the yields will be low or even worse in that the crops might fail to grow.
Class V	Lands are having a steep slope which is more than 33 degree and cause very severe erosion. The lands have excessive salinity, shallow soil depth and are subjected to frequent floods of long duration.
Class O4	Lands comprise organic soils with two or three severe limitations that limit the range of crops and require particular administration practices. The examples of land limitations are high water table, low fertility, flooding, low bulk density. These limitations result in poor anchorage for trees. The lands also shrink and subside upon draining of water to lower the water table.
Class O5	Lands are comprising of organic soils with severe limitations that made agriculture is not feasible. Examples of severe limitations are the deep accumulation of raw acid peat and low bulk density. These limitations hinder the growth of crops.

Source: Table reproduced from Department of Agriculture Sarawak (1982a).

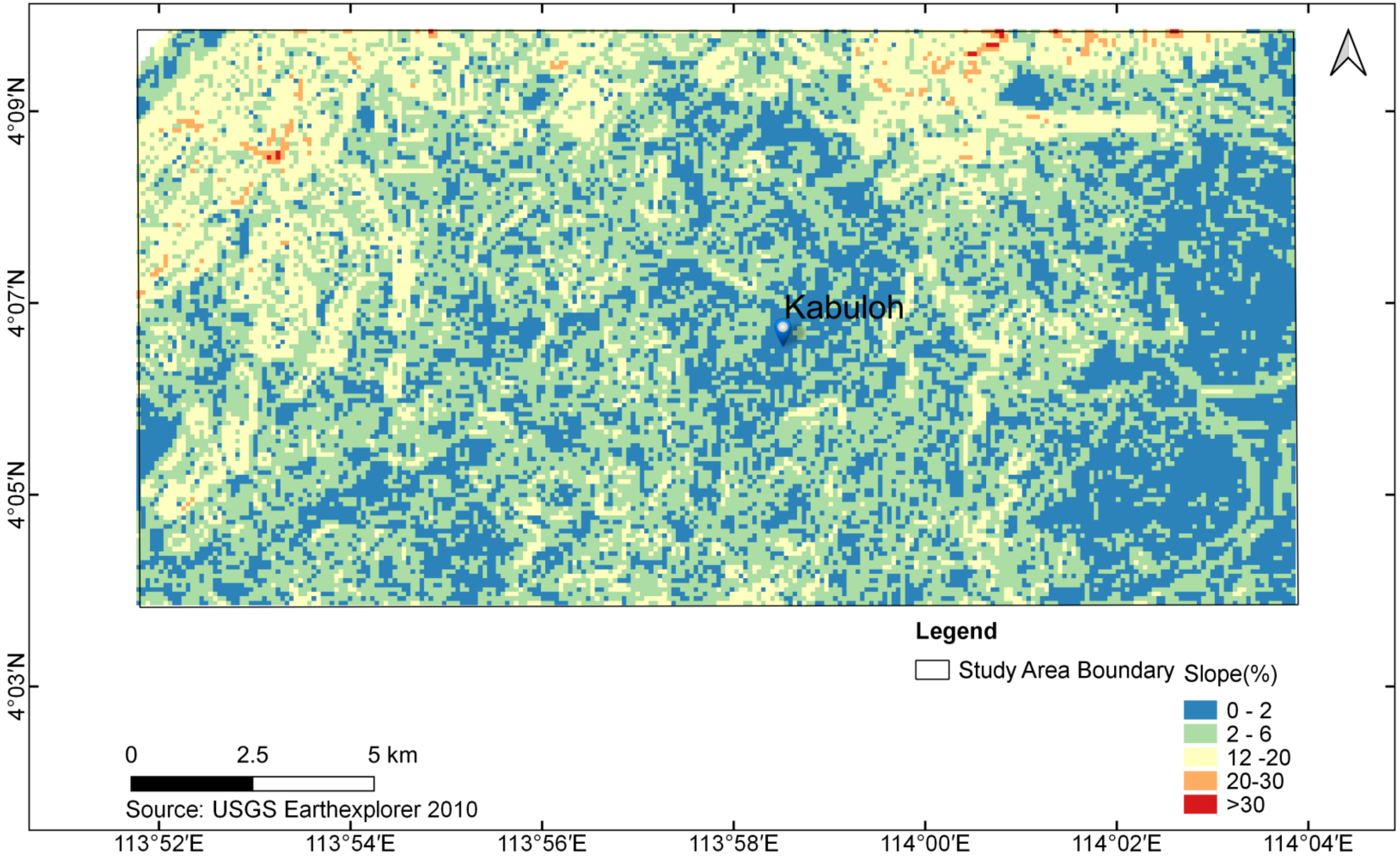

Figure 3.6: Slope map

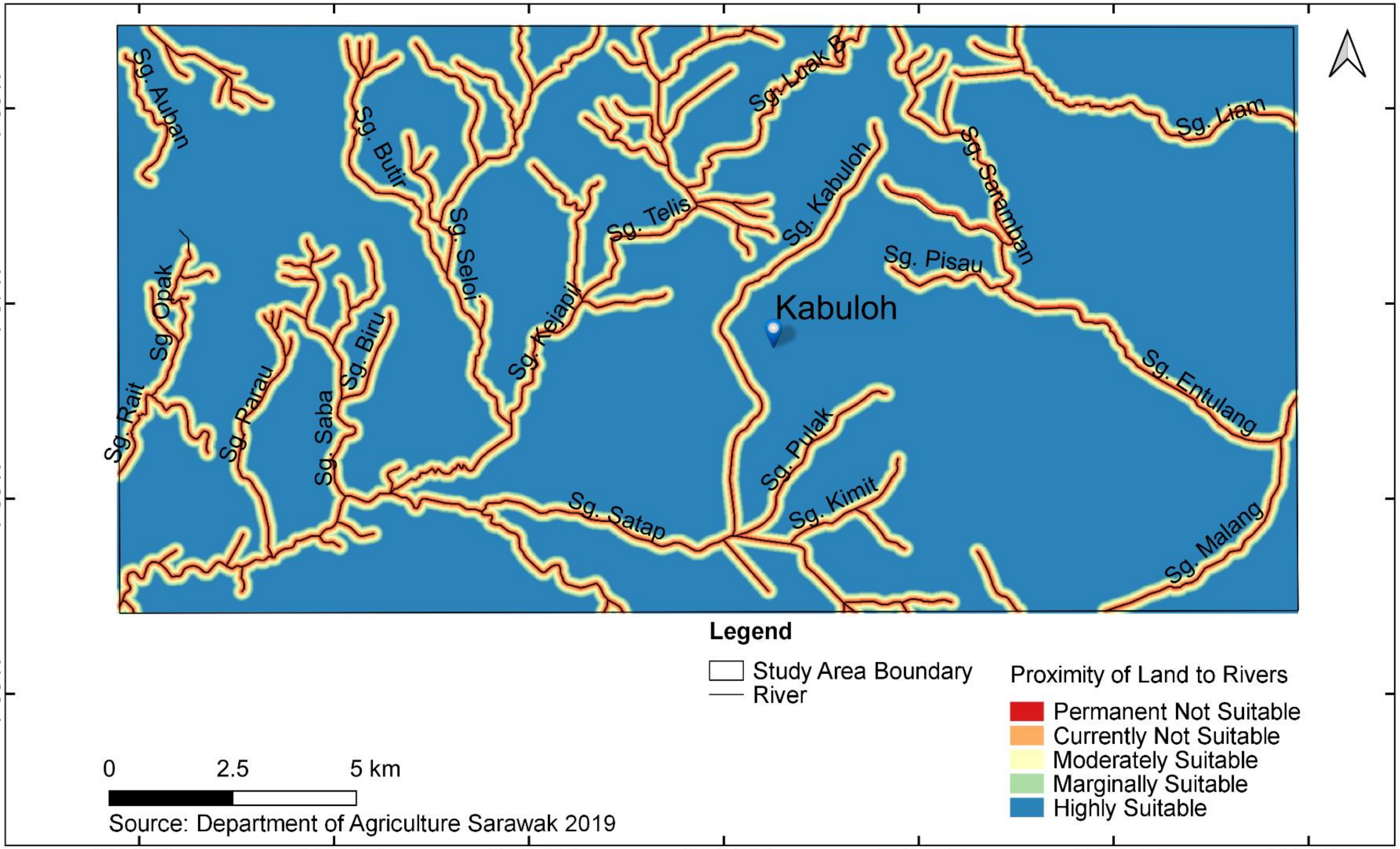

Figure 3.7: Proximity of land to rivers

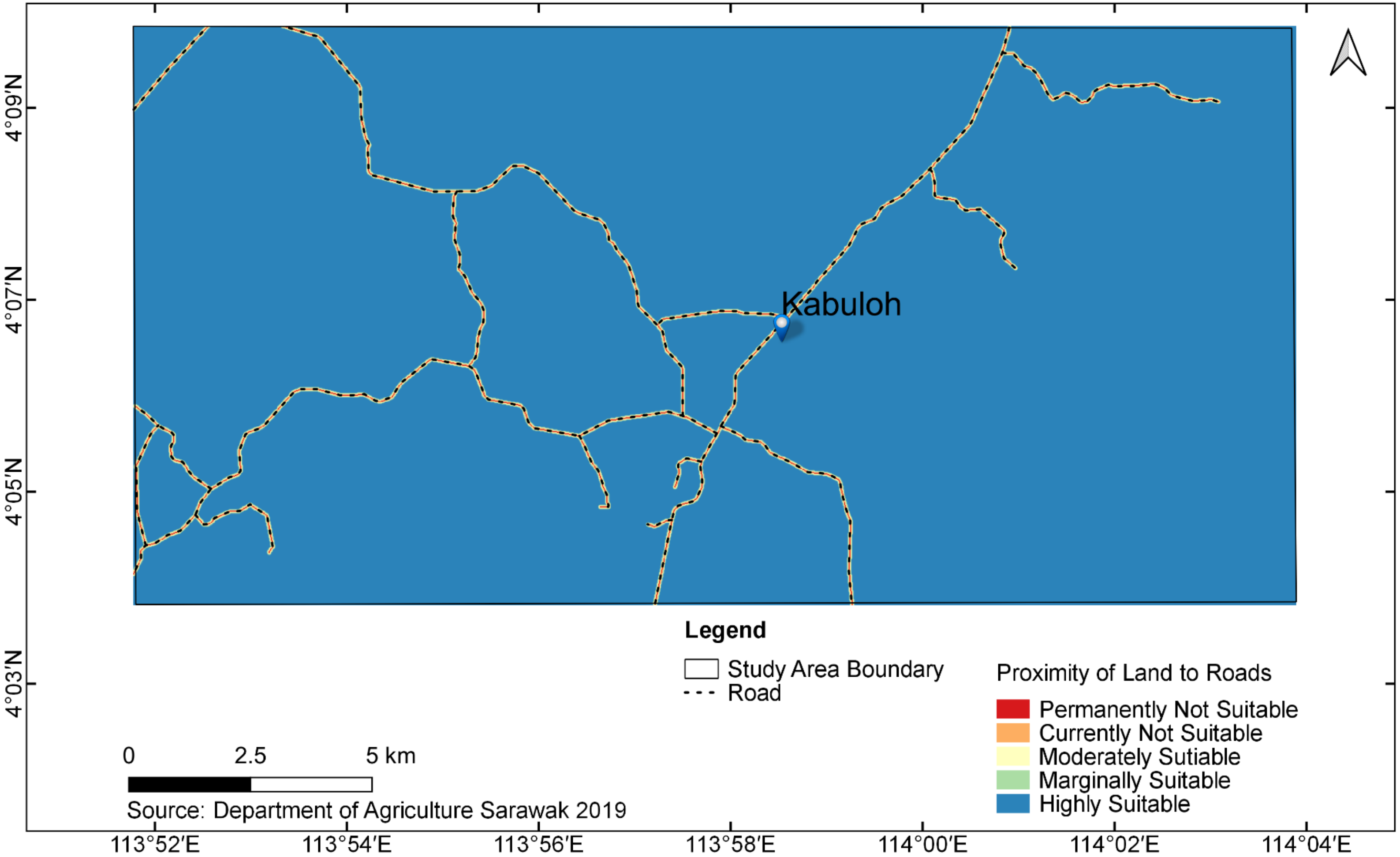

Figure 3.8: Proximity of land to roads

3.3 Determination of Criteria Weightage

Change of the weightage assigned to the criteria gives a different result of land suitability analysis. Decision-maker assigns the weightage to the criteria by input value between 0 to 1 to each raster layer before overlay analysis is processed (Romeijn et al. 2016). Reasonable weightage of the criteria needs to be identified to ensure the preciseness of the land suitability analysis.

The weightage of each criterion was obtained through the Fuzzy Analytic Hierarchy Process (FAHP). The FAHP approach examined the weightage of various criteria by applying for triangular fuzzy numbers, as shown in **Figure 3.9** (Maddahi et al. 2017). The triangular fuzzy numbers (TFNs) were applied for fuzzification of the pairwise comparison matrix. TFNs expressed each pair of criteria' relative strength and shown as $M = (l, m, u)$. In a fuzzy case, the parameters l, m, u symbolises the smallest possible value, the most promising value, and the largest possible value.

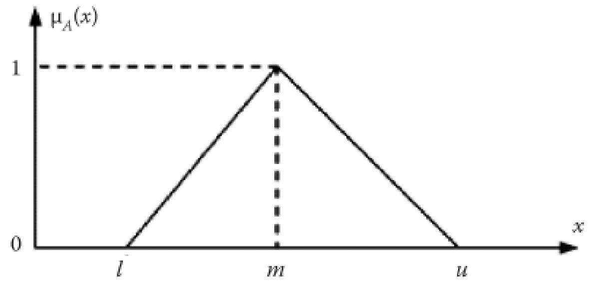

Figure 3.9: Triangular fuzzy number

Source: Figure reproduced from (Maddahi et al. 2017, 31).

The triangular membership function in **Equation 3.1** describes the linear relation of the fuzzy number (Chang 1996).

$$\mu_A(x) = \begin{cases} \frac{x-1}{m-1}, & l \leq x \leq m \\ \frac{u-x}{u-m}, & m \leq x \leq u \\ 0, & otherwise \end{cases}$$ **Equation 3.1**

Where μ_A = triangular fuzzy number, *l* = smallest possible value, *m* = most promising value, *u* = largest possible value

Diverse approaches were introduced in the literature, and the geometric mean method is one of the ways developed by Buckley (1985). The geometric mean method was implemented because it is simpler to compute (Pehlivan, Paksoy, and Çalik 2017). The steps of the geometric mean method are explained as follows:

First step: The fuzzy pairwise comparison matrix $\widetilde{D} = [\tilde{a}_{ij}]$ was formed as

$$\widetilde{D} = \begin{bmatrix} (1,1,1) & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ \tilde{a}_{21} & (1,1,1) & \dots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \dots & (1,1,1) \end{bmatrix}$$ **Equation 3.2**

where $\tilde{a}_{ij} \times \tilde{a}_{ji} \approx 1$ and $\tilde{a}_{ij} = w_i/w_j, i, j = 1,2, \dots, n$.

Second step: The fuzzy geometric mean value for each criterion was calculated as

$$\tilde{r}_i = (\tilde{a}_{i1} \times \tilde{a}_{i2} \times \dots \times \tilde{a}_{in})^{1/n}$$ **Equation 3.3**

Third step: The fuzzy weight for each criterion was computed as

$$\widetilde{w}_i = \tilde{r}_i \times (\tilde{r}_1 + \tilde{r}_2 + \dots + \tilde{r}_n)^{-1}$$ **Equation 3.4**

where $\tilde{r}_k = (l_k, m_k, u_k)$ and $\tilde{r}_k{}^{-1} = (1/u_k, 1/m_k, 1/l_k)$.

Fourth step: The fuzzy weights $\widetilde{w}_i = (l_i, m_i, u_i)$ were defuzzified by Centre of Area (CoA) method as below:

$$\widetilde{w}_i = \frac{l_i + m_i + u_i}{3}$$ **Equation 3.5**

(Buckley 1985; Tzeng and Huang 2011).

Linguistic variables were determined for various degrees of preference in **Table 3.3** to perform the pairwise comparison using TFNs.

Table 3.3: Triangular fuzzy numbers of linguistic variables

Linguistic variables for preference	**Crisp number**	**Triangular fuzzy numbers**	**Reciprocal triangular fuzzy numbers**
Extremely important	9	(9, 9, 9)	(1/9, 1/9, 1/9)
Strongly important	7	(6, 7, 8)	(1/8, 1/7, 1/6)
Essentially important	5	(4, 5, 6)	(1/6, 1/5, 1/4)
Moderately important	3	(2, 3, 4)	(1/4, 1/3, 1/2)
Equally important	1	(1, 1, 1)	(1, 1, 1)
Intermediate values	2, 4, 6, 8	(7, 8, 9), (5, 6, 7), (3, 4, 5), (1, 2, 3)	(1/9, 1/8, 1/7), (1/7, 1/6, 1/5), (1/5, 1/4, 1/3), (1/3, 1/2, 1)

A consistency ratio (CR) was determined by using **Equation 3.6** to examine the comparison's consistency. The CR value should be less than or equal to 0.1 to indicate a moderate consistency level, or the comparison is inconsistent (Ramík and Korviny 2010).

$$CR = CI/RI$$ **Equation 3.6**

$$CI = \frac{\lambda_{max} - n}{n - 1}$$ **Equation 3.7**

where:

CI = Consistency Index

λ_{max} = Principle Eigenvalue of Matrix *n* = Number of Criteria

RI = Random Index, obtained from **Table 3.4**. **Table 3.4** gives the RI for different N, N = number of criteria.

Table 3.4: Random inconsistency indices (RI)

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.24	1.41	1.45	1.49

3.4 Perform Standardization of Criteria

Standardization is the process to convert the assessment criteria of different extent and units into a standard range (Badr et al. 2018). A standardization process is needed before different raster layers can be overlaid. The standardization process converts the criteria measurement scales to a comparable measurement unit (Malmir et al. 2016). The assessment criteria that were considered as input were standardized through fuzzy linear membership functions.

Each sub-criteria score is tabulated in **Table 3.5** according to the scoring given in Akinci, Özalp, and Turgut (2013)'s study. Sub-criteria of great soil group and agricultural land use capability class were scored within the range of 0-1. The range of the crops that can be nurtured in the study area was considered in the scoring. Higher points were given to the sub-criteria that is more favourable for the cultivation of various species. For example, alluvial soil that establishes a very productive area for crop cultivation due to the physical and chemical properties was assigned 1 point (Dwevedi et al. 2017). The soil groups with less suitable physical and chemical properties were given a lower score based on the limiting factors. In this event, arenaceous soil was given a 0.1 point due to its low fertility and low water-holding capacity (Hashim 2003).

Table 3.5: Score of sub-criteria

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

Source: Table reproduced from Akinci, Özalp, and Turgut (2013, 78)

When assessing the study area in terms of ALUCC, land with class 2 was assigned 1 point because of the wide variety of the crops nurtured in class 2 land. Intermediate scorings were given to the other class in light of the limiting factors of each class. Class 5 and O5 land with severe limitations that hinder crop growth were given 0.1 points (Department of Agriculture Sarawak 1982a).

The slope of the study area was standardized based on the fuzzy linear function. The slope of land affects the suitability of agricultural land use through the limitations of the steeper slope. The steep slope causes difficulties in mechanizing crop management and accelerates water erosion (Orshoven et al. 2012). Therefore, low fuzzy membership bound was set at 25%, which the land with such a slope is not suitable for mechanization of crop management (Koulouri and Giourga 2007).

Proximity of land to roads and rivers were standardized based on the fuzzy linear function. The nearer the land to the roads or rivers means lower transportation and other relevant costs or better access to the water source for irrigation. However, there should be a buffer zone between agricultural land and roads or rivers. Hence, the high fuzzy membership bound was set as 50m and 200m to represent the zone that is not suitable for cultivation, respectively (Lees and Peres 2008; Tercan and Dereli 2020). Additionally, the land located distant from the roads or rivers can still be considered suitable for cultivation as long as the land is fertile.

3.4.1 Fuzzification of Criteria

Fuzzification is the approach of modifying the assessment criteria into fuzzy membership values based on fuzzy membership functions. The fuzzification process is similar to the normal reclassification process. The output of the fuzzification process is commensurate values in the extent between 0 and 1. Two techniques are available to determine a suitable fuzzy membership function (Burrough and McDonnell 1998). The first technique is the fuzzy k-means method. The fuzzy k-means method determines a suitable fuzzy membership function relying on extensive training data provision (Malczewski 2004). The fuzzy k-means approach is widely adopted in a sophisticated system where many variables are entailed, and a mass of training samples are ready. Another technique is the semantic import (SI) approach. SI approach is broadly applied when a decent amount of training samples are not obtainable (Qiu et al. 2014). In some previous studies, the general requirements of suitable agricultural land use characteristics are available (Sys et al. 1993; Akinci, Özalp, and Turgut 2013; Tercan and Dereli 2020). Hence, the SI approach was chosen to determine the fuzzy membership functions of this study's assessment criteria. The boundary condition of each criterion to delineate the agricultural land use suitability is tabulated in **Table 3.6.**

Table 3.6: Boundary condition of criteria for delineating agricultural land use suitability

Criteria	Membership function	Low fuzzy membership bound	High fuzzy membership bound	Researchers
Great soil group	Fuzzy linear	Arenaceous	Alluvial	Akinci, Özalp, and Turgut (2013)
Agricultural land use capability class	Fuzzy linear	Class O5	Class 2	
Slope	Fuzzy linear	25%	0%	
Proximity to roads	Fuzzy linear	0m	50m	Tercan and Dereli (2020)
Proximity to rivers	Fuzzy linear	0m	200m	Lees and Peres (2008)

3.4.2 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 were fixed between 0 and 1. Value of 0 means no membership of the specified fuzzy set, while 1 implies full membership in the altered layer. The membership function is determined as below:

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

Equation 3.8

μ(x): membership value, a: low bound, b: high bound (QGIS 2002)

3.5 Agricultural Land Use Suitability Map

After the criteria weights were appointed to each criterion layer in the Quantum Geographic Information Systems (QGIS) environment, each criterion layer's raster map was overlaid through the weighted sum overlay analysis. The agricultural land use suitability map was classified into five suitability classes of equal range according to the land suitability classification of the Food and Agriculture Organization (FAO) Framework produced by FAO (1976). The suitability classes are highly suitable, moderately suitable, marginally suitable, currently not suitable, and permanently not suitable. FAO Framework is a universal and scale-independent evaluation system to determine land suitability for specific use (Verheye 2002). The agricultural land use suitability map was later overlaid with the map of the current land cover map to determine the suitability of existing agricultural land use.

3.6 Identification of Potential Threats of Existing Agricultural Land Use

The existing agricultural land use was assessed qualitatively with respect to the land cover trajectory, habitat existence of protected flora and fauna, water catchment area, slope, river system, ownership of plantation area, and human settlement area before oil palm establishment to determine potential threats brought by the existing agricultural land use. The existing agricultural land use was spatially overlaid on various spatial data across the study area in the QGIS interface. The spatial data of the human settlement area was sourced from the Department of Agriculture Sarawak, as shown in **Figure 3.10**. The ownership of the plantation area was sourced from the Department of Survey and Mapping Malaysia. Furthermore, the habitat existence of the protected flora and fauna was sourced from the International Union for Conservation of Nature (IUCN) and Forest Research Institute Malaysia (FRIM). Sarawak Wild Life Protection Ordinance 1998 was referred to determine the protected flora and fauna species. The spatial data of the water catchment area was sourced from the Department of Irrigation and Drainage Sarawak. The data about slope and river system were the same as previously applied in the agricultural land use suitability assessment. The spatial data used to identify potential threats of existing agricultural land use and their sources are summarized in **Table 3.7**.

Table 3.7: Source of spatial data used for existing agricultural land use assessment

Spatial data	**Source of data**
Major agriculture commodities map	Department of Agriculture Sarawak 2019a
Human settlement area	Department of Agriculture Sarawak 2019b
Ownership of plantation area	Department of Survey and Mapping Malaysia 2015
Habitat existence of the protected flora	FRIM 2004
Habitat existence of the protected fauna	IUCN 2020
Water catchment area	Department of Irrigation and Drainage Sarawak 2008
Slope	USGS Earthexplorer 2010
River system	Department of Agriculture Sarawak 1982b
Land cover trajectory before oil palm establishment	Gaveau, Salim, and Arjasakusuma 2016

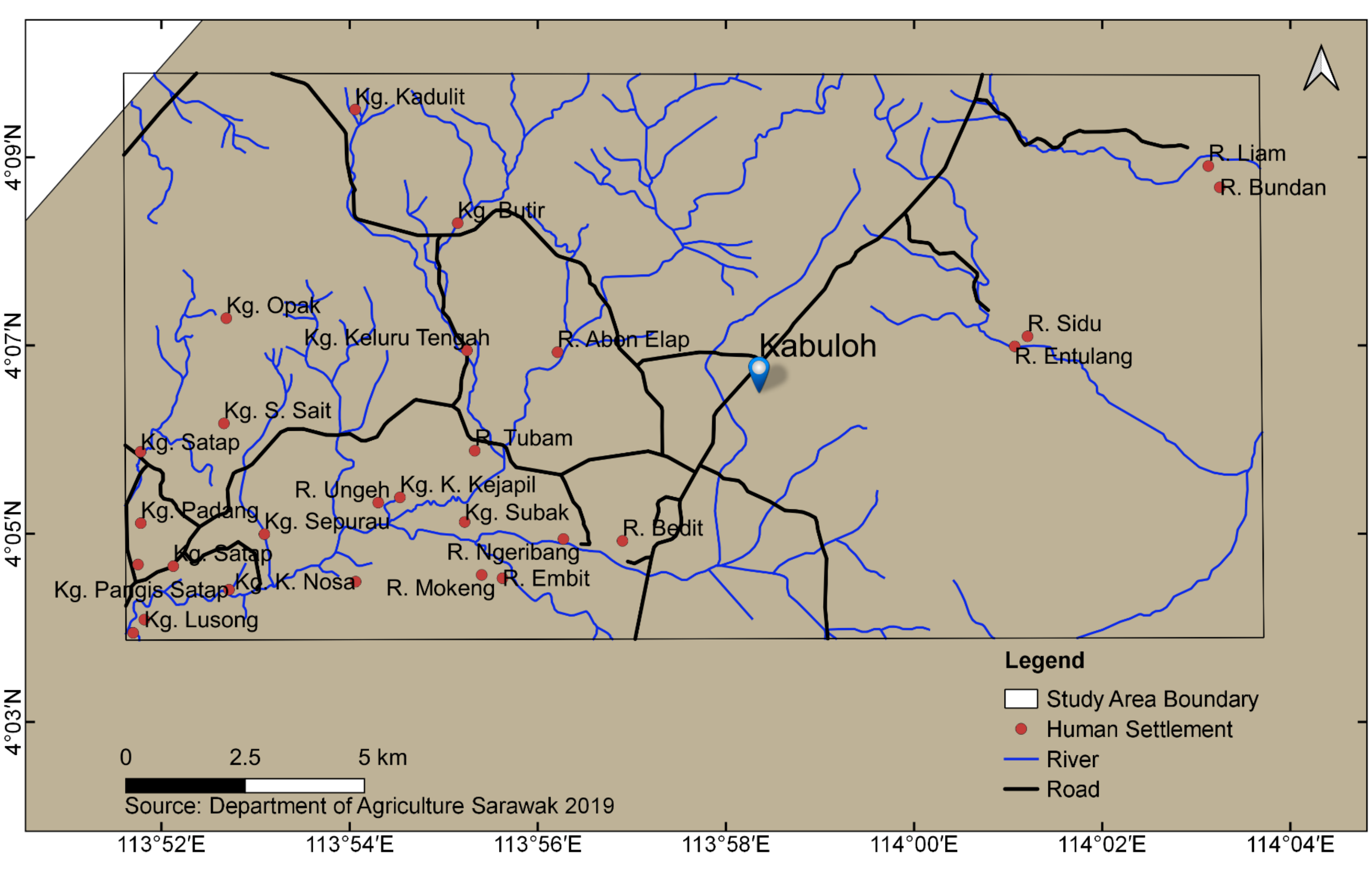

Figure 3.10: Human settlement area

3.7 Recommendation of Crops for Future Agricultural Land Use

Suitable crops were recommended based on the agricultural land use suitability assessment to optimize the agricultural land use in the study area. These crops were recommended to enhance the sustainability of agricultural land use. Specific crops were recommended for the agricultural land with severe limitations, such as high water table, high salinity, and high organic matter content. Several crops can thrive in the land with these severe limitations, paddy and sago, without the need for intense ground improvement. Paddy can be cultivated in a flooded area with imperfectly drained soil (Sys et al. 1993; Dengiz 2013). Sago can be planted in peat area as long as the pneumatophores are not submerged in water (Flach 1997; Hiroshi and Toyoda 2018). More paddy can be cultivated to improve Sarawak's rice production since Sarawak had only achieved 51% self-sufficiency in rice (Petingi 2019). On the other hand, the Sarawak state government is committed to developing the sago industry, and the projected export value of sago to reach RM100 million by 2030 (Tawie 2019).

An alternative crop of oil palm was recommended, which is coconut, to promote crop diversity in the study area. Coconut-derived products have rising demands from the market (Tan 2019). coconut was only utilized to produce coconut oil. However, now it can produce coconut drinks, powder, and milk (Krishnakumar and Thampan 2018). The local supply of coconut is insufficient. Therefore, 100 million to 220 million coconuts need to be imported from other countries every year (Tan 2019). Coconut is also the fourth significant industrial crop in Malaysia after oil palm, rubber, and paddy (Sivapragasam 2008). The crop suitability assessment of these crops was conducted using similar criteria as the earlier agricultural land use suitability assessment. However, the score allocated to each criterion was modified to suit each crop's characteristics, as shown in **Table 3.8** for sago, paddy, and coconut cultivation.

Table 3.8: Score of sub-criteria for sago, paddy, and coconut cultivation

Great soil group	Score		
	Sago	Paddy	Coconut
Alluvial	1	0.8	1
Red-yellow Podzolic	0.8	0.5	0.7
Gley	0.7	1	0.5
Organic	0.6	0.7	0.4
Podzol	0.2	0.2	0.2
Arenaceous	0.1	0.1	0.1
Agricultural land use capability class	**Score**		
	Sago	**Paddy**	**Coconut**
Class 2	1	1	1
Class 3	0.8	0.8	0.8
Class 4	0.6	0.7	0.6
Class O4	0.6	0.7	0.4
Class 5	0.5	0.6	0.1
Class O5	0.5	0.6	0.1

3.8 Zoning of Future Agricultural Land Use

The result of agricultural land use suitability assessment, qualitative assessment of existing agricultural land use, and future agricultural land use suitability assessment were integrated to produce a future agricultural land use map. The future agricultural land use map divides the study area into different zones:

i. The zone that is suitable to undergo agricultural activities;
ii. The zone that needs to be rehabilitated to restore the ecosystem functions;
iii. The zone that should be assigned as a buffer zone to mitigate potential threats brought by the existing agricultural land use; and
iv. The zone that should be assigned as remained at its original state to protect the ecosystem functions.

The assessment results of agricultural land use suitability and exising agricultural land use were used to determine the planning of future agricultural land use in the study location, which are discussed in the next chapter.

Chapter 4 Results and Discussion

The results of agricultural land use suitability assessment, potential threats of existing agricultural land use, mitigation strategies of potential threats and future agricultural land use map are presented in this chapter. The results of the criteria weightage calculation are presented in **Section 4.1**. The weightage was used for the agricultural land use suitability assessment. The suitability of agricultural land use in the study area is described in **Section 4.2**. Then, **Section 4.3** shows the potential threats of existing agricultural land use. Based on the identified potential threats, the recommendations to mitigate the threats are provided in **Section 4.4**. Additionally, several economic crops were recommended to promote polyculture cultivation in the study location. The suitability of recommended crops for future agricultural land use, such as sago, paddy, and coconut cultivation, is explained in **Section 4.5**. The outcome of agricultural land use suitability assessment, existing agricultural land use assessment and recommended crops' suitability assessment were integrated to produce the future agricultural land use plan as explained in **Section 4.6**. The research questions are answered in **Section 4.7**. Lastly, the limitations of the study are discussed in **Section 4.8**.

4.1 Calculation of Criteria Weightage

The FAHP method and the geometric mean method were implemented to calculate the weightage of the criteria. A pairwise comparison matrix was formed incorporated with the TFNs, as shown in **Table 4.1**. **Equations 3.2 - 3.5** were applied to turn the matrix into the weight of the criteria. The weightage of the criteria is shown in **Table 4.2** with the eigenvalue (λ_{max}), consistency index (CI), random index (RI), and consistency ratio (CR).

Table 4.1: Fuzzified pair-wise comparison matrix of the criteria

Criteria	Great soil group	Agricultural land use capability class	Slope	Proximity of land to roads	Proximity of land 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 of land to roads	(1/9, 1/8, 1/7)	(1/7, 1/6, 1/5)	(1/5, 1/4, 1/3)	1	1
Proximity of land to rivers	(1/9, 1/8, 1/7)	(1/7, 1/6, 1/5)	(1/5, 1/4, 1/3)	1	1

Table 4.2: Weight of criteria

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

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

Great soil group was given the highest weight in the agricultural land use suitability assessment (Akinci, Özalp, and Turgut 2013; Romeijn et al. 2016; Jamil, Sahana, and Sajjad 2018; Jamil, Ahmed, and Sajjad 2018; Kahsay et al. 2018). The great soil group has the highest impact since the features of great soil groups, such as fertility, drainage and texture, have a significant role in thriving crops. On the other hand, the distance to infrastructure was given the lowest weightage (Zabihi et al. 2015; Tercan and Dereli 2020). The distance of land to infrastructure will induce a minor impact on the overall suitability assessment since it has the lowest weightage.

Different soil types were classified, as shown in **Figure 3.4**, to determine the soils' conditions and behaviours. By knowing the characteristics of the soils, the soil performance can be estimated for agricultural activities. Hence, it is significant to know the major soil type in the study area when evaluating agricultural land use's suitability. The study area's primary soil type is red-yellow podzolic soil (Department of Agriculture Sarawak 1982b). In the east of the study area, organic soil is available (Department of Agriculture Sarawak 1982b). Along the area in which different rivers flow, alluvial soils can be found due to the accumulation of the sediments carried by the rivers' flows (Akinci, Özalp, and Turgut 2013).

4.2 Agricultural Land Use Suitability

The agricultural land use suitability map produced after the weighted sum overlay analysis was divided into five categories: highly suitable, moderately suitable, marginally suitable, currently not suitable, and permanently not suitable, as shown in **Figure 4.1**. The resolution of the agricultural land use suitability map is 90 m/pixel.

(a) Highly Suitable

Approximately 5% (1,424 ha) of the study area was categorized into the class "Highly suitable" for agriculture. The land classified into this class has alluvial soil, class 2 agricultural land use capability, gentle to moderate slope (<8%). The area is located close to the river and road. As long as the buffer zone to the road (50m) and river (200m) is maintained, the land is suitable for crop cultivation. Most of the land has been used as agricultural land. Oil palm plantation dominates this area of land. A minority of the land was used for paddy cultivation. There is land that remained as primary and secondary forest. The forested area should be conserved to protect the biodiversity at the study location. Furthermore, there are three villages located in this area. The villagers could have a higher yield of agricultural product in this zone.

(b) Moderately Suitable

About 42% (11,923 ha) of the study area was classified as moderately suitable land for agricultural land use. The land classified into this class has alluvial soil and red-yellow podzolic soil distributed evenly. The land has class 3 and class 4 agricultural land use capability and is located near the trunk road and river. The land is found to have a moderate and very steep slope (<20%) that becomes the lands' limitation. The land is covered by oil palm trees, primary and secondary forests. The forests should be protected to maintain biodiversity at the study location. A minority of the land has paddy cultivation. Moreover, nine villages are found in this area. The crops planted by the villagers in this area could have satisfying production.

(c) Marginally Suitable

There is 33% (9,353 ha) of the study area categorized as marginally suitable for agricultural land use. 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 and very steep slope (<20%), while a minority has a steep slope. The land is near to rivers but far from trunk roads. The land is covered by oil palm and primary forest evenly. The primary forest should be conserved to prevent further deterioration of biodiversity. Subsequently, a minority of land is used as paddy cultivation, sundry tree cultivation, and a small secondary forest patch. Additionally, seven villages are found to live in this area. Average crop yield can be expected for the crops planted by the villagers in this area.

(d) Currently Not Suitable

There is 19% (5,370 ha) of the land classified as currently not suitable for crop cultivation. The soil type found here are primarily organic soil, and a minority was red-yellow podzolic soil and podzol soil. The slope at this area is moderate, while a minority has a sheer slope (<30%). The land is located far from both rivers and trunk roads. In this zone, oil palm trees dominate the land cover and left with a small area planted with paddy. A small patch of primary and secondary forest can be found here. The forest should be conserved, which is vital for biodiversity maintenance. Besides, six villages can be found in this area. The villagers could not have ample crop yield in this area.

(e) Permanently Not Suitable

Approximately 1% (162 ha) of the land at the study area is grouped as permanently not suitable for agricultural land use. The type of soil found in the area is podzol soil. The sheer slope was determined in this area. The land here is only covered with secondary jungle and sundry tree cultivation, and no large scale plantation is found here since the land could not ensure the crop produces sufficient yield. Additionally, the land is located far from rivers and trunk roads, which brings difficulties for irrigation and transportation.

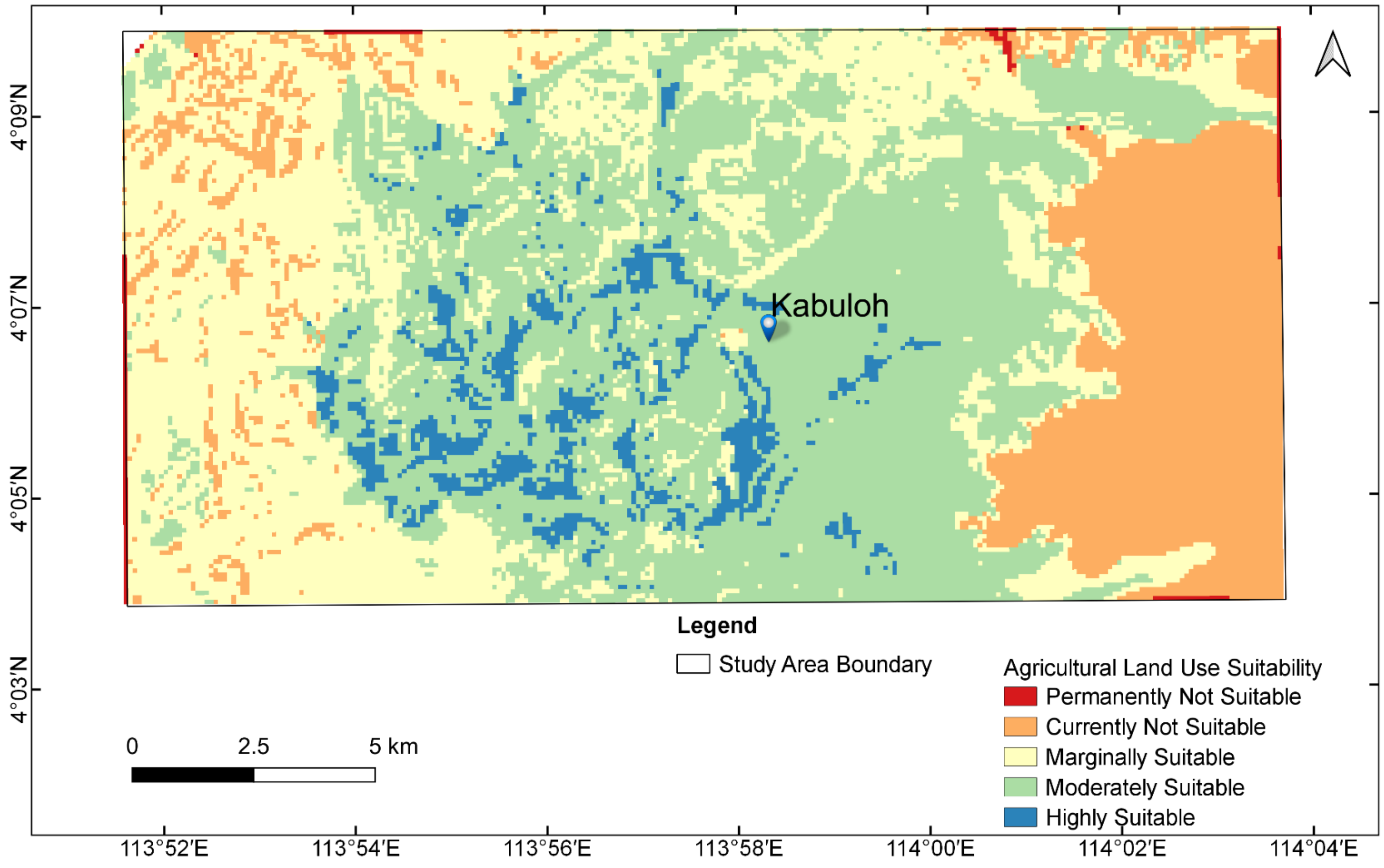

Figure 4.1: Agricultural land use suitability map

4.3 Potential Impacts of Existing Agricultural Land Use

Based on the overlay of the agricultural land use suitability map and the existing agricultural land use map, it was determined that some of the existing oil palm plantations are developed in the area that is currently not suitable for oil palm plantation. It is believed that this particular area has been modified to become a land that at least the oil palm can survive on the land. Various potential impacts of existing agricultural land use on the environment and society were identified based on map overlay analysis.

4.3.1 Potential Impact of Existing Agricultural Land Use on Forested Landscape

The major agriculture commodity of the study area is the oil palm tree, as evidenced in **Figure 3.3**. Oil palm tree covers 40% of the study area, which is equivalent to 11372.57 ha. The domination of a single type of crop in the study location could affect the balance of biodiversity. Part of the oil palm plantations is developed by deforestation by overlaying the land cover trajectory before oil palm establishment, as indicated in brown colour in **Figure 4.2**. The deforested zone found at the oil palm plantation is in line with Koh and Wilcove (2008)'s study, which determined that around 59% of the oil palm plantations in Malaysia is developed by deforestation**.** Deforestation found in the study location could bring some negative impacts to the environment and society. Before the area is developed to become an oil palm plantation, the study area can have a high biodiversity level due to different animal and plant species within the forest. The area developed to become an oil palm plantation could cause the protected flora and fauna in the study location to lose their habitat and threaten the animal and plant population. This presupposition is according to the past evidence from various studies which reported oil palm plantations developed by deforestation causes lower animal and plant population (Fitzherbert et al. 2008; Koh and Wilcove 2008; Mercer, Mercer, and Sayok 2013).

Furthermore, the oil palm plantation covering 40% of the study location, as demonstrated in **Figure 3.3**, could reduce the primary forest species in the Kabuloh region and the surrounding area. Only a minority of the species richness could be preserved after forests were converted into oil palm plantation in the study location, as has occurred in a Sabah's plantation area (Koh and Wilcove 2008). The impacted species could include but not limited to wood-inhabiting fungi, plants, dung beetles, ants, lizards, amphibians, birds, and mammals (Dislich et al. 2017). Other than lower species richness is found, the species that remain in the local ecosystem after deforestation is found to be common, while forest species is found to be absent after oil palm trees are cultivated. The reasons behind the biodiversity loss could be the low structural complexity of oil palm plantation compared to a forest and extreme microclimatic conditions; oil palm can be 6.5 °C warmer than forest (Luskin and Potts 2011; Hardwick et al. 2015). The rivers around oil palm plantation in the study area could have a lower abundance and diversity of invertebrate species due to damage of riverbank habitats and exposure to pesticides fighting Rhinoceros beetle (Mercer, Mercer, and Sayok 2013).

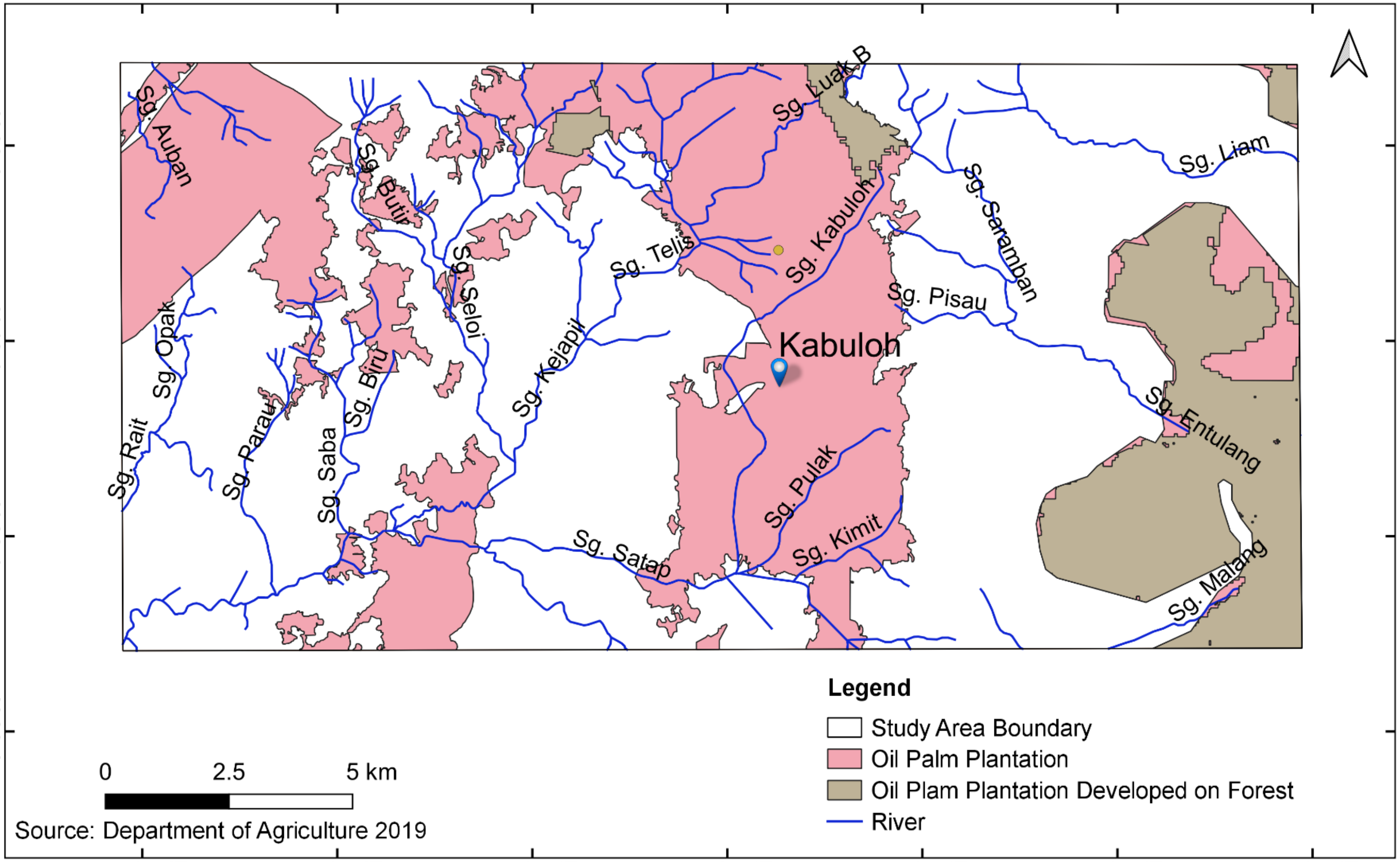

Figure 4.2: Oil palm plantation developed on forest

4.3.2 Potential Impact of Existing Agricultural Land Use on Peatland

The oil palm plantations could negatively impact 4584.2 ha of peatland in the study area, located in the study area's eastern zone, as shown in **Figure 4.3**. The peatland was deforested to establish oil palm plantations, which delivered the stored carbon into the environment and exacerbated global warming (Germer and Sauerborn 2008). The finding reinforces Wahid et al. (2010)'s work, revealing that peatland in Malaysia was converted into oil palm plantations.

The converted peatland in the study location, as presented in the red zone of **Figure 4.3**, could cause the carbon dioxide (CO_2) emission to become more severe and negatively impact the ecosystem to regulate the climate. A vast amount of CO_2 will be emitted when peatland is drained to cultivate the oil palm trees on it. The peat that remains in the peatland is allowed to oxidize and decompose when the stagnant water is drained. Drainage of peat could cause emissions ranged from 26 to 146 Mg CO_2/ha/year (Schrier-Uijl et al. 2013). The wide range of of the CO_2 emission rate depends on the depth of drainage, and the emission rate will change. An increase of 10 cm drainage depth of peat will bring an additional 9 Mg CO_2/ ha/ year to the environment (Couwenberg, Dommain, and Joosten 2010). The dissolved organic matter drained from the peatland releases additional CO_2 to the environment, and total carbon emission increases by 22% (Moore et al. 2013). It would take several decades to several centuries for the carbon emissions saved through the use of biofuel to compensate for the carbon lost through peatland conversion (Danielsen et al. 2009).

Additionally, oil palm plantations established on peatland in the study location, as demonstrated in **Figure 4.3**, could store less carbon than forest. Although oil palm trees can assimilate more CO_2 due to high fruit production, the higher rate of carbon uptake does not offset the carbon loss when the peatland was cleared for oil palm plantation. The reason is that peatland has more carbon aboveground and belowground biomass compared to oil palm plantations (Kotowska et al. 2015). In addition, the conversion of peatland could cause the oxidation of methane (Melling, Hatano, and Goh 2005)..

Besides that, the peatland converted to oil palm plantation in **Figure 4.3** could negatively impact the ecosystem to control the extreme event. The reason is that the organic content and the resins in the drained peat are very flammable. Additionally, the peat fires can burn underneath the ground level, increasing the difficulty of extinguishing the fire (Mackie 1984). Moreover, peatland conversion could cause the peatland that functions as ornamental resources to deteriorate. The reason is that the drainage of peat for oil palm cultivation causes the economically important ornamental fish species to decrease, such as the *Betta* spp. and the Arowana, *Scleropages formosos* (Yule 2010; Posa, Wijedasa, and Corlett 2011).

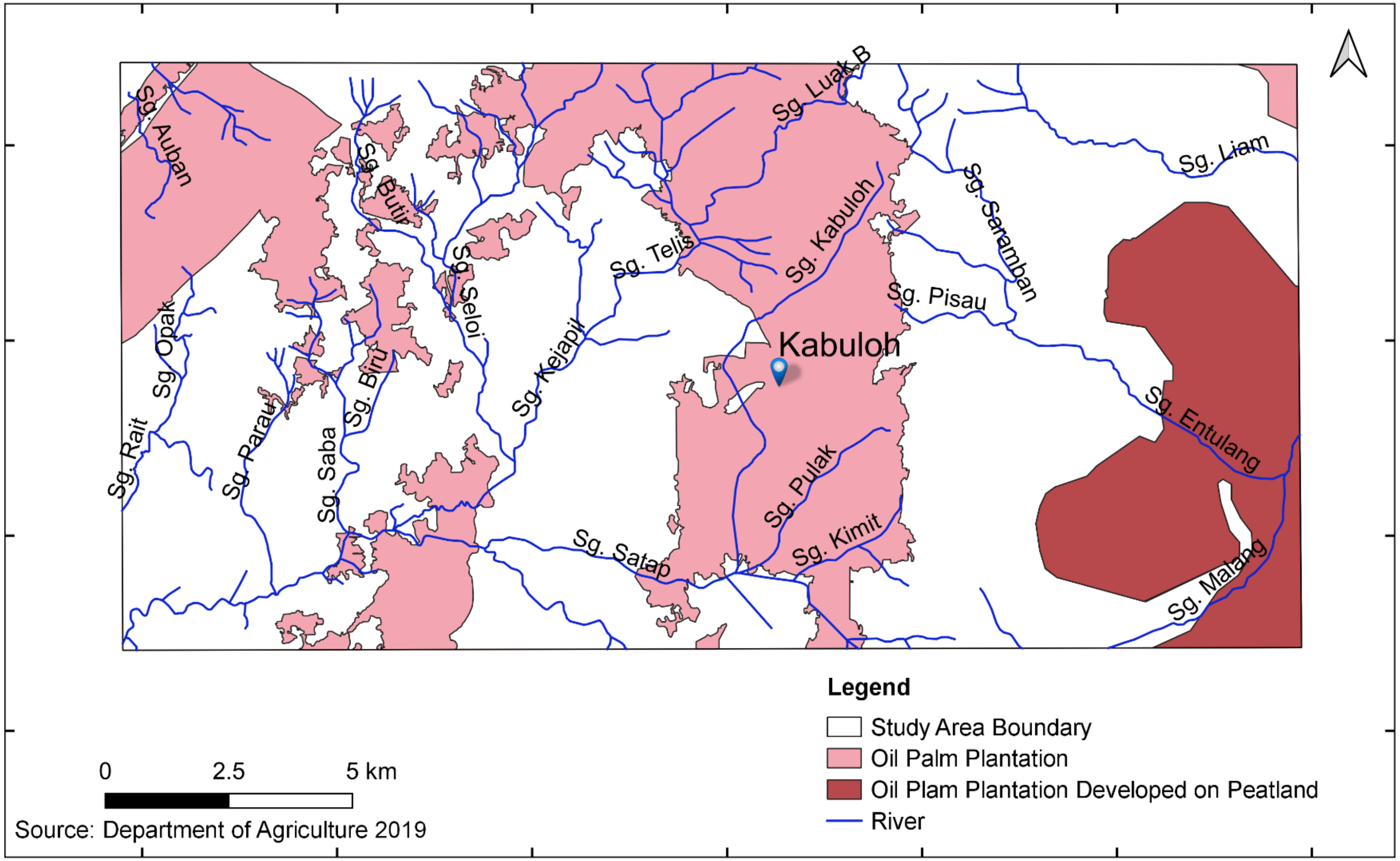

Figure 4.3: Oil palm plantation on peatland

4.3.3 Potential Impact of Existing Agricultural Land Use on Hydrological System

Plenty of rivers are crossing through the oil palm plantation based on the map in **Figure 4.4**. The rivers which cross through the oil palm plantation are highlighted in red colour on the map. Additionally, the oil palm plantations are established within the water catchment areas, as shown in **Figure 4.5**. Two different water catchment areas are highlighted in different colours. The water catchment areas are Buri Catchment Area (yellow zone) and Bekenu Catchment Area (orange zone). There is 37.3% of oil palm plantation established on Buri Catchment Area while 25.9% of oil palm plantation is established on Bekenu Catchment Area, as shown in **Table 4.3**.

The water regulation and supply of two water catchments in the study location could be negatively impacted by oil palm plantation, as shown in **Figure 4.4**. Water regulation and supply is about the quantity, quality, and timing of water collected in and flowed out of the natural ecosystem (Reid et al. 2005). The oil palm plantation could decrease the water storage of the water catchment area, raise annual water yield, and deteriorate the river's water quality at the study location (Comte et al. 2012).

Water storage of two water catchments in **Figure 4.4** could be lowered in numerous conditions by the oil palm plantation identified in the study location. For instance, water storage is decreased when irrigation is used to increase oil palm productivity during drought season (Famiglietti 2014). Additionally, the water storage is reduced when peatland was drained in favour of oil palm plantation (Merten et al. 2016). Peatland acts like a giant sponge that contains huge water volume before it was drained. After drainage was completed, the peat is unavoidably lost either due to fire or oxidation, reducing the catchment area’s water storage capability lastingly (Andriesse 1988). Soil subsidence which occurred after the peat is lost could lower the ground surface level significantly. The water table level can then rise above ground level during high rainfall season, subsequently bringing a more significant risk of flooding (Page et al. 2009).

Besides, the water storage of the water catchment areas in the study location could be reduced when the infiltration rate of water into the soil is lower. The infiltration rate of water into the soil was decreased due to soil compaction brought by heavy machinery and land clearing (Rieley 2007). Lowered infiltration rate could lead to a higher degree of surface run-off and decreased amount of groundwater recharge. This condition could amplify the response of catchment area to rainfall, such as shorter time-to-peak and higher peak discharge (Bruijnzeel 2004). In the end, the risk of flooding is increased, which is a similar consequence of peatland drainage. However, the magnitude of flooding risk depends on the difference in hydraulic conductivity before and after land conversion (Rieley 2007).

Furthermore, the oil palm plantation in the study location, as presented in **Figure 3.3**, could increase the water yield in the study location. An increment of water yield could be created by

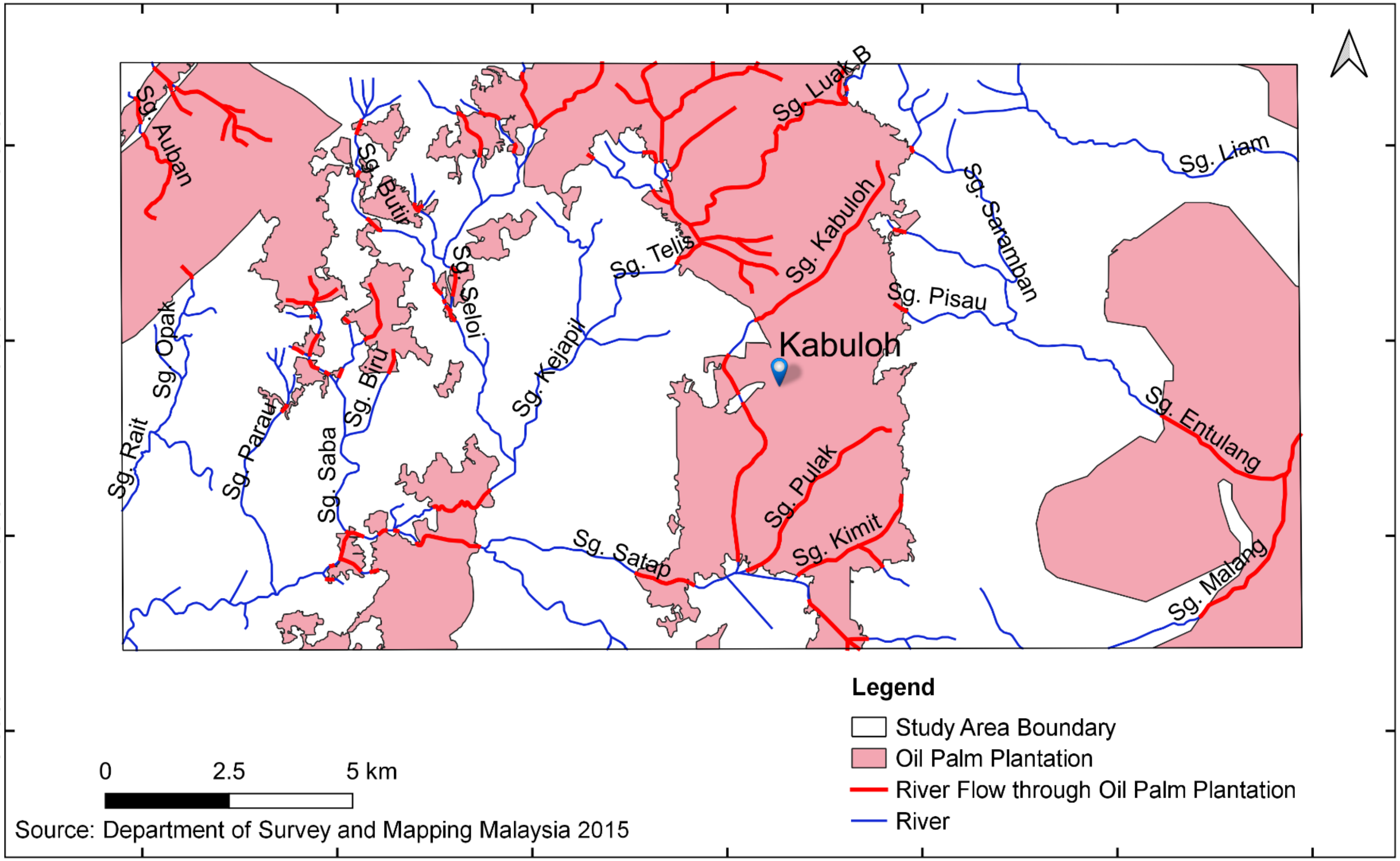

Figure 4.4: Oil palm plantation and rivers

a lower evapotranspiration rate and decreased infiltration rate of oil palm plantations compared to forests. In Malaysia, young oil palm plantations could experience 270-420% increment of water yield than forest (Department of Irrigation & Drainage 1989). However, the evapotranspiration rate difference between oil palm plantations and lowland forests could become smaller in the mature oil palm plantation (Bruijnzeel 2004). Although the annual water yield is higher in oil palm plantations, the streamflow coming from groundwater, which is the baseflow is lower. Based on Yusop, Chan, and Katimon (2007)'s study, baseflow only accounts for 54% of streamflow in oil palm plantations but 70% in the forests. This condition implies that when the primary water source comes from baseflow during the drought period, the risk of drought increases in oil palm plantations. The drought risk could be amplified if the oil palm plantation was developed on peatland due to a higher loss of water storage capacity after peatland drainage (Tan et al. 2009).

The establishment of the oil palm plantation could negatively influence the water quality of the rivers which flow through the plantation in the study location, as highlighted in the red line in **Figure 4.4**. The deterioration of river water quality in the study location could be due to sediment run-off from the ground surface of the oil palm plantation. Sediment run-off is heavily increased by less coverage of ground cover and higher surface run-off in the plantation. The sediment run-off increases from 50 Mg/km^2/year in a forest to 100 Mg/km^2/year in an oil palm plantation (Department of Irrigation & Drainage 1989). The sediment load that emerges from the extended surface run-off could be a severe threat to the aquatic system around the plantation area (Bilotta and Brazier 2008). The runoff of chemical substances such as pesticides, herbicides, fertilizers washed away from the plantation could cause eutrophication of water bodies and negatively alter water quality and aquatic life (Gharibreza et al. 2013). The decline of aquatic life could lead to economic losses of the villagers who rely on fishing as income (Norwana et al. 2011).

Furthermore, the water quality of Sg. Entulang and Sg. Matang in **Figure 4.4** could be negatively impacted by peatland drainage for oil palm plantation development in the study location, as presented in the red zone in **Figure 4.3**. The reason is that some peatland has acid sulphate soil at its lower layer. The acid sulphate soil is exposed to the atmosphere after the complete oxidation of peat. The acidity of soil increases as the oxidation process occurs in the acid sulphate soil after exposure to the atmosphere. The rise of acidity could negatively impact the water quality of the hydrology system in the study location (Wösten, Ismail, and van Wijk 1997).

Table 4.3: Area of oil palm plantation on the water catchment area

Water catchment area	Area (hectare)	Percentage (%)
Buri catchment area	4238	37.3
Bekenu catchment area	2945	25.9

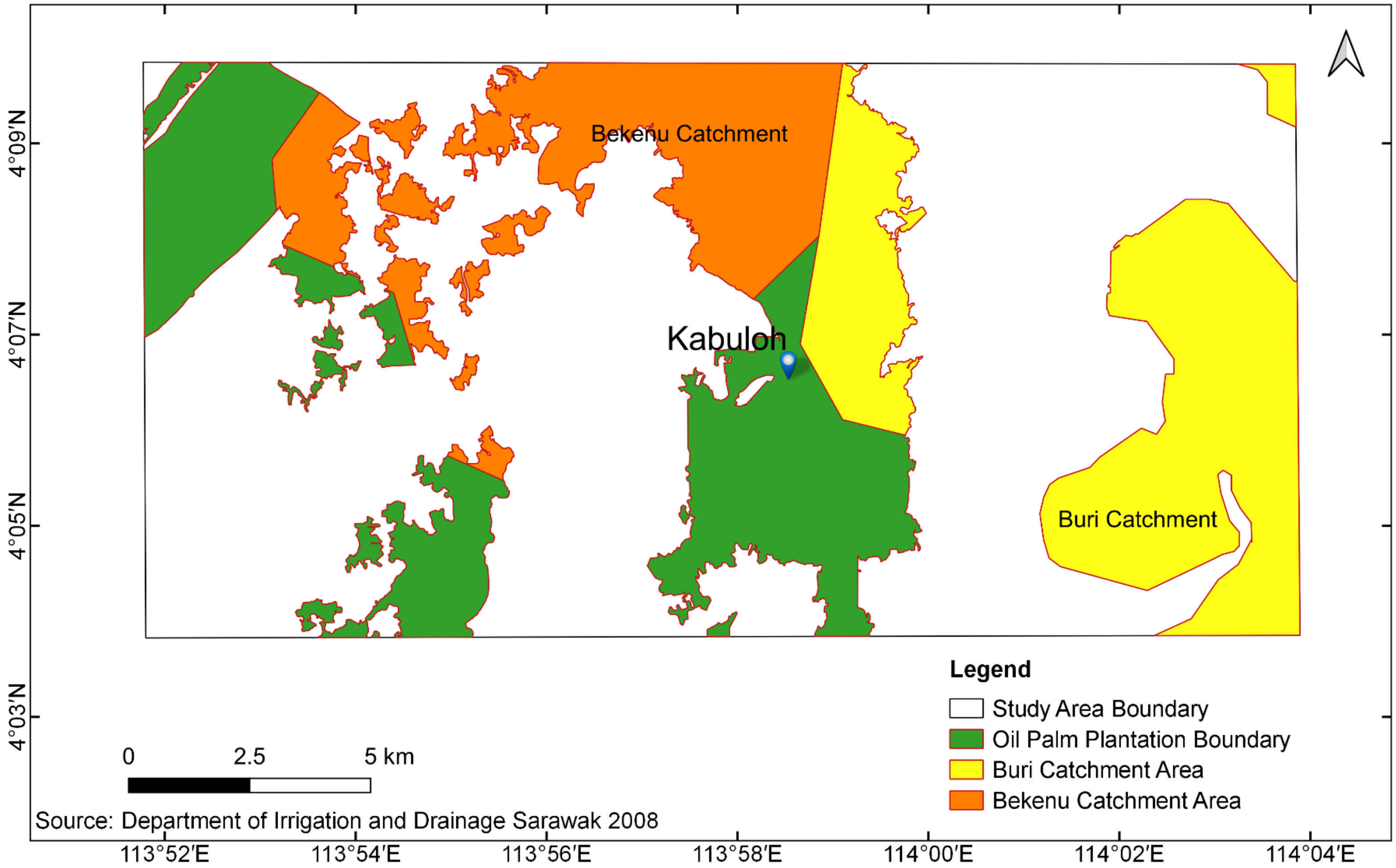

Figure 4.5: Oil palm plantation with respect to water catchment areas

4.3.4 Potential Impact of Existing Agricultural Land Use on Soil

The oil palm plantation was established on various great soil groups, as shown in **Figure 4.6**. Six different great soil groups were planted with oil palm, gley, alluvial, organic, arenaceous, red-yellow podzolic, and podzol. Based on **Table 4.4**, 57.8% of the oil palm plantation was established on the red-yellow podzolic soil, 26.9% of the oil palm plantation was established on the organic soil, 10.8% of the oil palm plantation was established on the alluvial soil.

Table 4.4: Area of oil palm plantation on different great soil group

Great soil group	Area (hectare)	Percentage (%)
Gley	465	4.1
Alluvial	1231	10.8
Organic	3057	26.9
Arenaceous	21	0.2
Red-yellow podzolic	6576	57.8
Podzol	23	0.2

Alluvial and red-yellow podzolic are suitable soil for oil palm cultivation since these soils are mineral soils (Paramananthan 2000). Organic soil is not suitable initially due to low nutrient levels (Gurmit et al. 1987) and challenging to manage (Andriesse 1988). However, planting oil palm trees on organic soil has begun due to the shortage of good mineral soils and enhanced understanding of organic soil planting (Corley and Tinker 2016). Gley is not suitable due to the waterlogged condition of the soil; arenaceous and podzol are not suitable due to the low level of nutrient and very sandy characteristics (Corley and Tinker 2016).

There is 31.4% of oil palm planted on unsuitable soil types, which are organic, gley, arenaceous, and podzol soil. Planting oil palm on an unsuitable soil type could lead to further soil degradation. Guillaume et al. (2016)‘s study showed that soil in oil palm plantations has lower carbon and nitrogen contents, carbon stocks, and higher bulk density. This phenomenon brings challenges to the sustainability of oil palm plantations.

The establishment of monoculture oil palm plantations in the study location, as shown in **Figure 3.3**, could cause a loss of soil fertility. Soil fertility is the reservation of adequate soil nutrients necessary for vegetation growth and the conservation of nutrient cycles between plants and soil. Before the oil palm plantation was established, the high ecosystem productivity of forest was maintained by the efficient cycling rock derived nutrients such as phosphorus and base cations between the plant and soil (Hedin et al. 2009). The cycling of nutrients is changed after the land use was altered to oil palm plantation (Ngoze et al. 2008). The massive numbers of nutrients earlier secured in the plants and soil organic matter are released via mineralization and decomposition due to land use conversion. However, the loss of soil fertility due to land use conversion depends on the original fertility of soil in the forest (Allen et al. 2015).

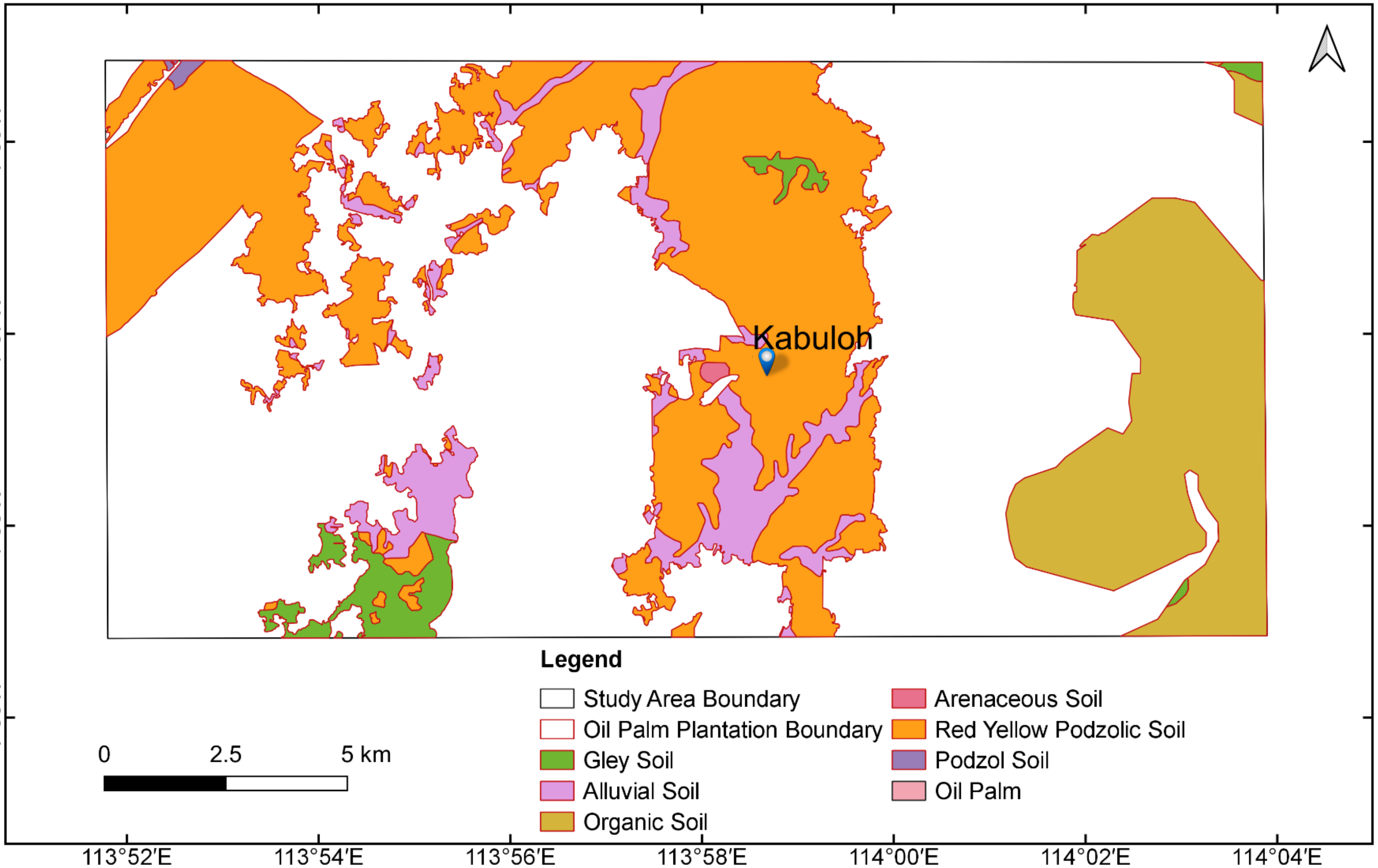

Figure 4.6: Oil palm plantation with respect to great soil group

The deforestation determined in the study location, as presented in the brown zone of **Figure 4.2**, could cause the land to lose high volumes of nutrients. The nutrients could be lost during plantation establishment due to forest clearing (Brouwer and Riezebos 1998). Additionally, significant amounts of nutrients could be lost during the harvest period of oil palm and the elimination of palm biomass (Hartemink 2005). Another possible way of nutrient loss is due to soil leaching. The rate of soil leaching is found to be higher for oil palm plantations compared to the forested area. The higher soil leaching rate induced lower efficiency of nitrogen retention and base cation retention in the soil which was found at developed oil palm plantations than the original lowland forest (Kurniawan 2016).

Furthermore, the low retention efficiency of oil palm plantations, as presented in **Figure 3.3**, could cause more significant nutrient leaching losses in the study location. Fertilizers, compost, lime, and nitrogen-fixing ground cover are the primary nutrient applied in oil palm plantations. The amount of mineral fertilizers input in the oil palm plantations is vast (Sheil et al. 2009). Fertilization rates are generally different, relying on available financial resources and proximity to fertilizer suppliers (Allen et al. 2015). The most commonly planted nitrogen-fixing ground cover when establishing a new oil palm plantation is the leguminous plants contributing 239 kg N/ha/year (Agamuthu and Broughton 1985). However, the leguminous plants eventually wither when the oil palm plantations mature, and the canopy closes, delivering a considerable amount of nitrogen that is susceptible to leaching (Campiglia et al. 2011). Waste products such as fronds, palm oil mill effluent, empty fruit bunches, and male inflorescences are applied as compost, which eventually decomposes and delivers nutrients into the soil (Comte et al. 2012). The increase in fertilization levels could lead to an increase in nutrient leaching (Kurniawan 2016). When the nutrients leach from the soil into the river, it will negatively affect the water quality of rivers, as highlighted in the red lines of **Figure 4.4** and the water catchment areas, as demonstrated in the yellow and orange zone of **Figure 4.5**.

Furthermore, the oil palm tree's locality and slope map were overlaid to investigate the potential hazard of planting oil palm trees on various slope gradients. The result of overlay analysis of oil palm and slope, as shown in **Figure 4.7**, shows that the oil palm plantation is established on various slope suitability. There are four types of slope suitability in the study area. The slope suitability class for oil palm was sourced from (Sys et al. 1993). 89.6% of oil palm plantation is established on the highly suitable slope, as shown in **Table 4.5**. Only less than 1% of oil palm plantations developed on land with currently not suitable slope. Hence, this result suggests that the potential hazards of planting oil palm trees on steep slopes, such as soil erosion and landslide, are less likely to happen in the study location.

Table 4.5: Area of various slope gradient suitable for oil palm

Slope suitability	Slope (%)	Area (hectare)	Percentage (%)
Highly suitable	0-8	10175	89.6
Moderately suitable	9-16	992	8.7
Marginally suitable	17-30	189	1.7
Currently not suitable	31-38	3	<1

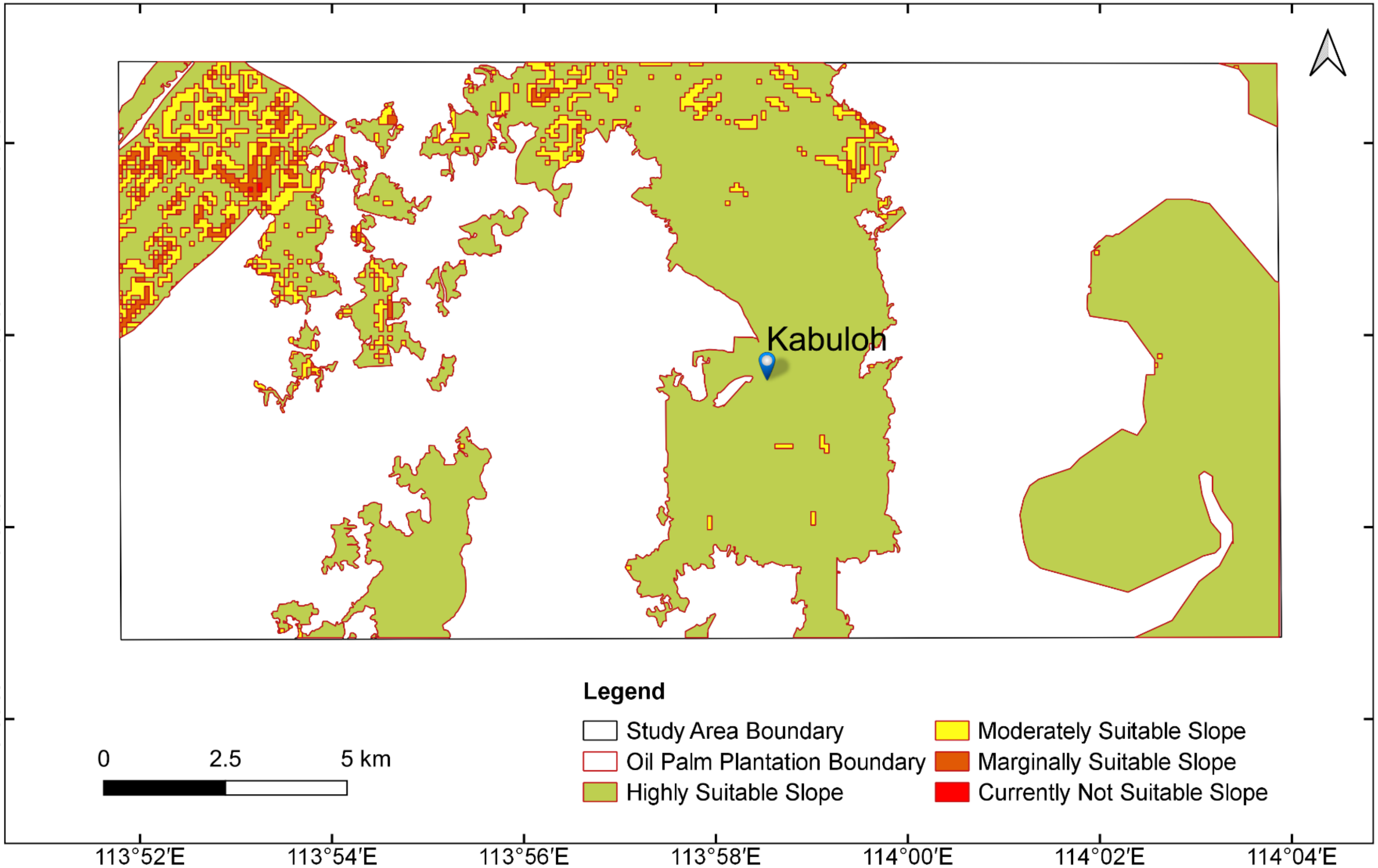

Figure 4.7: Oil palm plantation with respect to slope

4.3.5 Potential Impact of Existing Agricultural Land Use on Flora and Fauna

High diversity of totally protected and protected animals and protected plants are found in the study area based on the data sourced from the International Union for Conservation of Nature’s Red List of Threatened Species (IUCN 2020) and the Tree Flora of Nature's Sabah and Sarawak (FRIM 2004). There are 30 totally protected animals, 65 protected animals, and 9 protected plants in the study area, as shown in **Table 4.6**, **Table 4.7**, and **Table 4.8**. The totally protected animals can be further categorized into 2 animal classes, which are mammals and birds. Additionally, the protected animals can be further categorized into 3 animal classes, which are mammals, birds, and reptiles.

The animals can be categorized in terms of different categories of extinction risk. The categories are the least concern, near threatened, vulnerable, endangered, critically endangered, extinct in the wild, and extinct (IUCN 2020). In the totally protected birds, 2 birds are critically endangered, 3 birds are endangered, 5 birds are near threatened, 6 birds are vulnerable, and 9 birds are the least concerned. In the totally protected mammals, 1 mammal is near threatened, 3 mammals are vulnerable, and 1 mammal is the least concerned. In the protected bird, 35 birds are the least concerned, 11 birds are near threatened, and 9 birds are vulnerable. In the protected mammal, 2 mammals are critically endangered, 2 mammals are endangered, and 4 mammals are vulnerable. In the protected reptile, all of them are least concerned. The oil palm plantation, the pink colour zone in **Figure 3.3**, could significantly impact the animals with the critically endangered extinction risk. On the other hand, the impact of oil palm plantation on the animals with the least concern extinction risk could be less severe. Still, their existence should not be ignored before the survival of these animals is threatened, or else their population number could become less soon.

The oil palm plantations, as shown in **Figure 3.3**, could lessen the likelihood of survival of these animal species. The reason is that structure of the oil palm plantation is simpler than the forest. The oil palm plantation’s upper canopy consists of only single species. Growth of other plant types such as lianas is absent or reduced (Luskin and Potts 2011). In addition, Drescher et al. (2016) discovered that more light reaches the oil palm plantation's understorey than the forest, which causes the atmosphere hotter than the forest. Consequently, many forest species face the challenge of lacking appropriate environmental conditions to survive in oil palm plantations. Moreover, oil palm plantations are exposed to more exotic and weedy species due to high interference and reproductive stress levels and come into contact with more pesticides, further lessening the opportunities of survival for these animal species (Foster et al. 2011).

Besides, the development of oil palm plantations, as presented in **Figure 3.3**, could negatively impact the habitats of these animal species. The animal species could lose their habitat in various ways. The development of oil palm plantations ordinarily improve access to the forest. Improved access could cause a higher plausibility of habitat loss and bring more hunting activities, further threatens their survival (Meijaard et al. 2005). Additionally, oil palm plantation development frequently happens in forest fragmentation, catalysing intensified invasion of foreign species, diminished species mobility, edge effects, finally, more severe extinction risk (Fujinuma and Harrison 2012). All these aftermaths of oil palm plantation development could lead to habitat loss for these animal species.

Furthermore, the oil palm plantations, as demonstrated in **Figure 3.3**, could negatively impact the long-term viability of these animal species. The reason is that the land use change of forest to oil palm plantation decreases species abundances and richness of most animal species, resulting in a reduction of genetic resources in oil palm plantation. Genetic resources depict the organisms' genetic material in the natural world, in addition to the capability for subsequent evolution (de Groot, Wilson, and Boumans 2002). An example of genetic resources depletion is the reduction of genetic variability for ants in the Sabah fragmented forest due to oil palm plantations (Bickel et al. 2006). Assurance of genetic variability is significant for global food security, eco-diversity conservation, community health, and climate change mitigation and adaptation (Nagoya Protocol 2011).

Table 4.6: Existence of totally protected fauna in the study location

No.	Totally protected fauna	Category
	Mammal	
1	*Presbytis hosei*	Vulnerable (VU)
2	*Presbytis rubicunda*	Vulnerable (VU)
3	*Ratufa affinis*	Near Threatened (NT)
4	*Rheithrosciurus macrotis*	Vulnerable (VU)
5	*Cheiromeles torquatus*	Least Concern (LC)
	Bird	
6	*Anhinga melanogaster*	Near Threatened (NT)
7	*Bubulcus ibis*	Least Concern (LC)
8	*Ciconia stormi*	Endangered (EN)
9	*Leptoptilos javanicus*	Vulnerable (VU)
10	*Haliaeetus leucogaster*	Least Concern (LC)
11	*Argusianus argus*	Vulnerable (VU)
12	*Ducula bicolor*	Least Concern (LC)
13	*Ducula aenea*	Least Concern (LC)
14	*Ducula badia*	Least Concern (LC)
15	*Aceros comatus*	Endangered (EN)
16	*Anorrhinus galeritus*	Near Threatened (NT)
17	*Aceros corrugatus*	Endangered (EN)
18	*Aceros undulatus*	Vulnerable (VU)
19	*Anthracoceros malayanus*	Vulnerable (VU)
20	*Anthracoceros albirostris*	Least Concern (LC)
21	*Buceros rhinoceros*	Vulnerable (VU)
22	*Buceros vigil*	Critically Endangered (CR)
23	*Pitta sordida*	Least Concern (LC)
24	*Hydrornis caeruleus*	Near Threatened (NT)
25	*Hydrornis baudii*	Vulnerable (VU)
26	*Erythropitta granatina*	Near Threatened (NT)
27	*Pitta moluccensis*	Least Concern (LC)
28	*Hydrornis schwaneri*	Least Concern (LC)
29	*Pycnonotus zeylanicus*	Critically Endangered (CR)
30	*Pityriasis gymnocephala*	Near Threatened (NT)

Source: Table reproduced from IUCN (2020).

Table 4.7: Existence of protected fauna in the study location

No.	Protected fauna	Category
	Mammal	
1	*Nycticebus menagensis*	Vulnerable (VU)
2	*Presbytis rubicunda*	Vulnerable (VU)
3	*Hylobates funereus*	Endangered (EN)
4	*Presbytis chrysomelas*	Critically Endangered (CR)
5	*Manis javanica*	Critically Endangered (CR)
6	*Helarctos malayanus*	Vulnerable (VU)
7	*Lutra sumatrana*	Endangered (EN)
8	*Aonyx cinereus*	Vulnerable (VU)
	Bird	
9	*Pandion haliaetus*	Least Concern (LC)
10	*Microhierax fringillarius*	Least Concern (LC)
11	*Falco peregrinus*	Least Concern (LC)
12	*Argusianus argus*	Vulnerable (VU)
13	*Rollulus rouloul*	Near Threatened (NT)
14	*Rhizothera longirostris*	Near Threatened (NT)
15	*Lophura ignita*	Vulnerable (VU)
16	*Melanoperdix niger*	Vulnerable (VU)
17	*Synoicus chinensis*	Least Concern (LC)
18	*Lophura pyronota*	Vulnerable (VU)
19	*Argusianus argus*	Vulnerable (VU)
20	*Rollulus rouloul*	Near Threatened (NT)
21	*Rhizothera longirostris*	Near Threatened (NT)
22	*Lophura ignita*	Vulnerable (VU)
23	*Melanoperdix niger*	Vulnerable (VU)
24	*Synoicus chinensis*	Least Concern (LC)
25	*Phodilus badius*	Least Concern (LC)
26	*Otus lempiji*	Least Concern (LC)
27	*Ninox japonica*	Least Concern (LC)
28	*Otus rufescens*	Near Threatened (NT)
29	*Strix leptogrammica*	Least Concern (LC)
30	*Ketupa ketupu*	Least Concern (LC)
31	*Ninox scutulata*	Least Concern (LC)
32	*Bubo sumatranus*	Least Concern (LC)
33	*Collocalia esculenta*	Least Concern (LC)
34	*Ceyx erithaca*	Least Concern (LC)
35	*Lacedo melanops*	Least Concern (LC)
36	*Pelargopsis capensis*	Least Concern (LC)
37	*Todiramphus sanctus*	Least Concern (LC)
38	*Halcyon coromanda*	Least Concern (LC)
39	*Todiramphus chloris*	Least Concern (LC)
40	*Actenoides concretus*	Near Threatened (NT)
41	*Halcyon pileata*	Least Concern (LC)
42	*Alcedo meninting*	Least Concern (LC)
43	*Alcedo peninsulae*	Near Threatened (NT)
44	*Alcedo atthis*	Least Concern (LC)

45	*Meiglyptes grammithorax*	Least Concern (LC)
46	*Chrysophlegma humii*	Near Threatened (NT)
47	*Dryocopus javensis*	Least Concern (LC)
48	*Dinopium rafflesii*	Near Threatened (NT)
49	*Chrysocolaptes validus*	Least Concern (LC)
50	*Dinopium javanense*	Least Concern (LC)
51	*Sasia abnormis*	Least Concern (LC)
52	*Picoides moluccensis*	Least Concern (LC)
53	*Micropternus brachyurus*	Least Concern (LC)
54	*Chrysophlegma miniaceum*	Least Concern (LC)
55	*Mulleripicus pulverulentus*	Vulnerable (VU)
56	*Hemicircus sordidus*	Least Concern (LC)
57	*Picoides canicapillus*	Least Concern (LC)
58	*Picus puniceus*	Least Concern (LC)
59	*Blythipicus rubiginosus*	Least Concern (LC)
60	*Meiglyptes tukki*	Near Threatened (NT)
61	*Belocercus longicaudus*	Vulnerable (VU)
62	*Loriculus galgulus*	Least Concern (LC)
63	*Psittinus cyanurus*	Near Threatened (NT)
	Reptile	
64	*Varanus salvator*	Least Concern (LC)
65	*Python breitensteini*	Least Concern (LC)

Source: Table reproduced from IUCN (2020).

Table 4.8: Existence of protected flora in the study location

No.	Protected flora
1	*Shorea macrophylla*
2	*Shorea palembanica*
3	*Shorea ochracea*
4	*Ficus geocharis*
5	*Ficus uncinata*
6	*Koompassia excelsa*
7	*Koompassia malaccensis*
8	*Aquilaria beccariana*
9	*Eurycoma longifolia*

Source: Table reproduced from FRIM (2004).

4.3.6 Potential Socio-economic Impact of Existing Agricultural Land Use

The overlay of the oil palm plantation and the human settlement's location in the study location is shown in **Figure 4.8**. A high proportion of the villages are located in the western zone of the study location, R. Mokeng, Kg. Kadulit, Kg. Butir, Kg, Keluru Tengah, R. Abon Elap, Kg. S. Sait, Kg. Satap, R. Tubam, Kg. Padang, Kg. Sepurau, R. Ungeh, Kg. K. Kejapil, Kg. Subak, Kg. Lusong, Kg. Pangis Satap, Kg. K. Nosa, R. Ngeribang, R. Embit, and R. Bedit. Four villages, namely R. Liam, R. Bundan, R. Sidu, and R. Entulang, are located in the eastern zone of the study location. In addition, it can be observed that plenty of villages located around the oil palm plantation. The oil palm plantation established around these villages certainly impacts the livelihood of people living in these villages. Therefore, the people could be experiencing both positive and negative socio-economic impacts brought by the oil palm plantation.

Two types of social groups, smallholders and employees of oil palm plantations, are determined in the study location. Kg. Kadulit, Kg. S. Salit, Kg. Butir and Kg. Keluru Tengah is classified as the smallholder of the oil palm plantations in the study location. These villages are located near the Federal Land Consolidation and Rehabilitation Authority (FELCRA) oil palm plantation, the organization of smallholder's oil palm plantation. The blue zone in **Figure 4.8** is the FELCRA oil palm plantation. The remaining villages in the study location could be working as the employees of the oil palm plantation since the villages are located near the oil palm plantations (<10 km).

The employee group in the oil palm plantations, as presented in the orange dot in **Figure 4.8**, could receive more positive socio-economic impacts from the oil palm plantation. This condition can be explained by more income generated by working at the oil palm plantation, and they experience an enhanced standard of living (Norwana et al. 2011). The employees in the oil palm plantation could be given free accommodation, utility service, and medical allowance. Moreover, the employee's children could experience better access to schooling if the plantation company assists them. The form of assistance can be a provision of transportation to school or scholarship funding as the commitment to Corporate Social Responsibility (Tang and Al Qahtani 2020). On the other hand, the employee's family members who remain at home, typically women, could experience heavier family chores due to the men involved in a full-time job at the plantation (Norwana et al. 2011). In addition, the employee's family could experience higher daily expenses because fewer varieties of food can be sourced from the forest after the land was converted to an oil palm plantation. It causes the employee's family to buy the food from the market, which increases their daily expenses.

The smallholders of the oil palm plantations, as demonstrated in the black dot in **Figure 4.8**, can benefit from the oil palm plantation by selling the fresh fruit bunches to generate a higher revenue than subsistence farming (Zen, Barlow, and Gondowarsito 2006). However, the price of oil palm fruit is volatile. The high volatility of price could bring high instability to their livelihood (Schrier-Uijl et al. 2013). On the other hand, the smallholders could have more time on their

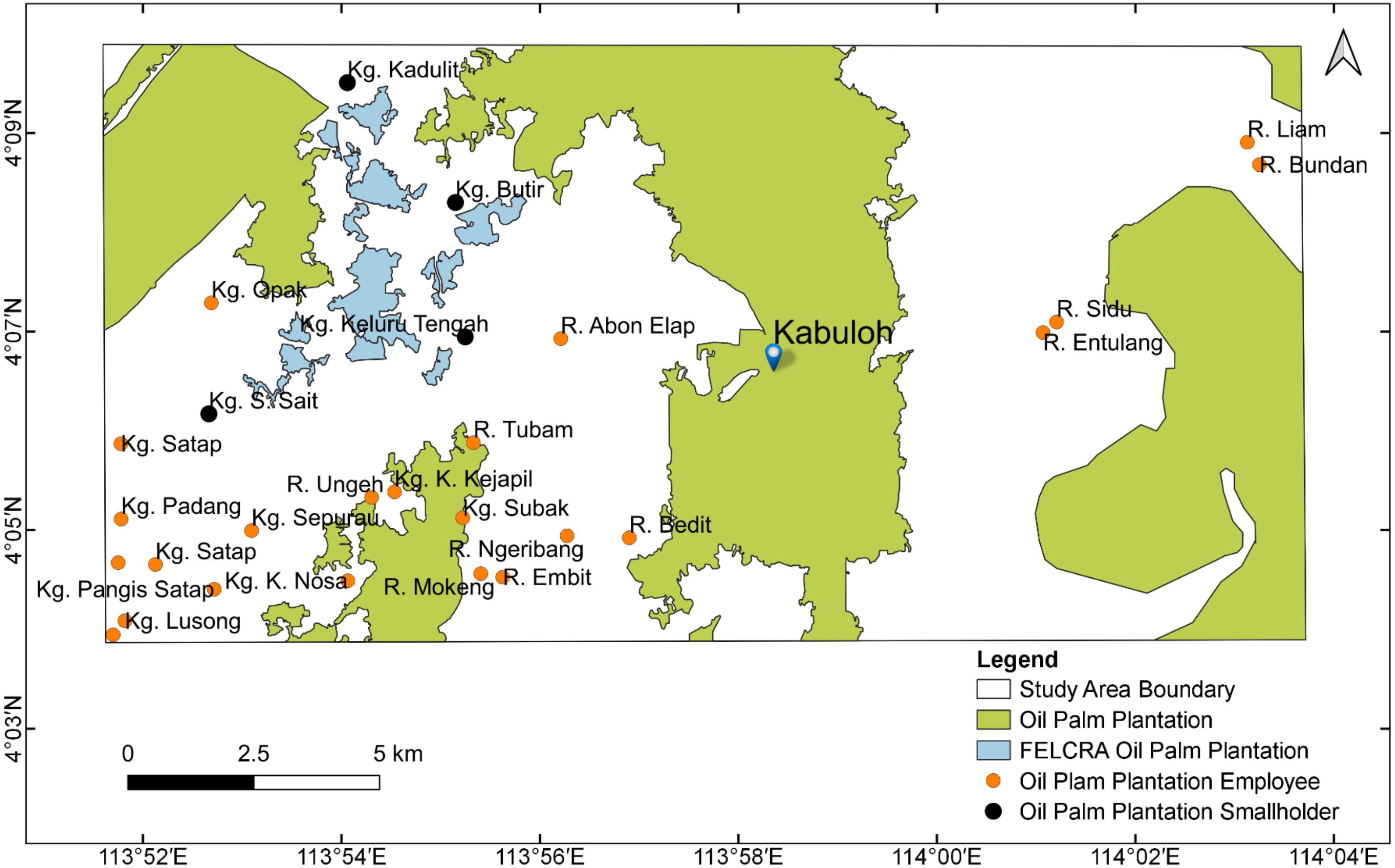

Figure 4.8: Oil palm plantation with respect to human settlement

hands when hiring workers to perform the plantation tasks (Norwana et al. 2011). By hiring workers to work for them, more time can be spent with their family members. The ability to spend more time with family members is a considerable difference experienced by smallholders before switching from small-scale subsistence activities such as rice planting and fishing to oil palm cultivation. They were not able to generate enough income to hire workers when practising small-scale subsistence activities.

These social groups found around the oil palm plantation area could experience different positive and negative impacts. The social groups with direct involvement in the oil palm plantation, such as local employees and smallholders, could benefit more from the oil palm plantation. Decision-makers such as government authorities and private companies should look into the actual social impact experienced by the social groups at the study location. Efforts should be made to rectify the negative impacts of the oil palm plantations to improve the overall socio-economic level of the local people, although they could have already experienced some benefits brought by the oil palm plantation development. The mitigation strategies of these negative impacts are recommended in **Section 4.4**.

4.4 Recommendation of Mitigation Strategies

Several mitigation strategies are recommended based on the identified potential environmental and socio-economic impacts of oil palm plantations. The strategies are recommended to minimize the impact of existing agricultural land use on the local environment and socio-economic development.

High-carbon and high biodiversity areas, such as primary forest and peatland, should be protected to minimize the impacts mentioned in **Section 4.3.1**, **4.3.2**, **4.3.5**, and **4.3.6** (Dislich et al. 2017). For example, the new concession for plantation in primary forest and peatland should be prohibited (Yule 2010; Austin et al. 2015). A portion of primary forest and peatland had been cleared for oil palm plantation, the brown zone in **Figure 4.2**, and the red zone in **Figure 4.3**. The primary forest and peatland in the study location are unique environments abundant in various flora and fauna species. For instance, the primary forest and peatland in the study location are a vital sanctuary for several endangered species such as Northern Gray Gibbon, Bornean Banded Langur, Sunda pangolin, Hairy-nosed otter, Storm's Stork, White-crowned Hornbill, Wrinkled Hornbill, and Straw-headed Bulbul (IUCN 2020). Additionally, Greenhouse Gases (GHG) emission can be mitigated by inhibiting the plantation expansion to primary forest and peatland, which are the zone with high carbon stocks (Austin et al. 2015). In summary, conservation of primary forest and peatland is crucial to maintain varieties of genetic resource for jeopardized species and reduce GHG emission.

In addition, the developed peatland, as presented in the red zone of **Figure 4.3**, should be rehabilitated to reduce the impacts discussed in **Section 4.3.1**, **4.3.2**, **4.3.5**, and **4.3.6** (Dislich et al. 2017). For instance, the water table at peatland should be kept as high as possible to keep the undecomposed dead biomass in waterlogged conditions (Hooijer et al. 2010). Moreover, a rewet of the soil in peatland is required to lower the CO_2 emissions (Couwenberg, Dommain, and Joosten 2010). Over the long term, the rewet of peatland could restore the capability of peatland to sequestrate carbon (Jauhiainen et al. 2008). After the water table level is restored to an appropriate level, vegetation cover on the peat should be maintained to lower the soil temperature and minimize the decomposition rate of the organic material in the peatland. Otherwise, the carbon emission could still be substantial (Hooijer et al. 2012). Rehabilitation of degraded peatland is vital to lower the carbon dioxide (CO_2) emissions from peat decomposition. The CO_2 emissions produced on peatland concentrate on 0.1% of the worldwide land area (Hooijer et al. 2010). This characteristic makes the peatland rehabilitation more feasible to implement than other GHG emissions produced by several sources and land conversion types.

The fertilizer practices in the oil palm plantation can be improved to reduce the leaching rate of chemical fertilizer, which could decrease the impacts stated in **Section 4.3.3**, and **4.3.4** (Dislich et al. 2017). For example, ground cover such as leguminous crops can be planted to cover the ground of oil palm plantations for ground surface protection. Leguminous crops commonly planted in oil palm plantations are *Mucuna bracteata*, *Puerariaphasesloides*, and

Calopogonium cearuleum (Comte et al. 2012). The leguminous crop can provide nitrogen to the oil palm tree through nitrogen fixation as well. Additionally, the leguminous crop can act as nitrogen storage during the early stage of oil palm growth, when the oil palm trees do not require much nitrogen from the soil during the early growth stage of oil palm (Agamuthu and Broughton 1985). The stored nutrient can later be released when the oil palm is mature. However, the release of nutrients must be controlled to avoid any excess nutrient leaching.

Another recommended fertilizer practice is to recycle waste generated from the palm oil mill and oil palm plantation as organic fertilizer (Comte et al. 2012; Griffiths and Fairhurst 2003). The recyclable wastes are the palm oil empty fruit bunches (EFB), pruned fronds and palm oil mill effluent (POME). These wastes consist of a considerable volume of organic matter and nutrients to supplement soil fertility and fulfil oil palm nutrient needs. The chemical fertilizers requirement can be reduced by more than 50% in an immature oil palm tree and 5% in a mature oil palm tree when EFB is applied as organic fertilizer (Tailliez 1998). Slow-release coated fertilizers can be applied to slow the leaching rate (Akiyama, Yan, and Yagi 2010). The application of organic fertilizer should be specific by accounting for local soil type and slope gradient to prevent excessive leaching (Goh, Härdter, and Fairhurst 2003). In short, the enhancement of fertilizer practice can minimize the waste produced from the oil palm industry and improve the overall sustainability of the oil palm life cycle.

Furthermore, hydrological practices can be enhanced to mitigate the negative impact on the aquatic system around the oil palm plantation, which stated in **Section 4.3.3** (Dislich et al. 2017). The mitigation strategy recommended for improving fertilizer practices can be implemented to improve the hydrological practice. For instance, planting leguminous crops as ground cover and stacking fronds on the ground surface can reduce soil and water movement speed, leading to less surface run-off. Additionally, riparian buffers around rivers should be maintained. The establishment of riparian buffers can help lessen the amount of sediments infiltrating the river, leading to the conservation of riparian species. Moreover, the riparian buffers have a significant role in the guardian of the riverbanks from erosion and maintenance of forest aesthetic value (Environment Conservation Department 2002). Silt-pits and foothill drains can be constructed to contain water sediments brought by surface runoff according to the recommendation given by the American Palm Oil Council (APOC). To sum up, the enhancement of hydrological practices can assist in the control of sediment and pollution from infiltrating into the rivers.

Besides that, the biodiversity practices can be improved in the oil palm plantation to promote more extraordinary biodiversity in the monoculture plantation zone to decrease the impacts stated in **Section 4.3.1**, **4.3.2**, **4.3.5**, and **4.3.6** (Dislich et al. 2017). Integrated pest management is recommended to replace the application of pesticides and herbicides. For example, biological control can replace pesticides, and manual weeding can replace the application of herbicides when possible (Caudwell and Orrell 1997; Ponnamma 2001; Environment Conservation Department 2002; Yusoff and Hansen 2007). The pests usually found in Sarawak oil palm plantations are bunch moth and termite. The application of *Beauveria sp.* and *Metarhizium sp.* are examples of biological pest control that use microbial pathogens to minimize the threat of these pests (Kamarudin et al. 2016). The riparian buffer zone established for surface runoff control can be utilized as a breeding ground for predators functional for reducing the population of rats in the plantations (Environment Conservation Department 2002). Chemical pesticides should only be applied when there is a severe pest outbreak.

Diversity and structural complexity within the oil palm plantation can be increased to enhance the biodiversity by including a zone for native vegetation growth to promote species diversity and abundance. For instance, ground-layer crops can be planted to promote the bird guilds' diversity and bring advantage to specific foraging groups in oil palm plantations. The growth of ground-layer crops can help birds have more food sources such as seeds and invertebrates (Azhar et al. 2013). Growth of native fruit trees such as *Ficus spp*. can also improve the abundance of endemic birds such as hornbills. Some epiphyte coverage is encouraged for species richness, not harming the oil palm's yield (Koh 2008; Prescott, Edwards, and Foster 2015).

Agroforestry buffer zones between plantation and forest should be included to build an extra heterogeneous landscape and enhance the landscape connectivity (Environment Conservation Department 2002; Koh, Levang, and Ghazoul 2009). The agroforestry buffer could significantly minimise the edge effect between the forest and oil palm plantation. Co-benefits for agricultural development, biodiversity and rural societies can be produced by establishing the agroforestry buffer zone (Koh, Levang, and Ghazoul 2009). Various types of plantations should be planned to cultivate diverse forest products and promote polyculture plantations. The reason is that the abundances of insectivores and frugivores are more in polyculture plantations (Azhar et al. 2014). Sufficient habitat should be planned for the original forest species to prevent permanent loss of these species (Yule 2010). For instance, the riparian ecosystem can be conserved by the implementation of the riparian buffer zone. The width of the riparian buffer is recommended to be 200m on each side of the river, according to Lees and Peres (2008)'s study to provide sufficient habitat for all mammal and bird species. This undeveloped area could provide sufficient sanctuary for the original forest species in the long run if the zone is wide enough.

4.5 Recommended Crops for Future Agricultural Land Use

A few types of popular economic crops were assessed to promote polyculture cultivation in the study location, which is one of the mitigation strategies stated in the previous section. The suitability of sago, paddy and coconut cultivation is determined in the sections below.

(a) Suitability of Sago Cultivation

The result reveals that 0.7% (198 ha) of the study area is highly suitable, 18.7% (5268 ha) is moderately suitable, 75.9% (21435 ha) is marginally suitable, 4.2% (1194 ha) is currently not suitable, 0.5% (136 ha) is permanently not suitable for the growth of sago, as shown in **Figure 4.9**. The highly suitable area has a nearly level field with alluvial soil and class 2 agricultural land use capability. The area has the nearest distance to road and river as well. The moderately suitable area has a moderate slope with alluvial soil and class 2 to 3 agricultural land use capability. The distance to the river and road is slightly further than the highly suitable area. The marginally suitable area has a moderate slope with gley soil, organic soil and red-yellow podzolic soil. Most of the area is located distant from the river and road. These zones have favourable soil conditions for sago crops to thrive, although a portion of the zone has organic soil or a high water table level. The sago's unique characteristics — the pneumatophores help sago thrive in these land conditions (Flach 1997; Hiroshi and Toyoda 2018), which is unsuitable for most cash crops. The currently not suitable area and permanently not suitable area have a very steep slope with red-yellow podzolic soil, podzol, and arenaceous soil, which are the limiting factors for sago cultivation. Hence, sago cultivation in a suitable zone could help the Sarawak government increase sago production and achieve RM100 million export value by 2030 (Tawie 2019).

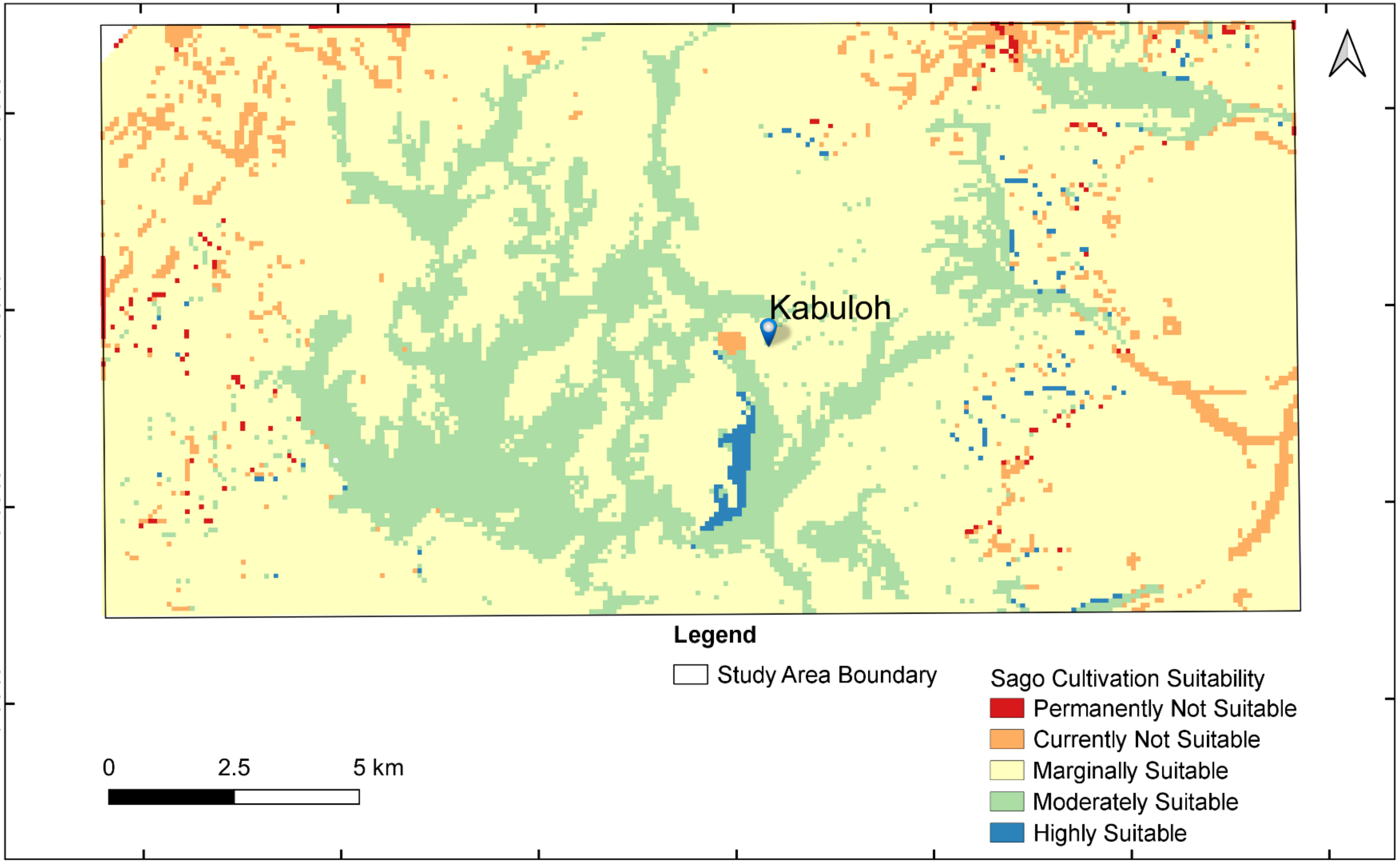

Figure 4.9: Sago cultivation suitability map

(b) Suitability of Paddy Cultivation

The result demonstrates that 1.9% (538 ha) of the study area is highly suitable, 52.2% (14713 ha) is moderately suitable, 45% (12684 ha) is marginally suitable, 0.6% (170 ha) is currently not suitable, 0.3% (74 ha) is permanently not suitable for paddy cultivation, as shown in **Figure 4.10**. The highly suitable area has flat land with alluvial soil or gley soil and class 2 to 3 agricultural land use capability. The gley soil is considered a suitable soil type for paddy cultivation because the gley soil is saturated with groundwater long term; the paddy can thrive in saturated soil, which is the paddy's unique characteristic (Chesworth 2008). The area is close to the road and river as well. The moderately suitable area has a moderate slope with alluvial soil, gley soil, red-yellow podzolic soil or organic soil and class 2, 3 or O4 agricultural land use capability. The distance to the river and road is slightly further than the highly suitable area. The marginally suitable land has a hilly terrain with red-yellow podzolic soil. Most of the area is far from the river and road. The currently not suitable area and permanently not suitable area are limited by a very steep slope and less suitable soil such as red-yellow podzolic soil and podzol. As previously mentioned, paddy cultivation can be planted in a suitable zone to help Sarawak achieve higher rice self-sufficiency.

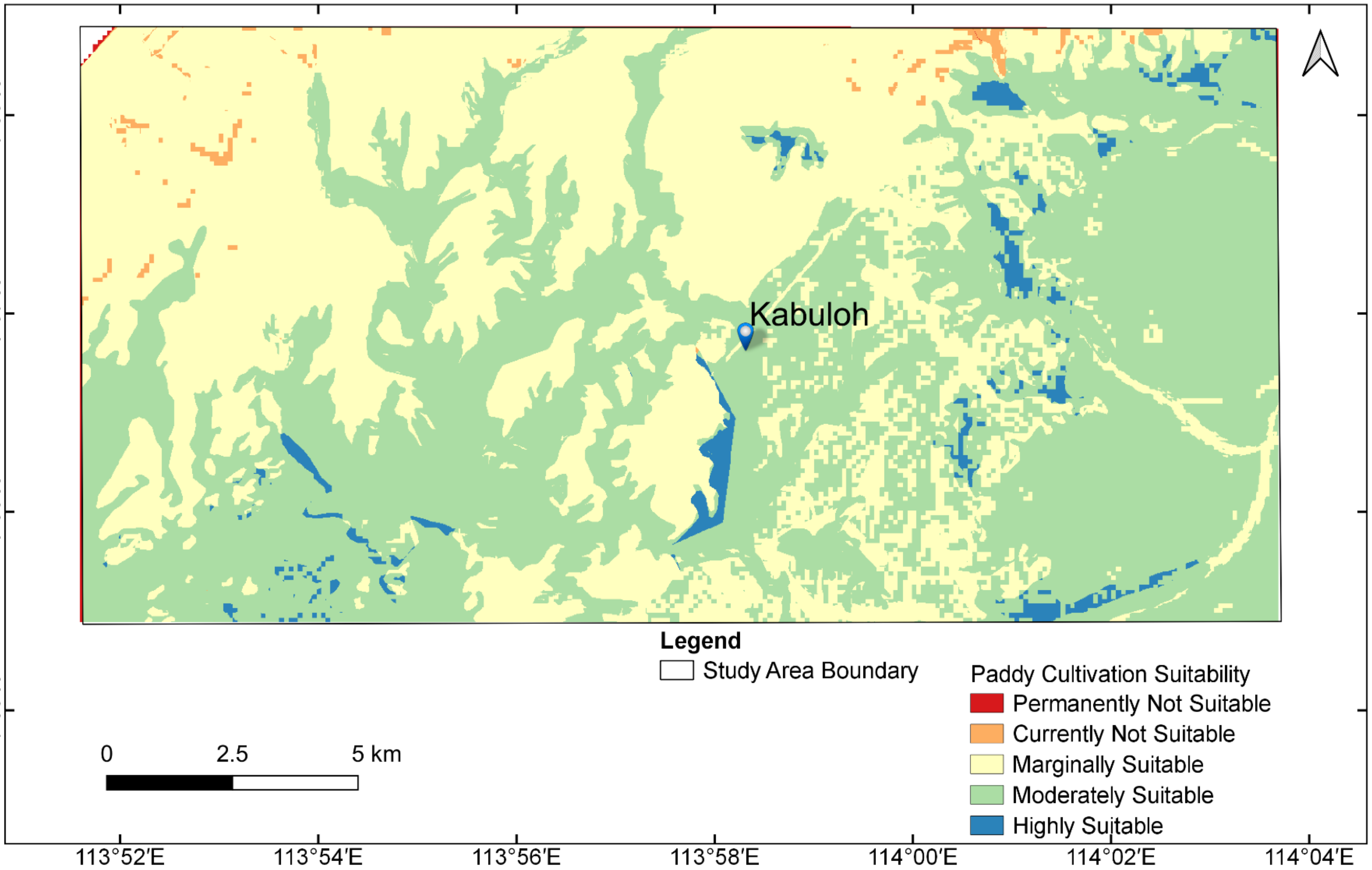

Figure 4.10: Paddy cultivation suitability map

(c) Suitability of Coconut Cultivation

The result shows that 6% (1692 ha) of the study area is highly suitable, 31% (8730 ha) is moderately suitable, 42% (11802 ha) is marginally suitable, 20.8% (5871 ha) is currently not suitable, 0.3% (86 ha) is permanently not suitable for coconut cultivation, as presented in **Figure 4.11**. The highly suitable area has flat ground with alluvial soil and class 2 agricultural land use capability. Alluvial soil is considered the best soil type for coconut cultivation (Sys et al. 1993). The area is close to the road and river as well. The moderately suitable area has the land covered by red-yellow podzolic soil with a gentle to moderate slope. The land has class 2, 3 or 4 agricultural land use capability. The river and road are located further from the area compared to the high suitability zone. The marginally suitable land has a very steep slope with gley soil, red-yellow podzolic soil or arenaceous soil. The river and road are far from this area. The currently not suitable area and permanently not suitable are characterized by a sheer slope (>26%) or low agricultural land use capability. Hence, coconut cultivation in a suitable area is recommended to promote crop diversity in the study area and increase the local supply of coconut.

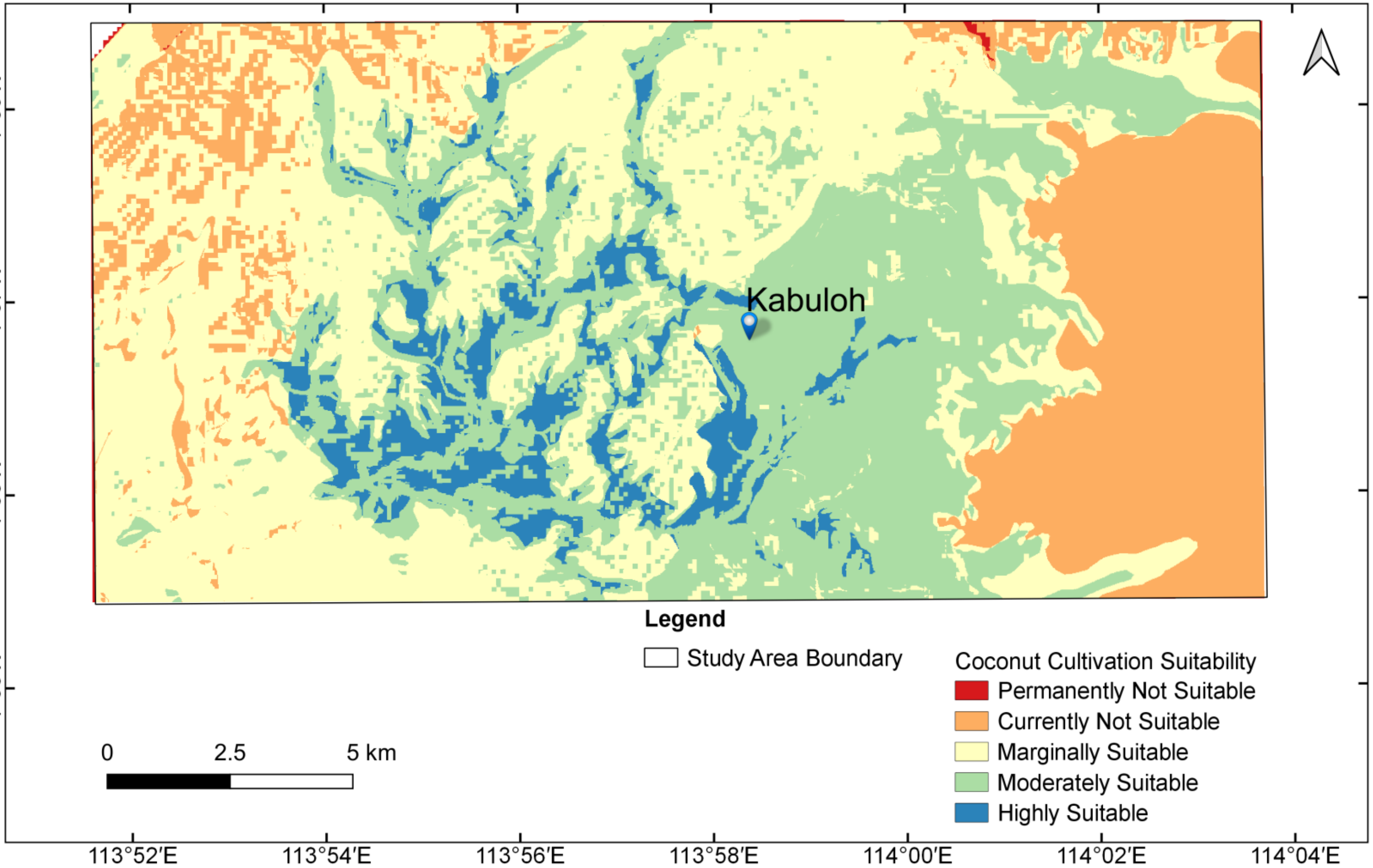

Figure 4.11: Coconut cultivation suitability map

4.6 Future Agricultural Land Use Plan

Based on agricultural land use suitability assessment, existing agricultural land use assessment and the suggested crop suitability assessment, the future agricultural land use plan was produced as shown in **Figure 4.12**. Four different zones are recommended for future agricultural land use, namely protected zone, peatland rehabilitation zone, buffer zone, and agriculture zone. The protected zone is allocated for the protection of ecosystem functions of the natural environment. This zone should not be further developed to prevent further deterioration of ecosystem functions. Then, the peatland rehabilitation zone is designated to protect the original peatland located in the study location. The developed peatland should be rehabilitated to partially restore its function as a carbon sink and natural habitat of flora and fauna. The agriculture zone is allocated for the use of cultivation activities. The area is suitable for agriculture activities with proper management practices such as a riparian buffer zone, integrated pest management, a buffer zone of plantation boundary, and replacement of chemical fertilizer with plantation waste.

The area covered with primary and secondary forest, the green colour zone in **Figure 4.12**, should not be further developed into agricultural land use. The reason is that the primary forest has high biodiversity value and essential for various ecosystem functions (Dislich et al. 2017). In addition, the primary forest is a habitat for various types of endemic flora and fauna. Additionally, there is a massive portion of the area has already been used as agricultural land. Primary forest protection could help to lessen the global CO_2 emission as well. The secondary forest located adjacent to the primary forest should be protected to prevent further forest fragmentation. Further fragmentation of forests could lead to the deterioration of ecosystem functions. This initiative will be an effort to enhance the sustainability of agricultural land use in the study location.

The developed peatland is recommended to undergo rehabilitation work to restore part of the unique characteristics of natural peatland, as highlighted in the brown zone in **Figure 4.12**. The peatland is generally concentrated with a high volume of carbon stored in the undecomposed plant. The carbon emission from peatland could continue to rise if the rehabilitation work is not done, lead to further deterioration of climate change. Several initiatives are recommended, such as a rewet of peatland, sufficient water table level maintenance, and replanting the ground cover to rehabilitate the deteriorated peatland (Hooijer et al. 2010; Jauhiainen et al. 2012).

The area planted with oil palm trees can be used as an agricultural zone except for the plantation developed on peatland, as presented in the pink zone in **Figure 4.12**. It is not feasible to remove the existing agricultural crop, which has been contributing fruit yield to the supply chain. However, the oil palm plantation needs to take the recommended mitigation strategies to mitigate the identified potential environmental and socio-economic impacts discussed in **Section 4.3**. The mitigation strategies to minimize the environmental and socio-

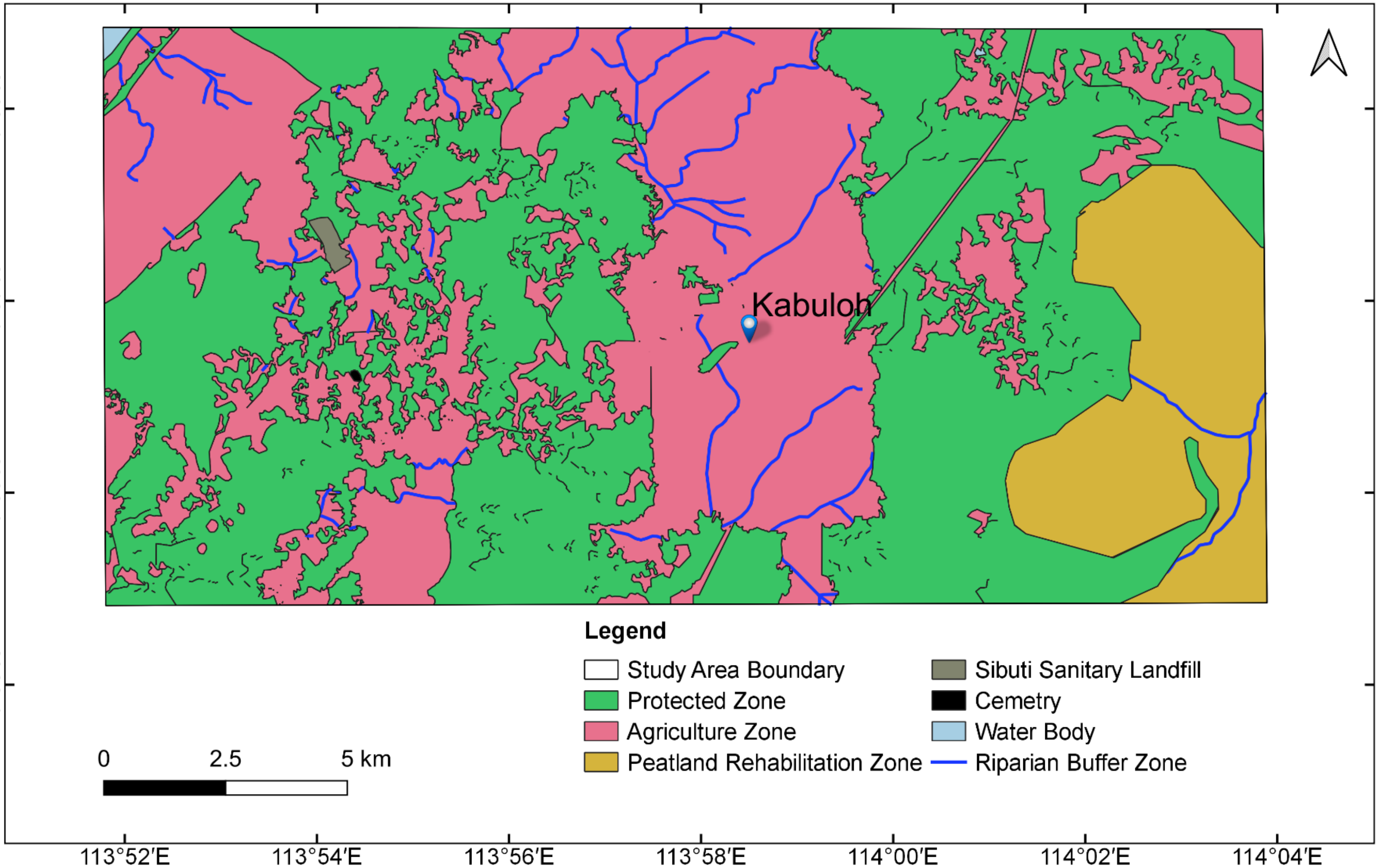

Figure 4.12: Future agricultural land use plan

economic impacts are provided and discussed in **Section 4.4**. The palm oil production sustainability can be enhanced by mitigating the identified potential impacts.

Lastly, the zone covered with sundry-tree and sundry non-tree cultivation and grass can be used as agricultural land since the landscape is similar to agricultural land use, as presented in the pink zone in **Figure 4.12**. However, it is recommended to plant other types of economic crops such as paddy, sago or coconut, which are recommended earlier in the suggested crop suitability map. This recommendation is due to the study location currently having a monoculture plantation, the oil palm plantation. As mentioned in the mitigation strategy, crop diversity can be promoted by planting various economic crops in the study location (Azhar et al. 2014).

4.7 Responses to Research Questions

i) What is the suitability of agricultural land use in the Kabuloh region?

The agricultural land use suitability in the study location can be classified into five categories, as presented in **Figure 4.1**. Based on the agricultural land use suitability map, 5% of the study location is highly suitable for agricultural land use. In addition, 75% of the study location is categorized under moderately suitable and marginally suitable for agricultural land use. Then, 19% of the study location is currently not suitable for agricultural land use. Lastly, only 1% of the study location is grouped as permanently not suitable for agricultural land use.

The zone under the highly suitable category can perform well in agricultural activities naturally. This suitability level implies that the land has a relatively suitable soil type for agricultural land use, such as alluvial soil (Boettinger 2005). Therefore, crop yield at this zone could be satisfied and match the average yield (Ayu Purnamasari, Noguchi, and Ahamed 2019). The management needed in this kind of land is relatively easy compared to the land under the other category. This zone is mainly found in an area with flat ground.

The zone under moderately suitable and marginally suitable categories can perform well if there is sufficient management input. The land under these categories comes with a certain degree of limitation for crop's growth. The landowner will be required to improve the ground condition before the land is appropriate to undergo cultivation activities. The management effort required for this kind of land will be more significant than the land that falls under the highly suitable category. These zones spread over the entire study location except the eastern part of the study location.

The zone that under currently not suitable categories is a problematic area for agricultural activities. The reason is that there is a severe limitation of the land caused by the soil characteristics of this type of land. A massive soil improvement effort is required to modify the land condition to become favourable for crop cultivation. The crop yield can only become satisfied when the landowner conducts the soil improvement on this kind of land. However, modification of land could cause some negative impact on the environment since the area is primarily constituted of peatland, a high conservation value area. The management effort required in this kind of land is very intensive compared to the last three categories of agricultural land. This zone mainly located at the eastern zone of the study location, which is formed of peat soil.

The zone that under permanently not suitable categories is a problematic area for agricultural activities. The limitation of this area is the most severe, which make it not feasible for agricultural activities. The land could have intense nutrient leaching, which will heavily lower the yield of the crop. In addition, the topography here could need a considerable effort of modification before performing any cultivation activities. It could be not economical to undergo agricultural activity on this land. However, the land can be used for other land use purposes such as construction or recreational land.

To sum up, a high proportion (80%) of the land in the study location can have the potential for agricultural land development. However, different degrees of input will be required for different categories of suitability. The highly suitable land will require minimum input to get a satisfying crop yield. The land with marginal and moderate suitability could be used as agricultural land with intermediate input to give a satisfactory outcome. The currently unsuitable land can be improved with a high amount of input to enhance the land condition to give an average crop yield. It is recommended that agricultural activity not be conducted in a permanently not suitable area for agricultural land use. The Kabuloh region has a high potential to be developed as agricultural land, given that proper environmental and socio-economic impact assessment is performed.

The work done to answer this research question aligns with the Sarawak Digital Economic Strategy Strategy's strategic actions for the agriculture sector, adopting ICT and digital technologies to transform the agricultural sector, and drive innovation (Sarawak State Service Modernisation Unit 2017). This research integrates the Geospatial system —Geographic Information System (GIS) for agriculture land use planning. With the help of GIS integration in the agriculture sector, this research can improve the productivity and efficiency of the agricultural sector (Sarawak State Service Modernisation Unit 2017).

Furthermore, the study confirms that integrating GIS and MCDA approaches can be a helpful method to analyse the agricultural land use suitability and produce a meaningful result to help develop agricultural activities. A similar methodology can be applied in the other region of Sarawak and eventually will lead to a complete database about the agricultural land use suitability of Sarawak since the Sarawak government is giving close attention to the digital development of the agricultural sector. The socio-economic and environmental needs can be fulfilled when agricultural land use suitability assessment is conducted throughout the state.

The research assisted in furthering the understanding of the agricultural land use suitability in a zone located in the southern region of Miri. The research can be conducted in the area that can be developed as agricultural land in the other region of Sarawak. With the research outcome, the sustainability of agricultural land use can be further enhanced because the research looks into agricultural land development from the perspective of environment, social and economic perspective. This study is the first study to assess agricultural land use suitability in Sarawak. By expanding the application of agricultural land use suitability to other regions of Sarawak, it is believed that the agricultural sector in Sarawak can be developed sustainably.

ii) What is the potential impact of existing agricultural land use on the environment and the local society by map overlay analysis?

Based on the existing land cover map, oil palm plantations covered 40% of the study location. Hence, the area is mainly covered by oil palm plantations, which is monoculture cultivation. The monoculture cultivation could induce impacts to the environments and local socio-economic development, mainly when it is planted oil palm plantation, which raised huge debate around the world since it is the most significant agricultural product in Malaysia. Moreover, it was claimed that palm oil is significant renewable energy for the future (Lam et al. 2009). Several potential impacts to the environment and the local socio-economic condition are identified based on the map overlay analysis. The environmental impacts identified are imbalance biodiversity, peatland degradation, deterioration of the hydrological system, soil degradation, and extinction of flora and fauna, as discussed from **Section 4.3.1** to **Section 4.3.5**. Imbalance biodiversity could be due to the domination of a single crop in the study location, the oil palm tree (Koh and Wilcove 2008). Peatland degradation could be caused by establishing an oil palm plantation on peat soil when there is a lack of mineral soil. The increased surface runoff and peatland drainage could cause hydrological system deterioration. Soil degradation could be due to the planting of oil palm on unsuitable soil, such as organic soil and gley soil (Guillaume et al. 2016). Extinction of flora and fauna could be the aftermath of habitat loss after establishing the oil palm plantations.

The potential impact of oil palm plantation on the socio-economic development of the study location could vary on the social groups. Two different social groups could exist in the study location. The first social group is the employee of oil palm plantations. This particular group of people could experience more positive impact compared to negative impact. The employees are given various welfares such as free accommodation, utility service, and medical allowance. Their children could have better access to schooling given that the plantation company is committed to Corporate Social Responsibility. On the other hand, the employee's family members who remain at home might have more household chores burden when the man adults of family work full time in the oil plantation.

Then, the second social group is the smallholders of the oil palm plantation. They can gain an advantage by selling fresh fruit bunches to have a higher income than subsistence farming. However, there is a risk for the smallholder, the market price instability of oil palm fruit. Additionally, the smallholders could spend more time with their family members when they can hire workers to perform the daily tasks in oil palm plantations.

The research identifies several potential risks brought by the existing agricultural land use in the study location. Several actions are required to mitigate the identified potential risks to enhance the sustainability of agricultural land use at the study location. The suggested actions to mitigate the potential risks are conservation of forest and peatland, improved fertilizer, hydrological and biological practices, promotion of structural diversity and complexity in the plantation, and agroforestry zone establishment around the perimeter of the plantation. If any potential risks are not mitigated, the consequences could be further deterioration of the identified negative environmental and socio-economic impacts.

iii) What is the recommended future agricultural land use in the Kabuloh region by map overlay analysis?

A few crops are suggested for future agricultural land use. The study area is currently having a single type of large scale plantation that is less favourable for the biodiversity of the study location. However, it cannot be avoided since oil palm product has high economic value. Besides oil palm, other crops have high economic value and have a significant role in the development of Malaysia. Three suitable crops in this area are recommended, namely sago, paddy, and coconut.

The sago is recommended because it can be grown in the peat area due to its unique characteristics of pneumatophores (Flach 1997; Hiroshi and Toyoda 2018). The pneumatophores can help the sago tree survive in a peat area that generally has a high water table level. A peat area is located in the eastern zone of the study location. As a result, sago is recommended to be planted in this area. Cultivating sago in this area will require minor modification of problematic soil characteristics in the study area, the high water table level. Without the need of lowering the water table level, the sago can grow in the peat soil with the help of pneumatophores. When the water table level is not required to be lower, the peat area will not be negatively impacted due to water drainage. A suitability map of sago cultivation, as shown in **Figure 4.9**, can be referred to when the decision-maker wants to implement sago cultivation in the study location. The suitability map suggests that 95% of the study area is suitable for sago cultivation. Sago production in Sarawak can be increased by planting more sago, and it will help achieve the Sarawak government's goal of RM100 million export value of sago in the year 2030 (Tawie 2019).

The second crop recommended is the paddy. The unique characteristic of paddy is that it can grow in soil that is having poor drainage. There is the existence of poorly drained soil in the study location due to the gley soil group. The gley soil group usually is fully saturated with water which is not favourable for general crop cultivation. However, paddy can grow in this kind of soil due to its characteristics. The self-sufficiency rate of rice in Sarawak can be enhanced by planting more paddy in Sarawak since Sarawak now only has 51% of rice's self-sufficiency rate (Petingi 2019). Additionally, paddy is the third important economic crop in Malaysia, which comes after oil palm and rubber. A suitability map of paddy cultivation in the study location is presented in **Figure 4.10**. The map shows that 99% of the study area is suitable for paddy cultivation due to paddy can be planted on a wide variety of land conditions.

The third crop that is suggested is coconut. Coconut is recommended to increase the crop diversity in the study location since it is now only having a single type of crop planted in the study location. By planting more coconut in the study location, the variety of harvest will be more diverse, suitable for the local biodiversity. Besides, the coconut-derived product is having more demand from the market. Hence, coconut has increasing economic value, which will help the planter to generate higher income by planting coconut. Additionally, the local supply of coconut is insufficient, which makes a condition that coconut still needs to be imported from other countries to fulfil the local demand (Tan 2019). By planting more coconut trees, the gap of the local demand can be eventually closed and decreases the reliance on coconut from foreign countries. A suitability map of coconut cultivation is demonstrated in **Figure 4.11**, and the map shows that 79% of the study area is suitable for coconut cultivation. More coconut should be cultivated in the study area to enhance the biodiversity in the study area.

Lastly, agricultural land use suitability assessment, existing agricultural land use assessment and suggested crops suitability assessment were integrated to produce a future agricultural land use plan. The future agricultural land use plan will divide the study area into four different zones, as presented in **Figure *4.12***. The four zones are the agriculture zone, protected zone, buffer zone and rehabilitation zone. The agriculture zone can be allocated with various agricultural activities, while the protected area is required to preserve the local ecosystem functions and biodiversity. The buffer zone is purposed to minimize the edge effect of adjacent plantations to the protected area. Lastly, the rehabilitation zone is needed to restore the function of peatland as a global carbon sink.

The work done to answer this research question aligns with the Department of Agriculture Sarawak's vision to build "a high-income community and agro-food exporter by 2030" (Department of Agriculture Sarawak 2021, 1). The agriculture land use plan can aid the development of agriculture in Sarawak to become more sustainable. Additionally, the agriculture land use plan could facilitate the landowner to utilize and manage the land resources more competently, lead to sustainability of the agriculture sector. The sustainable development of the agriculture industry in Sarawak could eventually assist the local community in generating higher income and exporting the agro-food to other regions.

The recommendation given to rehabilitate the peatland is in line with the goal of Wetland International. The goal of wetland international for peatland in Wetlands International's Strategic Intent 2020-2030 is "to scale up the conservation and restoration of peatlands as a contribution to biodiversity conservation, climate change mitigation and adaptation, and sustainable development" (Wetlands International 2020, 68). The rehabilitation of peatland is an effort to conserve and restore the ecosystem functions of peatland. Drainage of peatland needs to be prohibited to ensure no further decomposition of dead vegetation. Peatland rehabilitation could aid to prevent further deterioration of carbon emission, lead to mitigation of climate change.

The research identified the potential risks and provided some strategies to mitigate the potential risks. It is believed that the negative impact could be minimized if the mitigation strategies are considered by the stakeholders and apply accordingly. The future agricultural land use plan can be applied to enhance the sustainability of local agricultural land use. Moreover, the study determines several economic crops which can be cultivated in the study location. Hence, multiple economic crops, such as sago, paddy and coconut, can be cultivated to protect the environment and enhance socio-economic development in the study location.

4.8 Limitation of Study

The first limitation is the type of study. This research was conducted by using the desktop study method, in which no site visit was involved. Hence, the actual condition at the study location could be slightly different compared to the secondary data obtained from the different government authorities and other secondary resources produced by previous studies. The theoretical result obtained from the research could need on-site verification, which cannot be done in this research due to limited time and the COVID-19 pandemic that happened during the research period. The site visit could help to increase the reliability of the research outcome. The site visit is not encouraged when the pandemic remains severe, and the pandemic remains severe throughout the research period. The verification acts as additional support to apply the research outcome in agricultural production practice effectively. The desktop study was conducted without actual visits to the study location, which could cause some difference between the secondary data obtained and the actual condition of the study location. The reason for using the secondary data is due to the limited time, 1.5 years, given in this research. Additionally, secondary data collection is a relatively convenient and achievable within the limited timeframe. The best condition for the research is that there is no difference between the secondary data and the actual site condition. However, there is always some difference between the secondary data and the actual site condition. The secondary data is the already collected data compiled by the other group of people applied for other purposes. The data was collected from this group of people and used in this research for a different purpose. Adopting primary data could further enhance the accuracy and reliability of the desktop study. Primary data can be collected through remote sensing for existing agricultural land use, soil sampling for great soil groups, flora and fauna sampling for the existence of protected flora and fauna. However, these primary data collection activities are unlikely to be completed within 1.5 years.

The second limitation of the research comes from the resolution of the thematic layers. Each thematic layer has a different resolution. The outcome of the map depends on the thematic layer with the lowest resolution. Hence, the low resolution of the outcome is caused by the impact of the low-resolution thematic layer. The higher resolution of the thematic layer could be obtained by collecting primary data. However, additional time and spending are required to conduct primary data collection. The data with higher resolution contains more details that can improve the accuracy of the result. Furthermore, the resolution of each thematic layer cannot be changed after the secondary data was obtained. Therefore, the resolution of the secondary data is fixed when it was collected as the primary data by other groups of people or researchers.

The third limitation of the research is the generalizability of the research outcome. The research was conducted in a specific area that has its unique characteristics. Hence, the applicability of the research outcome to the other location with several different characteristics is still a question to be solved. However, a similar research flow from this study, as presented in **Figure *3.1***, can be applied in the other region close to the study location. When the study location is getting further from the current study location, the degree of generalizability could be lower. If a more comprehensive study location can be involved in the research, the generalizability of the research could be improved. However, the budget and time required are higher when we want to widen the study location involved in the research. A higher budget is required to obtain the secondary data from relevant government authorities, and a more extended period is needed to process the secondary data in the GIS system. Future research can be conducted using a similar method in this research, as demonstrated in **Figure *3.1***, to test the generalizability of this research. If this research is generalizable, it can be immediately applied to an area that has the potential to be developed as an agricultural plantation to determine the suitability of this particular area as agricultural land. The decision-maker in the other state of Malaysia could apply a similar research methodology to understand the suitability of the particular area in their state as agricultural land use since the agricultural product has increased demand from the entire world. If the particular area is suitable for sustainable agricultural production, it can be assured that the agricultural land use will bring enormous benefits to the local society and the economy of the surrounding area. The precious environment can be conserved at the same time.

The following limitation of the research is the criteria used in the research. Different criteria could lead to a different type of outcome of the research. The criteria in this research were chosen based on secondary data availability in the study location and the literature review. If the data used in past literature is not available in the study location, the criteria cannot be chosen to assess the suitability of agricultural land use. Future research could involve some primary data collection to obtain the data of the criteria, which could tell whether the application of different results will bring us different research outcomes. The application of different criteria could bring new insight to a similar research problem.

The limitation that comes after that is the weightage of the criteria. Different weightage of criteria could bring different impacts on the outcome of the assessment. In this study, the suitability of agricultural land use is impacted by the weightage of each criterion. If the weightage of criteria is changed, there could be a certain degree of impact on the suitability of agricultural land use in the study location. A sensitivity analysis can be conducted in future research to study the degree of impact to the suitability of agricultural land use in the study location when the weightage of criterion varies. Besides that, in this study, the soil-related factors were given relatively higher weightage, which made these criteria dominate the suitability of agricultural land use in the study location. The other type of criteria, such as the proximity of infrastructure, was given lower weightage, which shows a minor impact on agricultural land use suitability. Ioki et al. (2019)'s study showed that the participatory geographic information system (PGIS) method could be implemented to conduct village-scale land use planning. By implementing PGIS, the interview is conducted to ask the opinion of different groups of stakeholders. A different group of stakeholders can bring a different kind of view to the research process. For example, the smallholder could give higher importance to infrastructure availability around their small plantation, which is not a critical issue for the prominent plantation owner. The big plantation owner will have their capital to construct infrastructures such as bridges, roads, and drainage before establishing oil palm plantations. The smallholders could not have such capability to build the infrastructures for themselves. Therefore, the weightage of each criterion will not be universal. The weightage allocation could hugely depend on the local socio-economic condition and the ownership of the plantation area.

Furthermore, the degree of correlation of the research outcome with the observed crop yields is unclear. Hence, it is suggested to determine the actual yield for a particular type of suggested crops associated with the study location. After studying the actual crop yield, the degree of correlation of the research method can be enhanced by adjusting the research methodology, such as the choice of criteria, weightage of criteria, and mathematical translation of criteria. Since the yield assessment is not within the scope of this study, it can be recommended for future research to conduct the assessment. The assessment could help to increase the applicability of the research outcome.

Additionally, only two socio-economic factors were considered in the research: the proximity of land to the river and the proximity of land to the road. More socio-economic factors could be included when more available secondary data can be utilized. It will enable the research to give a new insight into the impact of other socio-economic factors. Other potential socio-economic factors such as proximity to market, cultivation pattern, and available labour force can be the choice of secondary data.

Lastly, the optimum distance allowed for the agricultural land from the road and river was not determined in this research. The optimum distance was not determined because there is no available research that can be referred to for such data. Hence, although some areas are far from the river and road, it was still considered suitable for agricultural land use as long the area is fertile for cultivation. There are some strategies to overcome this problem with an investment of capital to construct the required infrastructures. These limitations could cause a certain degree of inaccuracy and bring challenges to improving agricultural land use sustainability in the study location.

Chapter 5 Conclusion and recommendation of future works

5.1 Conclusion

Existing agricultural land use is recommended to be examined to enhance the sustainable development of the agricultural industry in Malaysia. Additionally, sustainable agriculture land use is vital for the economic development of Malaysia. Sustainable agriculture land use can ensure Malaysia remains competitive in the global agriculture product market, particularly the oil palm market. Hence, agricultural land use suitability assessment was conducted at Kabuloh and its surrounding area to enhance the sustainability of agricultural land use. Several assessment criteria were considered, such as great soil group, agricultural land use capability, slope, and proximity of the land to rivers and roads. The weightage of each criterion was determined by the Fuzzy Analytic Hierarchy Process (FAHP). After the weightage was determined, the analysis was conducted in Quantum Geographic Information System (QGIS). The result shows that 5% of the study location is highly suitable, followed by 42% is moderately suitable, 33% is marginally suitable, 19% is currently not suitable, and 1% is permanently not suitable for agricultural land use. It is recommended to undergo polyculture cultivation in the zone suitable for agricultural land use to protect the ecosystem's biodiversity. The area suitable for cultivation generally has fertile soil and a suitable slope gradient.

After assessing the agricultural land use suitability, the existing agricultural land use in the study location was examined. It is determined that oil palm plantation dominates the existing agricultural land use in the study location, occupying 40% of the study area. Therefore, the existing oil palm plantation could induce different environmental and socio-economic impacts based on map overlay analysis. The identified potential environmental impacts are imbalance biodiversity, peatland degradation, deterioration of the hydrological system, soil degradation, and extinction of protected flora and fauna.

Additionally, the potential socio-economic impacts were identified based on two different social groups typically found around oil palm plantations. Based on the literature and map overlay analysis, the potential socio-economic impacts are higher income and living allowance for the employees in oil palm plantations. Besides, the children of the employees could have a chance to access better education. However, the employees' families could experience a higher workload of household chores and daily expenses. The second social group, plantation smallholders, could have higher revenue and more time to spend with family. On the other hand, the smallholders could experience instability of livelihood due to the unstable price of the oil palm fruit.

Due to the identified negative environmental and socio-economic impacts, several mitigation strategies are recommended to minimize the impacts of the oil palm plantation and enhance the sustainability of agricultural land use in the study area. The mitigation strategies were recommended based on the identified potential negative impacts include conservation of forest, rehabilitation of peatland, enhanced fertilizer and hydrological practices, implementation of polyculture cultivation and establishment of agroforestry buffer zones.

Then, the future agricultural land use plan was recommended based on the agricultural land use suitability and the mitigation strategies to enhance the sustainability of agricultural land use in the study location. The future agricultural land use can be divided into four different zones; namely, protected zone, peatland rehabilitation zone, buffer zone, and agriculture zone. Firstly, the primary and secondary forests should be allocated in the protected zone. The forests should be conserved to protect the biodiversity in the study location. The retention of secondary forest is equally essential for the connectivity of the entire forested landscape. Furthermore, the peatland rehabilitation zone is recommended for restoring peatland's function as a carbon sink and natural habitat of flora and fauna. Additionally, buffer zones at different locations should be established. For instance, a riparian buffer zone should be constructed to protect the hydrological ecosystem in the study location. Moreover, the buffer zone at the plantation boundary should be established to minimize the edge effect brought by the plantation on the primary and secondary forest. Lastly, the existing plantation, cultivation area and the area covered with grass can be assigned for the agriculture zone for future agriculture development.

The study strengthens that the integration of GIS and MCDM is a valuable tool to analyse the agricultural land use suitability before an agricultural land use plan can be produced. Furthermore, the decision-maker can apply the findings from the study to produce the future agricultural land use planning of an area with potential agricultural development, such as the Kabuloh region. With the successful application of a sustainable agricultural land use plan in the Kabuloh region, the mapping of a wider area can be produced in future. Thus, global sustainability concerns of oil palm plantations in Malaysia can be addressed by implementing sustainable agricultural land use planning.

5.2 Recommendations for future research:

The recommendations for future research are listed as follows:

- A detailed study of the socio-economic impact of the existing oil palm plantation should be conducted in light of the identified potential impacts from the map overlay analysis conducted in this research. An on-site study is recommended to interview or distribute a questionnaire with the local villagers to know about the actual impact felt by the local society at the study location based on the outcome of the desktop study.
- A detailed study of the environmental impact of the existing oil palm plantation should be assessed in light of the identified potential environmental impacts based on the map overlay analysis. An on-site study is recommended to determine the actual impact on the environment at the study location based on the preliminary finding in this research.
- The study on rehabilitating the converted peatland in Sarawak is still unexplored. Additionally, there are oil palm plantations that identified to be developed by peatland conversion. Hence, it was recommended to conduct a study about the rehabilitation of Sarawak's peatland to conserve the precious peatland. The peatland should be rehabilitated in light of climate change which is getting more severe from time to time. Moreover, peatland is a vital carbon stock area for the global climate.
- The degree of correlation of the research method with the observed crop yields is unclear. Hence, it is suggested to determine the actual yield for a particular type of suggested crops associated with the study location. After knowing the actual yield of a particular crop, the degree of correlation of the research method can be enhanced by adjusting the research methodology, such as the choice of criteria, weightage of criteria and mathematical translation of criteria. The applicability of the research outcome could be enhanced by studying the degree of correlation of the research method with the observed crop yields.
- Future agricultural land use suitability assessment could involve the application of primary data. A deeper understanding of the agricultural land use suitability of a region could be achieved by applying primary data in the assessment. A sensitivity analysis can be implemented after the agricultural land use suitability assessment to know the degree of impact of different assessment criteria on the result.
- The participatory geographic information system (PGIS) method could be applied to involve the local communities in the study. The interview can be conducted with the local people to understand the actual need of the local environment and society. The opinion from the local people could assist in producing a more sustainable agricultural land use plan.

References

AbdelRahman, Mohamed A. E., Adel Shalaby, and E. F. Essa. 2018. "Quantitative Land Evaluation Based on Fuzzy-Multi-Criteria Spatial Model for Sustainable Land-Use Planning." *Modeling Earth Systems and Environment* 4 (4): 1341–53. https://doi.org/10.1007/s40808-018-0478-1.

Agamuthu, P, and W J Broughton. 1985. "Nutrient Cycling within the Developing Oil Palm-Legume Ecosystem." *Agriculture, Ecosystems & Environment* 13 (2): 111–23. https://doi.org/10.1016/0167-8809(85)90054-4.

Ahmed, Goma Bedawi, Abdul Rashid M. Shariff, Siva Kumar Balasundram, and Ahmad Fikri Bin Abdullah. 2016. "Agriculture Land Suitability Analysis Evaluation Based Multi Criteria and GIS Approach." *IOP Conference Series: Earth and Environmental Science* 37 (1). https://doi.org/10.1088/1755-1315/37/1/012044.

Aizen, Marcelo A, and Lawrence D Harder. 2009. "The Global Stock of Domesticated Honey Bees Is Growing Slower Than Agricultural Demand for Pollination." *Current Biology* 19 (11): 915–18. https://doi.org/https://doi.org/10.1016/j.cub.2009.03.071.

Akinci, Halil, Ayşe Yavuz Özalp, and Bülent Turgut. 2013. "Agricultural Land Use Suitability Analysis Using GIS and AHP Technique." *Computers and Electronics in Agriculture* 97: 71–82. https://doi.org/10.1016/j.compag.2013.07.006.

Akiyama, Hiroko, Xiaoyuan Yan, and Kazuyuki Yagi. 2010. "Evaluation of Effectiveness of Enhanced-efficiency Fertilizers as Mitigation Options for N2O and NO Emissions from Agricultural Soils: Meta-analysis." *Global Change Biology* 16 (6): 1837–46. https://doi.org/10.1111/j.1365-2486.2009.02031.x.

Akpoti, Komlavi, Amos T. Kabo-bah, and Sander J. Zwart. 2019. "Agricultural Land Suitability Analysis: State-of-the-Art and Outlooks for Integration of Climate Change Analysis." *Agricultural Systems* 173 (March): 172–208. https://doi.org/10.1016/j.agsy.2019.02.013.

Al-shalabi, Mohamed A., Shattri Bin Mansor, Nordin Bin Ahmed, and Rashid Shiriff. 2006. "GIS Based Multicriteria Approaches to Housing Site Suitability Assessment." *XXIII FIG Congress. Shaping the Change. Munich, Germany, October 8-13*, 1–17.

Albaji, Mohammad, Mona Golabi, Saeed Boroomand Nasab, and Mohammad Jahanshahi. 2014. "Land Suitability Evaluation for Surface, Sprinkler and Drip Irrigation Systems." *Transactions of the Royal Society of South Africa* 69 (2): 63–73. https://doi.org/10.1080/0035919X.2014.892038.

Allen, Kara, Marife D Corre, Aiyen Tjoa, Edzo Veldkamp, and Upendra M Sainju. 2015. "Soil Nitrogen-Cycling Responses to Conversion of Lowland Forests to Oil Palm and Rubber Plantations in Sumatra, Indonesia." *PloS One.* San Francisco, CA : https://doi.org/10.1371/journal.pone.0133325.

Amiri, Fazel, and Abdul Rashid B. Mohamed Shariff. 2012. "Application of Geographic Information Systems in Land-Use Suitability Evaluation for Beekeeping: A Case Study of Vahregan Watershed (Iran)." *African Journal of Agricultural Reseearch* 7 (1): 89–97. https://doi.org/10.5897/ajar10.1037.

Andriesse, J P. 1988. *Nature and Management of Tropical Peat Soils*. Food & Agriculture Org.

Arshad, Adzemi Mat. 2015. "Physical Land Evaluation for Oil Palm Cultivation in District of Temerloh and Kuantan, Pahang, Peninsular Malaysia." *Journal of Biology, Agriculture and Healthcare.* 5 (4): 104–12.

Arumugam, Anandkumar. 2016. "Ecological Risk Assessment of the Miri Coast, Sarawak, Borneo - A Biogeochemical Approach," no. May.

Austin, Kemen G, Prasad S Kasibhatla, Dean L Urban, Fred Stolle, and Jeffrey Vincent. 2015. "Reconciling Oil Palm Expansion and Climate Change Mitigation in Kalimantan, Indonesia." *PLOS ONE* 10 (5): e0127963. https://doi.org/10.1371/journal.pone.0127963.

Ayu Purnamasari, Riska, Ryozo Noguchi, and Tofael Ahamed. 2019. “Land Suitability Assessments for Yield Prediction of Cassava Using Geospatial Fuzzy Expert Systems and Remote Sensing.” *Computers and Electronics in Agriculture* 166 (October 2018): 105018. https://doi.org/10.1016/j.compag.2019.105018.

Azhar, Badrul, David B Lindenmayer, Jeff Wood, Joern Fischer, Adrian Manning, Chris Mcelhinny, Mohamed Zakaria, and Stuart Marsden. 2013. “The Influence of Agricultural System, Stand Structural Complexity and Landscape Context on Foraging Birds in Oil Palm Landscapes.” *Ibis (London, England)* 155 (2): 297–312. https://doi.org/10.1111/ibi.12025.

Azhar, Badrul, Chong Leong Puan, Mohamed Zakaria, Nuraishah Hassan, and Mohd Arif. 2014. “Effects of Monoculture and Polyculture Practices in Oil Palm Smallholdings on Tropical Farmland Birds.” *Basic and Applied Ecology* 15 (4): 336–46. https://doi.org/10.1016/j.baae.2014.06.001.

Aznar-Sánchez, José A., María Piquer-Rodríguez, Juan F. Velasco-Muñoz, and Francisco Manzano-Agugliaro. 2019. “Worldwide Research Trends on Sustainable Land Use in Agriculture.” *Land Use Policy* 87 (May): 104069. https://doi.org/10.1016/j.landusepol.2019.104069.

Badr, Golnaz, Gerrit Hoogenboom, Michelle Moyer, Markus Keller, Richard Rupp, and Joan Davenport. 2018. “Spatial Suitability Assessment for Vineyard Site Selection Based on Fuzzy Logic.” *Precision Agriculture* 19 (6): 1027–48. https://doi.org/10.1007/s11119-018-9572-7.

Baidya, Priyanka, Dibyajyoti Chutia, Singuluri Sudhakar, Chandan Goswami, Jonali Goswami, Victor Saikhom, Puyam S. Singh, and Kamini Kanta Sarma. 2014. “Effectiveness of Fuzzy Overlay Function for Multi-Criteria Spatial Modeling—A Case Study on Preparation of Land Resources Map for Mawsynram Block of East Khasi Hills District of Meghalaya, India.” *Journal of Geographic Information System* 06 (06): 605–12. https://doi.org/10.4236/jgis.2014.66050.

Baja, Sumbangan, David M Chapman, and Deirdre Dragovich. 2007. “Spatial Based Compromise Programming for Multiple Criteria Decision Making in Land Use Planning.” *Environmental Modeling & Assessment* 12 (3): 171–84. https://doi.org/10.1007/s10666-006-9059-1.

Banai, Reza. 1993. “Fuzziness in Geographical Information Systems: Contributions from the Analytic Hierarchy Process.” *International Journal of Geographical Information Systems* 7 (4): 315–29. https://doi.org/10.1080/02693799308901964.

Bandyopadhyay, S., R. K. Jaiswal, V. S. Hegde, and V. Jayaraman. 2009. “Assessment of Land Suitability Potentials for Agriculture Using a Remote Sensing and GIS Based Approach.” *International Journal of Remote Sensing* 30 (4): 879–95. https://doi.org/10.1080/01431160802395235.

Baniya, Nabarath, Michael Böehme, and Saroja Baniya. 2009. “Physical Land Suitability Assessment for the Large Cardamom Amomum Subulatum Roxb. Cultivation in Hills of Kathmandu Valley.” *Chinese Journal of Population Resources and Environment* 7 (4): 59–63. https://doi.org/10.1080/10042857.2009.10684954.

Barakat, A., W. Ennaji, A. El Jazouli, R. Amediaz, and F. Touhami. 2017. “Multivariate Analysis and GIS-Based Soil Suitability Diagnosis for Sustainable Intensive Agriculture in Beni-Moussa Irrigated Subperimeter (Tadla Plain, Morocco).” *Modeling Earth Systems and Environment* 3 (1): 1–8. https://doi.org/10.1007/s40808-017-0272-5.

Bickel, Tobias O, Carsten A Brühl, Jürgen R Gadau, Bert Hölldobler, and K Eduard Linsenmair. 2006. “Influence of Habitat Fragmentation on the Genetic Variability in Leaf Litter Ant Populations in Tropical Rainforests of Sabah, Borneo BT - Arthropod Diversity and Conservation.” In , edited by David L Hawksworth and Alan T Bull, 143–61. Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-1-4020-5204-0_10.

Bilotta, G. S., and R. E. Brazier. 2008. “Understanding the Influence of Suspended Solids on

Water Quality and Aquatic Biota." *Water Research* 42 (12): 2849–61. https://doi.org/10.1016/j.watres.2008.03.018.

Binkley, Dan, and Richard F. Fisher. 2013. *Ecology and Management of Forest Soils: Fourth Edition*. *Wiley-Blackwell*. John Wiley & Sons, Ltd Wiley-Blackwell. https://doi.org/10.1002/9781118422342.

Boettinger, J L. 2005. "Alluvium and Alluvial Soils." In , edited by Daniel B T - Encyclopedia of Soils in the Environment Hillel, 45–49. Oxford: Elsevier. https://doi.org/https://doi.org/10.1016/B0-12-348530-4/00008-4.

Brouwer, Leo C, and Hans Th. Riezebos. 1998. "Nutrient Dynamics in Intact and Logged Tropical Rain Forest in Guyana." In *Soils of Tropical Forest Ecosystems*, edited by Andreas Schulte and Daddy Ruhiyat, 73–86. Berlin, Heidelberg: Springer Berlin Heidelberg.

Bruijnzeel, L A. 2004. "Hydrological Functions of Tropical Forests: Not Seeing the Soil for the Trees?" *Agriculture, Ecosystems & Environment.* Amsterdam. https://doi.org/10.1016/j.agee.2004.01.015.

Buckley, J J. 1985. "Fuzzy Hierarchical Analysis." *Fuzzy Sets and Systems* 17 (3): 233–47. https://doi.org/https://doi.org/10.1016/0165-0114(85)90090-9.

Burrough, Peter A., and Rachael A. McDonnell. 1998. *Principles of Geographical Information Systems / Peter A. Burrough and Rachael A. McDonnell.* Edited by Rachael McDonnell and P A Burrough. Oxford: Oxford.

Campiglia, Enio, Roberto Mancinelli, Emanuele Radicetti, and Sara Marinari. 2011. "Legume Cover Crops and Mulches: Effects on Nitrate Leaching and Nitrogen Input in a Pepper Crop (Capsicum Annuum L.)." *Nutrient Cycling in Agroecosystems*. Dordrecht : https://doi.org/10.1007/s10705-010-9404-2.

Caudwell, R W, and I Orrell. 1997. "Integrated Pest Management for Oil Palm in Papua New Guinea." *Integrated Pest Management Reviews* 2 (1): 17–24. https://doi.org/10.1023/A:1018420211050.

Cengiz, Tülay, and Cengiz Akbulak. 2009. "Application of Analytical Hierarchy Process and Geographic Information Systems in Land-Use Suitability Evaluation: A Case Study of Dümrek Village (Çanakkale, Turkey)." *International Journal of Sustainable Development & World Ecology* 16 (4): 286–94. https://doi.org/10.1080/13504500903106634.

Chandio, Imtiaz Ahmed, A N Matori, K Yusof, M A Hussain Talpur, and M Aminu. 2014. "GIS-Basedland Suitability Analysis of Sustainable Hillside Development." *Procedia Engineering* 77: 87–94. https://doi.org/https://doi.org/10.1016/j.proeng.2014.07.009.

Chang, Da-Yong. 1996. "Applications of the Extent Analysis Method on Fuzzy AHP." *European Journal of Operational Research* 95 (3): 649–55. https://doi.org/https://doi.org/10.1016/0377-2217(95)00300-2.

Chang, Ni-Bin, G Parvathinathan, and Jeff B Breeden. 2008. "Combining GIS with Fuzzy Multicriteria Decision-Making for Landfill Siting in a Fast-Growing Urban Region." *Journal of Environmental Management* 87 (1): 139–53. https://doi.org/https://doi.org/10.1016/j.jenvman.2007.01.011.

Chellaiah, Darshanaa, and Catherine M. Yule. 2018. "Effect of Riparian Management on Stream Morphometry and Water Quality in Oil Palm Plantations in Borneo." *Limnologica* 69 (November 2017): 72–80. https://doi.org/10.1016/j.limno.2017.11.007.

Chen, Y, J. Yu, and S. Khan. 2010. "Spatial Sensitivity Analysis of Multi-Criteria Weights in GIS-Based Land Suitability Evaluation." *Environmental Modelling and Software* 25 (12): 1582–91. https://doi.org/10.1016/j.envsoft.2010.06.001.

Chesworth, Ward, ed. 2008. "Gley BT - Encyclopedia of Soil Science." In , 299. Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-1-4020-3995-9_251.

Chua, Sam. 2019. "Three Million Ha of Sarawak Landmass Marked for Agricultural Devt – Len Talif." *The Borneo Post*, June 19, 2019. https://www.theborneopost.com/2019/06/19/three-million-ha-of-sarawak-landmass-marked-for-agricultural-devt-len-talif/.

Collins, Michael G., Frederick R. Steiner, and Michael J. Rushman. 2001. "Land-Use Suitability Analysis in the United States: Historical Development and Promising Technological Achievements." *Environmental Management* 28 (5): 611–21. https://doi.org/10.1007/s002670010247.

Comte, Irina, François Colin, Joann K Whalen, Olivier Grünberger, and Jean-Pierre Caliman. 2012. "Agricultural Practices in Oil Palm Plantations and Their Impact on Hydrological Changes, Nutrient Fluxes and Water Quality in Indonesia." *Advances in Agronomy.* Amsterdam. https://doi.org/10.1016/B978-0-12-394277-7.00003-8.

Corley, R H V, and P B Tinker. 2016. *The Oil Palm*. 5th ed.. Chichester, England : Wiley Blackwell.

Couwenberg, John, René Dommain, and Hans Joosten. 2010. "Greenhouse Gas Fluxes from Tropical Peatlands in South-east Asia." *Global Change Biology* 16 (6): 1715–32. https://doi.org/10.1111/j.1365-2486.2009.02016.x.

Cramb, Rob, and John F McCarthy, eds. 2016. *The Oil Palm Complex*. NUS Press. https://doi.org/10.2307/j.ctv1xz0km.

D'haeze, D, J Deckers, D Raes, T A Phong, and H V Loi. 2005. "Environmental and Socio-Economic Impacts of Institutional Reforms on the Agricultural Sector of Vietnam: Land Suitability Assessment for Robusta Coffee in the Dak Gan Region." *Agriculture, Ecosystems & Environment* 105 (1): 59–76. https://doi.org/https://doi.org/10.1016/j.agee.2004.05.009.

Dadhich, Gautam, Parul R. Patel, and Manik H. Kalubarme. 2017. "Agriculture Land Suitability Evaluation for Wheat Cultivation Using Geomatics for Patan District, India." *International Journal of Agricultural Resources, Governance and Ecology* 13 (1): 91–108. https://doi.org/10.1504/IJARGE.2017.084038.

Danielsen, Finn, Hendrien Beukema, Neil D. Burgess, Faizal Parish, Carsten A. BrÜhl, Paul F. Donald, Daniel Murdiyarso, et al. 2009. "Biofuel Plantations on Forested Lands : Double Jeopardy for Biodiversity and Climate." *Conservation Biology* 23 (2): 348–58. https://doi.org/10.1111/j.1523-1739.2008.01096.x.

Deng, Fei, Xiaobing Li, Hong Wang, Meng Zhang, Ruihua Li, and Xu Li. 2014. "GIS-Based Assessment of Land Suitability for Alfalfa Cultivation: A Case Study in the Dry Continental Steppes of Northern China." *Spanish Journal of Agricultural Research* 12 (2): 364–75. https://doi.org/10.5424/sjar/2014122-4672.

Dengiz, Orhan. 2013. "Land Suitability Assessment for Rice Cultivation Based on GIS Modeling." *Turkish Journal of Agriculture and Forestry* 37 (3): 326–34. https://doi.org/10.3906/tar-1206-51.

Dent, David, and Anthony Young. 1981. *Soil Survey and Land Evaluation.* George Allen & Unwin.

Department of Agriculture Sarawak. 1982a. "Agriculture Capability Map."

Department of Agriculture Sarawak. 1982b. "Soil Map with River System."

Department of Agriculture Sarawak. 2019a. "Major Agriculture Commodities Map."

Department of Agriculture Sarawak. 2019b. "Settlement Area."

Department of Agriculture Sarawak. 2021. "Department of Agriculture Sarawak's Vision and Mission." 2021. https://doa.sarawak.gov.my/page-0-190-767-Vision-and-Mission.html.

Department of Irrigation & Drainage. 1989. "Sungai Tekam Experimental Basin Final Report, July 1977 to June 1986."

Department of Irrigation and Drainage Sarawak. 2008. "Location of Water Catchments In Sarawak."

Department of Statistics Malaysia. 2019. "Malaysia Econimic Statistics - Time Series 2019." 2019. https://www.dosm.gov.my/v1/index.php?r=column/ctimeseries&menu_id=bnk3bk0wTTkxOXVHaVg3SUFDMlBUUT09.

Department of Statistics Malaysia. 2020. "Selected Agricultural Indicators, Malaysia, 2020." 2020. https://www.dosm.gov.my/v1/index.php?r=column/ctwoByCat&parent_id=45&menu_id=Z0VTZGU1UHBUT1VJMFlpaXRRR0xpdz09#:~:text=Selected Agricultural Indicators%2C Malaysia%2C 2020&text=5 billion) to the Gross,%25) and rubber (3.0%25).

Department of Survey and Mapping Malaysia. 2015. "Exisitng Land Cover Map."

Dislich, Claudia, Alexander C. Keyel, Jan Salecker, Yael Kisel, Katrin M. Meyer, Mark Auliya, Andrew D. Barnes, et al. 2017. "A Review of the Ecosystem Functions in Oil Palm Plantations, Using Forests as a Reference System." *Biological Reviews* 92 (3): 1539–69. https://doi.org/10.1111/brv.12295.

Drescher, Jochen, Katja Rembold, Kara Allen, Philip Backschäfe, Damayanti Buchori, Yann Clough, Heiko Faust, et al. 2016. "Ecological and Socio-Economic Functions across Tropical Land Use Systems after Rainforest Conversion." *Philosophical Transactions. Biological Sciences* 371 (1694): 1–8.

Dwevedi, Alka, Promod Kumar, Pravita Kumar, Yogendra Kumar, Yogesh K. Sharma, and Arvind M. Kayastha. 2017. *Soil Sensors: Detailed Insight into Research Updates, Significance, and Future Prospects*. *New Pesticides and Soil Sensors*. Elsevier Inc. https://doi.org/10.1016/b978-0-12-804299-1.00016-3.

Ennaji, Widad, Ahmed Barakat, Mohamed El Baghdadi, Hakima Oumenskou, Mohamed Aadraoui, Lalla Aicha Karroum, and Abdessamad Hilali. 2018. "GIS-Based Multi-Criteria Land Suitability Analysis for Sustainable Agriculture in the Northeast Area of Tadla Plain (Morocco)." *Journal of Earth System Science* 127 (6): 1–14. https://doi.org/10.1007/s12040-018-0980-x.

Environment Conservation Department. 2002. "Environmental Impact Assessment (EIA) Guidelines on Oil Palm Plantation Development." t. Environmental Conservation Department, Kota Kinabalu, Sabah, Malaysia.

Erensal, Yasemin Claire, Temel Öncan, and Murat Levent Demircan. 2006. "Determining Key Capabilities in Technology Management Using Fuzzy Analytic Hierarchy Process: A Case Study of Turkey." *Information Sciences* 176 (18): 2755–70. https://doi.org/https://doi.org/10.1016/j.ins.2005.11.004.

Famiglietti, J S. 2014. "The Global Groundwater Crisis." *Nature Climate Change.* [London] : https://doi.org/10.1038/nclimate2425.

FAO. 1976. *A Framework for Land Evaluation. Soils Bulletin 32*. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO. 1985. *Guidelines: Land Evaluation for Irrigated Agriculture. Soils Bulletin 55*. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO. 1993. *Guidelines for Land-Use Planning*. Food and Agriculture Organization of the United Nations, Rome, Italy.

Feizizadeh, Bakhtiar, and Thomas Blaschke. 2013. "Land Suitability Analysis for Tabriz County, Iran: A Multi-Criteria Evaluation Approach Using GIS." *Journal of Environmental Planning and Management* 56 (1): 1–23. https://doi.org/10.1080/09640568.2011.646964.

Fitzherbert, Emily B., Matthew J. Struebig, Alexandra Morel, Finn Danielsen, Carsten A. Brühl, Paul F. Donald, and Ben Phalan. 2008. "How Will Oil Palm Expansion Affect Biodiversity?" *Trends in Ecology and Evolution* 23 (10): 538–45. https://doi.org/10.1016/j.tree.2008.06.012.

Flach, Michiel. 1997. *Sago Palm. Metroxylon Sagu Rottb. Promoting the Conservation and Use of Underutilized and Neglected Crops*. *International Plant Genetic Resources Institute, Rome, Italy*.

Foster, William A, Jake L Snaddon, Edgar C Turner, Tom M Fayle, Timothy D Cockerill, M D Farnon Ellwood, Gavin R Broad, et al. 2011. "Establishing the Evidence Base for Maintaining Biodiversity and Ecosystem Function in the Oil Palm Landscapes of South East Asia." *Philosophical Transactions: Biological Sciences* 366 (1582): 3277–91. https://doi.org/10.1098/rstb.2011.0041.

FRIM. 2004. *Tree Flora of Sabah and Sarawak*. Kuala Lumpur, Malaysia: Forest Research Institute Malaysia (FRIM).

Fujinuma, Junichi, and Rhett D Harrison. 2012. "Wild Pigs (Sus Scrofa) Mediate Large-Scale Edge Effects in a Lowland Tropical Rainforest in Peninsular Malaysia." *PloS One.* San Francisco, CA : https://doi.org/10.1371/journal.pone.0037321.

Gandaseca, Seca, Noraini Rosli, Mohammad Shawkat Hossain, and Chandra Imam Arianto. 2014. "Assessment of Oil Palm Plantation and Tropical Peat Swamp Forest Water Quality by Multivariate Statistical Analysis." *American Journal of Environmental Sciences* 10 (4): 391–402. https://doi.org/10.3844/ajessp.2014.391.402.

Gaveau, D L A, M Salim, and S Arjasakusuma. 2016. "Deforestation and Industrial Plantations Development in Borneo." *Center for International Forestry Research (CIFOR)* 2.

Germer, J, and J Sauerborn. 2008. "Estimation of the Impact of Oil Palm Plantation Establishment on Greenhouse Gas Balance." *Environment, Development and Sustainability* 10 (6): 697–716. https://doi.org/10.1007/s10668-006-9080-1.

Gharibreza, Mohammadreza, John Kuna Raj, Ismail Yusoff, Muhammad Aqeel Ashraf, Zainudin Othman, and Wan Zakaria Wan Muhamad Tahir. 2013. "Effects of Agricultural Projects on Nutrient Levels in Lake Bera (Tasek Bera), Peninsular Malaysia." *Agriculture, Ecosystems and Environment* 165: 19–27. https://doi.org/10.1016/j.agee.2012.12.004.

Global Forest Watch. 2020. "Tree Cover Loss in Malaysia." 2020. https://www.globalforestwatch.org/dashboards/country/MYS/?category=summary&dashboardPrompts=eyJzaG93UHJvbXB0cyI6dHJ1ZSwicHJvbXB0c1ZpZXdlZCI6WyJzaGFyZVdpZGdldCIsImRvd25sb2FkRGFzaGJvYXJkU3RhdHMiLCJ3aWRnZXRTZXR0aW5ncyJdLCJzZXR0aW5ncyI6eyJzaG93UHJvbXB0cyI6dHJ.

Goh, Kah-Joo, R Härdter, and T Fairhurst. 2003. "Fertilizing for Maximum Return." In .

Griffiths, William, and Thomas Fairhurst. 2003. "Implementation of Best Management Practices in an Oil Palm Rehabilitation Project." *Better Crops International* 17 (1): 16–19. http://www.potafos.org/ppiweb/bcropint.nsf/$webindex/1F3E8E542C30071C85256D340072DDE0/$file/i03-1p16.pdf.

Groot, Rudolf S de, Matthew A Wilson, and Roelof M J Boumans. 2002. "A Typology for the Classification, Description and Valuation of Ecosystem Functions, Goods and Services." *Ecological Economics*. New York, NY . https://doi.org/10.1016/S0921-8009(02)00089-7.

Guerra, Antônio José Teixeira, Michael Augustine Fullen, Maria do Carmo Oliveira Jorge, José Fernando Rodrigues Bezerra, and Mohamed S. Shokr. 2017. "Slope Processes, Mass Movement and Soil Erosion: A Review." *Pedosphere* 27 (1): 27–41. https://doi.org/10.1016/S1002-0160(17)60294-7.

Guillaume, Thomas, Anna Mareike Holtkamp, Muhammad Damris, Bernhard Brümmer, and Yakov Kuzyakov. 2016. "Soil Degradation in Oil Palm and Rubber Plantations under Land Resource Scarcity." *Agriculture, Ecosystems and Environment* 232: 110–18. https://doi.org/10.1016/j.agee.2016.07.002.

Gumma, Muralikrishna, Prasad S Thenkabail, Hideto Fujii, and Regassa Namara. 2009. "Spatial Models for Selecting the Most Suitable Areas of Rice Cultivation in the Inland Valley Wetlands of Ghana Using Remote Sensing and Geographic Information Systems." *Journal of Applied Remote Sensing* 3 (1): 1–21. https://doi.org/10.1117/1.3182847.

Gurmit, Singh, Yap Pau Tan, C V Rajah Padman, and Foo Wah Lee. 1987. "Experiences on the Cultivation and Management of Oil Palms on Deep Peat in United Plantations Berhad." *Planter* 63 (733): 143–57.

Hardwick, Stephen R., Ralf Toumi, Marion Pfeifer, Edgar C. Turner, Reuben Nilus, and Robert M. Ewers. 2015. "The Relationship between Leaf Area Index and Microclimate in Tropical Forest and Oil Palm Plantation: Forest Disturbance Drives Changes in Microclimate." *Agricultural and Forest Meteorology* 201: 187–95. https://doi.org/10.1016/j.agrformet.2014.11.010.

Hartemink, Alfred E. 2005. "Plantation Agriculture in the Tropics." *Outlook on Agriculture*. Oxford. https://doi.org/10.5367/0000000053295150.

Hashim, Ghulam M. 2003. "Salt-Affected Soils of Malaysia." 2003. http://www.fao.org/tempref/agl/agll/ladadocs/malaysia.doc.

Hedin, Lars O, E N Jack Brookshire, Duncan N L Menge, and Alexander R Barron. 2009. "The Nitrogen Paradox in Tropical Forest Ecosystems." *Annual Review of Ecology, Evolution, and Systematics.* Palo Alto, Calif. : https://doi.org/10.1146/annurev.ecolsys.37.091305.110246.

Hiroshi, Ehara, and Yukio Toyoda. 2018. *Sago Palm: Multiple Contributions to Food Security and Sustainable Livelihoods*. Edited by Dennis V Johnson. Springer Nature. https://doi.org/10.1007/978-981-10-5269-9.

Hooijer, A, S Page, J G Canadell, M Silvius, J Kwadijk, H Wösten, and J Jauhiainen. 2010. "Current and Future CO2 Emissions from Drained Peatlands in Southeast Asia." *Biogeosciences* 7 (5): 1505–14. https://doi.org/10.5194/bg-7-1505-2010.

Hooijer, A, S Page, J Jauhiainen, W A Lee, X X Lu, A Idris, and G Anshari. 2012. "Subsidence and Carbon Loss in Drained Tropical Peatlands." *Biogeosciences* 9 (3): 1053–71. https://doi.org/10.5194/bg-9-1053-2012.

Hopkins, Lewis D. 1977. "Methods for Generating Land Suitability Maps: A Comparative Evaluation." *Journal of the American Planning Association* 43 (4): 386–400. https://doi.org/10.1080/01944367708977903.

Howell, Colleen J., Kurt A. Schwabe, Azizan Haji Abu Samah, Robert C. Graham, and Nur Iskandar Taib. 2005. "Assessment of Aboriginal Smallholder Soils for Rubber Growth in Peninsular Malaysia." *Soil Science* 170 (12): 1034–49. https://doi.org/10.1097/01.ss.0000187346.30201.40.

Ichikawa, Masahiro. 2007. "Degradation and Loss of Forest Land and Land-Use Changes in Sarawak, East Malaysia: A Study of Native Land Use by the Iban." *Ecological Research* 22 (3): 403–13. https://doi.org/10.1007/s11284-007-0365-0.

Ioki, Keiko, Norlina Mohd Din, Ralf Ludwig, Daniel James, Su Wah Hue, Shazrul Azwan Johari, Remmy Alfie Awang, Rosila Anthony, and Mui How Phua. 2019. "Supporting Forest Conservation through Community-Based Land Use Planning and Participatory GIS – Lessons from Crocker Range Park, Malaysian Borneo." *Journal for Nature Conservation* 52 (September): 125740. https://doi.org/10.1016/j.jnc.2019.125740.

IUCN. 2020. "The IUCN Red List of Threatened Species Version 2020-3." 2020. https://www.iucnredlist.org/.

Jamil, Mubashir, Raihan Ahmed, and Haroon Sajjad. 2018. "Land Suitability Assessment for Sugarcane Cultivation in Bijnor District, India Using Geographic Information System and Fuzzy Analytical Hierarchy Process." *GeoJournal* 83 (3): 595–611. https://doi.org/10.1007/s10708-017-9788-5.

Jamil, Mubashir, Mehebub Sahana, and Haroon Sajjad. 2018. “Crop Suitability Analysis in the Bijnor District, UP, Using Geospatial Tools and Fuzzy Analytical Hierarchy Process.” *Agricultural Research* 7 (4): 506–22. https://doi.org/10.1007/s40003-018-0335-5.

Jauhiainen, J, H Silvennoinen, R Hämäläinen, K Kusin, S Limin, R J Raison, and H Vasander. 2012. “Nitrous Oxide Fluxes from Tropical Peat with Different Disturbance History and Management.” *Biogeosciences* 9 (4): 1337–50. https://doi.org/10.5194/bg-9-1337-2012.

Jauhiainen, Jyrki, Suwido Limin, Hanna Silvennoinen, and Harri Vasander. 2008. “Carbon Dioxide and Methane Fluxes in Drained Tropical Peat before and after Hydrological Restoration.” *Ecology* 89 (12): 3503–14. https://doi.org/10.1890/07-2038.1.

Jiang, Hong, and J. Ronald Eastman. 2000. “Application of Fuzzy Measures in Multi-Criteria Evaluation in GIS.” *International Journal of Geographical Information Science* 14 (2): 173–84. https://doi.org/10.1080/136588100240903.

Kahsay, Araya, Mitiku Haile, Girmay Gebresamuel, and Muktar Mohammed. 2018. “Land Suitability Analysis for Sorghum Crop Production in Northern Semi-Arid Ethiopia: Application of GIS-Based Fuzzy AHP Approach.” *Cogent Food & Agriculture* 4 (1): 1–24. https://doi.org/10.1080/23311932.2018.1507184.

Kalogirou, S. 2002. “Expert Systems and GIS: An Application of Land Suitability Evaluation.” *Computers, Environment and Urban Systems* 26 (2): 89–112. https://doi.org/https://doi.org/10.1016/S0198-9715(01)00031-X.

Kamarudin, Norman, Ramle Mslim, Mohamed Mazmira Mohd Masri, and Idris Abu Seman. 2016. “Current Challenges On Pests and Diseases of Oil Palm Cultivation.” In *SASS - DOA Seminar*, 1–10. Malaysian Palm Oil Board (MPOB), Selangor.

Kenate, Girma Alemu and. 2017. “GIS Based Land-Use Suitability Analysis for Selected Perennial Crops in Gumay Woreda of Jimma Zone, South West Ethiopia,” 3–18.

Keshavarzi, Ali, Fereydoon Sarmadian, Ahmad Heidari, and Mahmoud Omid. 2010. “Land Suitability Evaluation Using Fuzzy Continuous Classification (A Case Study: Ziaran Region).” *Modern Applied Science* 4 (7): 72–81. https://doi.org/10.5539/mas.v4n7p72.

Koh, Lian Pin. 2008. “Can Oil Palm Plantations Be Made More Hospitable for Forest Butterflies and Birds?” *The Journal of Applied Ecology* 45 (4): 1002–9. https://doi.org/10.1111/j.1365-2664.2008.01491.x.

Koh, Lian Pin, Patrice Levang, and Jaboury Ghazoul. 2009. “Designer Landscapes for Sustainable Biofuels.” *Trends in Ecology and Evolution* 24 (8): 431–38. https://doi.org/10.1016/j.tree.2009.03.012.

Koh, Lian Pin, and David S. Wilcove. 2008. “Is Oil Palm Agriculture Really Destroying Tropical Biodiversity?” *Conservation Letters* 1 (2): 60–64. https://doi.org/10.1111/j.1755-263x.2008.00011.x.

Kotowska, Martyna M, Christoph Leuschner, Triadiati Triadiati, Selis Meriem, and Dietrich Hertel. 2015. “Quantifying Above- and Belowground Biomass Carbon Loss with Forest Conversion in Tropical Lowlands of Sumatra (Indonesia).” *Global Change Biology* 21 (10): 3620–34. https://doi.org/10.1111/gcb.12979.

Koulouri, M., and Chr Giourga. 2007. “Land Abandonment and Slope Gradient as Key Factors of Soil Erosion in Mediterranean Terraced Lands.” *Catena* 69 (3): 274–81. https://doi.org/10.1016/j.catena.2006.07.001.

Krishnakumar, V., and P. K. Thampan. 2018. *The Coconut Palm (Cocos Nucifera L.) - Research and Development Perspectives*. Edited by K. U.K. Nampoothiri and M. Achuthan Nair. *The Coconut Palm (Cocos Nucifera L.) - Research and Development Perspectives*. Springer Nature Singapore Pte Ltd. https://doi.org/10.1007/978-981-13-2754-4.

Kurniawan, Syahrul. 2016. “Conversion of Lowland Forests to Rubber and Oil Palm Plantations Changes Nutrient Leaching and Nutrient Retention Efficiency in Highly

Weathered Soils of Sumatra, Indonesia." University of Göttingen.

La Rosa, D De, F Mayol, E Diaz-Pereira, M Fernandez, and D de la Rosa. 2004. "A Land Evaluation Decision Support System (MicroLEIS DSS) for Agricultural Soil Protection: With Special Reference to the Mediterranean Region." *Environmental Modelling & Software* 19 (10): 929–42. https://doi.org/https://doi.org/10.1016/j.envsoft.2003.10.006.

Lam, Man Kee, Kok Tat Tan, Keat Teong Lee, and Abdul Rahman Mohamed. 2009. "Malaysian Palm Oil: Surviving the Food versus Fuel Dispute for a Sustainable Future." *Renewable and Sustainable Energy Reviews* 13 (6–7): 1456–64. https://doi.org/10.1016/j.rser.2008.09.009.

Lambin, Eric F., and Patrick Meyfroidt. 2011. "Global Land Use Change, Economic Globalization, and the Looming Land Scarcity." *Proceedings of the National Academy of Sciences of the United States of America* 108 (9): 3465–72. https://doi.org/10.1073/pnas.1100480108.

Lees, Alexander C., and Carlos A. Peres. 2008. "Conservation Value of Remnant Riparian Forest Corridors of Varying Quality for Amazonian Birds and Mammals." *Conservation Biology* 22 (2): 439–49. https://doi.org/10.1111/j.1523-1739.2007.00870.x.

Loehr, Raymond. 2012. *Pollution Control for Agriculture*. 2nd ed. United States of America: Elsevier.

Longley, P.A., M.F. Frank Goodchild, D.J. Maguire, and D.W. Rhind. 2020. "Geographic Information Science and Systems." In *International Encyclopedia of Human Geography*. https://doi.org/10.1016/b978-0-08-102295-5.10557-8.

Lord, S, and J Clay. 2006. "Environmental Impacts of Oil Palm–Practical Considerations in Defining Sustainability for Impacts on the Air, Land and Water." In *International Planters Conference on Higher Productivity and Efficient Practices for Sustainable Agriculture, Putrajaya, Malaysia*, 1–37. http://www.nbpol.com.pg/wp-content/uploads/downloads/2011/02/EnvironmentalImpactOfOilPalm.pdf.

Lorion, Christopher M, and Brian P Kennedy. 2009. "Riparian Forest Buffers Mitigate the Effects of Deforestation on Fish Assemblages in Tropical Headwater Streams Published by : Ecological Society of America Linked References Are Available on JSTOR for This Article : Your Use of the JSTOR Archive Indicate." *Ecological Applications* 19 (2): 468–79.

Luskin, Matthew Scott, and Matthew D. Potts. 2011. "Microclimate and Habitat Heterogeneity through the Oil Palm Lifecycle." *Basic and Applied Ecology* 12 (6): 540–51. https://doi.org/10.1016/j.baae.2011.06.004.

Mackie, Cynthia. 1984. "The Lessons behind East Kalimantan's Forest Fires." *Borneo Research Bulletin* 16 (2): 63–74.

Maddahi, Zeinab, Ahmad Jalalian, M M Kheirkhan Zarkesh, and Naser Honarjo. 2014. "Land Suitability Analysis for Rice Cultivation Using Multi Criteria Evaluation Approach and GIS." *European Journal of Experimental Biology* 4 (3): 639–48.

Maddahi, Zeinab, Ahmad Jalalian, Mir Masoud Kheirkhah Zarkesh, and Naser Honarjo. 2017. "Land Suitability Analysis for Rice Cultivation Using a GIS-Based Fuzzy Multi-Criteria Decision Making Approach: Central Part of Amol District, Iran." *Soil and Water Research* 12 (1): 29–38. https://doi.org/10.17221/1/2016-SWR.

Malczewski, Jacek. 2000. "On the Use of Weighted Linear Combination Method in GIS: Common and Best Practice Approaches." *Transactions in GIS* 4 (1): 5–22. https://doi.org/10.1111/1467-9671.00035.

Malczewski, Jacek. 1999. *GIS and Multicriteria Decision Analysis*. New York: New York : J. Wiley & Sons.

Malczewski, Jacek. 2004. "GIS-Based Land-Use Suitability Analysis: A Critical Overview." *Progress in Planning* 62 (1): 3–65. https://doi.org/10.1016/j.progress.2003.09.002.

Malmir, Maryam, Mir Masoud Kheirkhah Zarkesh, Seyed Masoud Monavari, Seyed Ali Jozi, and Esmail Sharifi. 2016. “Analysis of Land Suitability for Urban Development in Ahwaz County in Southwestern Iran Using Fuzzy Logic and Analytic Network Process (ANP).” *Environmental Monitoring and Assessment* 188 (8). https://doi.org/10.1007/s10661-016-5401-5.

Marrewijk, Marcel Van. 2003. “Concepts and Definitions of CSR and Corporate Sustainability: Between Agency and Communion.” *Journal of Business Ethics* 44 (2): 95–105.

Mas, J F, H Puig, J L Palacio, and A Sosa-López. 2004. “Modelling Deforestation Using GIS and Artificial Neural Networks.” *Environmental Modelling & Software* 19 (5): 461–71. https://doi.org/https://doi.org/10.1016/S1364-8152(03)00161-0.

Masoud, J., W. A. Agyare, G. Forkuor, R. Namara, and E. Ofori. 2013. “Modeling Inland Valley Suitability for Rice Cultivation.” *ARPN Journal of Engineering and Applied Sciences* 8 (1): 9–19.

McDowell, R. W., T. Snelder, S. Harris, L. Lilburne, S. T. Larned, M. Scarsbrook, A. Curtis, B. Holgate, J. Phillips, and K. Taylor. 2018. “The Land Use Suitability Concept: Introduction and an Application of the Concept to Inform Sustainable Productivity within Environmental Constraints.” *Ecological Indicators* 91 (February): 212–19. https://doi.org/10.1016/j.ecolind.2018.03.067.

McHarg, Ian L. 1969. *Design With Nature*. Wiley, New York.

Meijaard, Erik, Douglas Sheil, Robert Nasi, David Augeri, Barry Rosenbaum, Djoko Iskandar, Titiek Setyawati, Martjan Lammertink, Ike Rachmatika, and Anna Wong. 2005. *Life after Logging: Reconciling Wildlife Conservation and Production Forestry in Indonesian Borneo*. Bogor: CIFOR, Bogor.

Melling, Lulie, Ryusuke Hatano, and Kah Joo Goh. 2005. “Methane Fluxes from Three Ecosystems in Tropical Peatland of Sarawak, Malaysia.” *Soil Biology and Biochemistry.* 37 (8): 1445–53. https://doi.org/10.1016/j.soilbio.2005.01.001.

Memarbashi, Elnaz, Hossein Azadi, Ali Akbar Barati, Fatemeh Mohajeri, Steven Van Passel, and Frank Witlox. 2017. “Land-Use Suitability in Northeast Iran: Application of AHP-GIS Hybrid Model.” *ISPRS International Journal of Geo-Information* 6 (12). https://doi.org/10.3390/ijgi6120396.

Mendas, Abdelkader, and Amina Delali. 2012. “Integration of MultiCriteria Decision Analysis in GIS to Develop Land Suitability for Agriculture: Application to Durum Wheat Cultivation in the Region of Mleta in Algeria.” *Computers and Electronics in Agriculture* 83: 117–26. https://doi.org/10.1016/j.compag.2012.02.003.

Mercer, Edwina V., Theresa G. Mercer, and Alexander K. Sayok. 2013. “Effects of Forest Conversions to Oil Palm Plantations on Freshwater Macroinvertebrates: A Case Study from Sarawak, Malaysia.” *Journal of Land Use Science* 9 (3): 260–77. https://doi.org/10.1080/1747423X.2013.786149.

Merten, Jennifer, Alexander Röll, Thomas Guillaume, Ana Meijide, Suria Tarigan, Herdhata Agusta, Claudia Dislich, et al. 2016. “Water Scarcity and Oil Palm Expansion: Social Views and Environmental Processes.” *Ecology and Society* 21 (2). https://doi.org/10.5751/ES-08214-210205.

Meyer, Julie R, C Lee Campbell, Thomas J Moser, George R Hess, John O Rawlings, Steven Peck, and Walter W Heck. 1992. “Indicators of the Ecological Status of Agroecosystems BT - Ecological Indicators: Volume 1.” In , edited by Daniel H McKenzie, D Eric Hyatt, and V Janet McDonald, 629–58. Boston, MA: Springer US. https://doi.org/10.1007/978-1-4615-4659-7_35.

Miettinen, Jukka, Al Hooijer, Daniel Tollenaar, Sue Page, and Chris Malins. 2012. “Historical Analysis and Projection of Oil Palm Plantation Expansion on Peatland in Southeast Asia.” *Indirect Effects of Biofuel Production*, no. 17: 1–49.

Miettinen, Jukka, Chenghua Shi, and Soo Chin Liew. 2016. “Land Cover Distribution in the

Peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with Changes since 1990." *Global Ecology and Conservation* 6: 67–78. https://doi.org/https://doi.org/10.1016/j.gecco.2016.02.004.

Mikhailov, L, and P Tsvetinov. 2004. "Evaluation of Services Using a Fuzzy Analytic Hierarchy Process." *Applied Soft Computing* 5 (1): 23–33. https://doi.org/https://doi.org/10.1016/j.asoc.2004.04.001.

Mishra, Ashutosh Kumar, Shikhar Deep, and Abhishek Choudhary. 2015. "Identification of Suitable Sites for Organic Farming Using AHP & GIS." *The Egyptian Journal of Remote Sensing and Space Science* 18 (2): 181–93. https://doi.org/https://doi.org/10.1016/j.ejrs.2015.06.005.

Mokarram, M., and F. Aminzadeh. 2010. "Gis-Based Multicriteria Land Suitability Evaluation Using Ordered Weight Averaging with Fuzzy Quantifier: A Case Study in Shavur Plain,Iran." *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives* 38: 508–12.

Moore, Sam, Chris D Evans, Susan E Page, Mark H Garnett, Tim G Jones, Chris Freeman, Aljosja Hooijer, Andrew J Wiltshire, Suwido H Limin, and Vincent Gauci. 2013. "Deep Instability of Deforested Tropical Peatlands Revealed by Fluvial Organic Carbon Fluxes." *Nature* 493 (7434): 660–63. https://doi.org/10.1038/nature11818.

Nagoya Protocol. 2011. "The Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from Their Utilization to the Convention on Biological Diversity." Secretariat of the Convention on Biological Diversity, Montreal.

Nantha, Hemanath Swarna, and Clem Tisdell. 2009. "The Orangutan-Oil Palm Conflict: Economic Constraints and Opportunities for Conservation." *Biodiversity and Conservation* 18 (2): 487–502. http://link.springer.com/article/10.1007%2Fs10531-008-9512-3.

Ngoze, Solomon, Susan Riha, Johannes Lehmann, Louis Verchot, James Kinyangi, David Mbugua, and Alice Pell. 2008. "Nutrient Constraints to Tropical Agroecosystem Productivity in Long-Term Degrading Soils." *Global Change Biology*. [Oxford, England] : https://doi.org/10.1111/j.1365-2486.2008.01698.x.

Nguyen, Hao Huu. 2017. "Evaluation of Coastal Sandy Land in Thanh Hoa Province for Agricultural Development With Case Study of Quang Xuong District." Geography Institute of Greifswald University. https://epub.ub.uni-greifswald.de/frontdoor/index/index/year/2017/docId/1980.

Nguyen, Thanh Tuan, Ann Verdoodt, Tran Van Y, Nele Delbecque, Thuy Chi Tran, and Eric Van Ranst. 2015. "Design of a GIS and Multi-Criteria Based Land Evaluation Procedure for Sustainable Land-Use Planning at the Regional Level." *Agriculture, Ecosystems and Environment* 200: 1–11. https://doi.org/10.1016/j.agee.2014.10.015.

Noor, Norshaheeda Mohd, Khairunnisa Mardzuki, and Mohd Noor Mamat. 2018. "Linkages between Sector in Malaysia Agriculture Industry: An Application of Inputoutput Analysis for Growth Promotion." *International Journal of Business and Management* 2 (1): 33–37. https://doi.org/10.26666/rmp.ijbm.2018.1.6.

Norwana, A A B Dayang, R Kanjappan, Melissa Chin, G C Schoneveld, Lesley Potter, and Reubeta Andriani. 2011. "The Local Impacts of Oil Palm Expansion in Malaysia; An Assessment Based on a Case Study in Sabah State." *Center for International Forestry Research (CIFOR) Working Paper* 78: 1–17.

Olaniyi, Akeem, Ahmad Makmom Abdullah, and M.F. Ramli. 2015. "Agricultural Land Use Suitability Assessment in Malaysia." *Bulgarian Journal of Agricultural Sciences* 21(3) (April): 576–88.

Orshoven, J., J.M. Terres, T. Tóth, R. Jones, C.L. Bas, F. Nachtergaele, D. Rossiter, R. Schulte, and H. Velthuizen. 2012. *Updated Common Bio-Physical Criteria to Define Natural Constraints for Agriculture in Europe : Definition and Scientific Justification for* *the Common Biophysical Criteria : Technical Factsheets.* https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/updated-common-bio-physical-criteria-define-natural-constraints-agriculture-europe-0.

Page, Susan, Agata Hościło, Henk Wösten, Jyrki Jauhiainen, Marcel Silvius, Jack Rieley, Henk Ritzema, et al. 2009. “Restoration Ecology of Lowland Tropical Peatlands in Southeast Asia: Current Knowledge and Future Research Directions.” *Ecosystems* 12 (6): 888–905. https://doi.org/10.1007/s10021-008-9216-2.

Paramananthan, S. 2000. “Soil Requirements of Oil Palm for High Yields.” In *Managing Oil Palm for High Yields: Agronomic Principles*, 18–38.

Passuello, Ana, Vikas Kumar, Oda Cadiach, and Marta Schuhmacher. 2014. “Bayesian Network Application to Land Suitability Classification in the Sewage Sludge Amendment of Agricultural Soils.” *Human and Ecological Risk Assessment: An International Journal* 20 (4): 1077–98. https://doi.org/10.1080/10807039.2013.793092.

Pehlivan, Nimet Yapici, Turan Paksoy, and Ahmet Çalik. 2017. “Comparison of Methods in FAHP with Application in Supplier Selection.” In *Fuzzy Analytic Hierarchy Process*, edited by Ali Emrouznejad and William Ho, 45–72. CRC Press.

Petingi, Galileo. 2019. “Two Mln Hectares to Be Developed for Food Crop Cultivation – Uggah.” *The Borneo Post*, 2019.

Pilevar, Ahmad Reza, Hamid Reza Matinfar, Akbar Sohrabi, and Feridon Sarmadian. 2020. “Integrated Fuzzy, AHP and GIS Techniques for Land Suitability Assessment in Semi-Arid Regions for Wheat and Maize Farming.” *Ecological Indicators* 110 (August 2019): 105887. https://doi.org/10.1016/j.ecolind.2019.105887.

Ponnamma, K N. 2001. “Biological Control of Pests of Oil Palm BT - Biocontrol Potential and Its Exploitation in Sustainable Agriculture: Volume 2: Insect Pests.” In , edited by R K Upadhyay, K G Mukerji, and B P Chamola, 235–60. Boston, MA: Springer US. https://doi.org/10.1007/978-1-4615-1377-3_15.

Posa, Mary Rose C, Lahiru S Wijedasa, and Richard T Corlett. 2011. “Biodiversity and Conservation of Tropical Peat Swamp Forests.” *BioScience.* Washington, D.C. : https://doi.org/10.1525/bio.2011.61.1.10.

Prakash, Teluve Nagarajara. 2003. “Land Suitability Analysis for Agricultural Crops: A Fuzzy Multicriteria Decision Making Approach.” International Institute for Geo-information Science and Earth Observation.

Prescott, Graham W, David P Edwards, and William A Foster. 2015. “Retaining Biodiversity in Intensive Farmland: Epiphyte Removal in Oil Palm Plantations Does Not Affect Yield.” *Ecol Evol* 5 (10): 1944–54. https://doi.org/10.1002/ece3.1462.

Purnomo, Herry, Beni Okarda, Ade Ayu Dewayani, Made Ali, Ramadhani Achdiawan, Hariadi Kartodihardjo, Pablo Pacheco, and Kartika S. Juniwaty. 2018. “Reducing Forest and Land Fires through Good Palm Oil Value Chain Governance.” *Forest Policy and Economics* 91 (January): 94–106. https://doi.org/10.1016/j.forpol.2017.12.014.

QGIS. 2002. “Fuzzify Raster (Linear Membership).” QGIS Documentation. 2002. https://docs.qgis.org/3.16/en/docs/user_manual/processing_algs/qgis/rasteranalysis.html#id61.

Qin, Yan, and Zhang Jixian. 2002. “Integrated Application of RS and GIS to Agriculture Land Use Planning.” *Geo-Spatial Information Science* 5 (2): 51–55. https://doi.org/10.1007/BF02833886.

Qiu, Fang, Bryan Chastain, Yuhong Zhou, Caiyun Zhang, and Harini Sridharan. 2014. “Modeling Land Suitability/Capability Using Fuzzy Evaluation.” *GeoJournal* 79 (2): 167–82. https://doi.org/10.1007/s10708-013-9503-0.

Radočaj, Dorijan, Mladen Jurišić, Mateo Gašparović, and Ivan Plaščak. 2020. “Optimal

Soybean (Glycine Max L.) Land Suitability Using Gis-Based Multicriteria Analysis and Sentinel-2 Multitemporal Images." *Remote Sensing* 12 (9). https://doi.org/10.3390/RS12091463.

Ramamurthy, V., G.P.O. Reddy, and N. Kumar. 2020. "Assessment of Land Suitability for Maize (Zea Mays L) in Semi-Arid Ecosystem of Southern India Using Integrated AHP and GIS Approach." *Computers and Electronics in Agriculture* 179 (May). https://doi.org/10.1016/j.compag.2020.105806.

Ramík, Jaroslav, and Petr Korviny. 2010. "Inconsistency of Pair-Wise Comparison Matrix with Fuzzy Elements Based on Geometric Mean." *Fuzzy Sets and Systems* 161 (11): 1604–13. https://doi.org/10.1016/j.fss.2009.10.011.

Ranst, E.V., H Tang, R Groenemam, and S Sinthurahat. 1996. "Application of Fuzzy Logic to Land Suitability for Rubber Production in Peninsular Thailand." *Geoderma* 70 (1): 1–19. https://doi.org/https://doi.org/10.1016/0016-7061(95)00061-5.

Reid, Walter V, Harold A Mooney, Angela Cropper, Doris Capistrano, Stephen R Carpenter, Kanchan Chopra, Partha Dasgupta, Thomas Dietz, Anantha Kumar Duraiappah, and Rashid Hassan. 2005. *Ecosystems and Human Well-Being-Synthesis: A Report of the Millennium Ecosystem Assessment*. Island Press.

Reshmidevi, T. V., T. I. Eldho, and R. Jana. 2009. "A GIS-Integrated Fuzzy Rule-Based Inference System for Land Suitability Evaluation in Agricultural Watersheds." *Agricultural Systems* 101 (1–2): 101–9. https://doi.org/10.1016/j.agsy.2009.04.001.

Rieley, J O. 2007. "Tropical Peatland-The Amazing Dual Ecosystem: Co-Existence and Mutual Benefit." In *Proceedings of the International Symposium and Workshop on Tropical Peatland*, 1–14. Citeseer.

Ritung, Sofyan, Wahyunto, Fahmuddin Agus, and Hapid Hidayat. 2007. "Land Suitability Evaluation with a Case Map of Aceh Barat District." *Indonesian Soil Research Institute and World Agroforestry Centre, Bogor, Indonesia*.

Romano, G, P Dal Sasso, G Trisorio Liuzzi, and F Gentile. 2015. "Multi-Criteria Decision Analysis for Land Suitability Mapping in a Rural Area of Southern Italy." *Land Use Policy* 48: 131–43. https://doi.org/https://doi.org/10.1016/j.landusepol.2015.05.013.

Romeijn, Harmen, Robert Faggian, Vasco Diogo, and Victor Sposito. 2016. "Suitability Analysis in a Changing Climate." *ISPRS International Journal of Geo-Information* 5 (6). https://doi.org/10.3390/ijgi5060099.

Saaty, Thomas L. 1990. *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*. 2nd ed. RWS.

Sarawak State Service Modernisation Unit. 2017. "Sarawak Digital Economy Strategy 2018-2022: An Overview Booklet," 1–35. http://www.sarawak.gov.my/ebook/DEbooklet/.

Schrier-Uijl, A.P., M. Silvius, F. Parish, K.H. Lim, S. Rosediana, and G. Anshari. 2013. "Environmental and Social Impacts of Oil Palm Cultivation on Tropical Peat: A Scientific Review." *Roundtable of Sustainable Palm Oil, Kuala Lumpur, Malaysia*, 131–68.

Sheil, Douglas, Anne Casson, Erik Meijaard, Meine Van Noordwijk, Joanne Gaskell, Jacqui Sunderland-Groves, Karah Wertz, and Markku Kanninen. 2009. *The Impacts and Opportunities of Oil Palm in Southeast Asia: What Do We Know and What Do We Need to Know?* Vol. 51. Center for International Forestry Research Bogor, Indonesia.

Shimizu, Hiroko, and Pierre Desrochers. 2012. "The Health, Environmental and Economic Benefits of Palm Oil." *IEM's Economic Note*, 1–4.

Sicat, Rodrigo S, Emmanuel John M Carranza, and Uday Bhaskar Nidumolu. 2005. "Fuzzy Modeling of Farmers' Knowledge for Land Suitability Classification." *Agricultural Systems* 83 (1): 49–75. https://doi.org/https://doi.org/10.1016/j.agsy.2004.03.002.

Sime Darby Plantation Berhad. 2020. "Raising The Bar On Sustainable Growth - Sustainability

Report 2019.” 2020. https://www.simedarbyplantation.com/sites/default/files/Sime Darby Plantation Berhad Sustainability Report 2019.pdf.

Sivapragasam, A. 2008. “Coconut in Malaysia: Current Developments and Potential for Re-Vitalization.” In *2nd International Plantation Industry Conference and Exhibition (IPICEX2008)*, 1–9.

Soil Science Division Staff. 2017. “Soil Survey Manual.”

Suhairi, T.A.S.T.M., E. Jahanshiri, and N.M.M. Nizar. 2018. “Multicriteria Land Suitability Assessment for Growing Underutilised Crop, Bambara Groundnut in Peninsular Malaysia.” *IOP Conference Series: Earth and Environmental Science* 169 (1). https://doi.org/10.1088/1755-1315/169/1/012044.

Sys, C., E.V. Ranst, and J. Debaveye. 1991. “Land Evaluation. Part II: Methods in Land Evaluation. Agricultural Publications No. 7, GADC, Brussels, Belgium.”

Sys, C., E.V. Ranst, J. Debayeye, and F. Beernaert. 1993. “Land Evaluation, Part III, Crop Requirements.” *Agricultural Publications. General Administration for Development Cooperation, Belgium*.

Tailliez, B. 1998. “Oil Palm: A New Crop.... for Which Future?” *OCL-Oléagineux, Corps Gras, Lipides* 5 (2): 106–9.

Tan, K. T., K. T. Lee, A. R. Mohamed, and S. Bhatia. 2009. “Palm Oil: Addressing Issues and towards Sustainable Development.” *Renewable and Sustainable Energy Reviews* 13 (2): 420–27. https://doi.org/10.1016/j.rser.2007.10.001.

Tan, Zhai Yun. 2019. “Agriculture: A Coconut Revival.” *The Edge Markets Malaysia*, 2019. https://www.theedgemarkets.com/article/agriculture-coconut-revival.

Tang, Kuok Ho Daniel, and Hamad M.S. Al Qahtani. 2020. “Sustainability of Oil Palm Plantations in Malaysia.” *Environment, Development and Sustainability* 22 (6): 4999–5023. https://doi.org/10.1007/s10668-019-00458-6.

Tawie, Sulok. 2019. “Sarawak Govt to Set up Board to Regulate, Enhance Sago Industry.” Malay Mail.

Tercan, Emre, and Mehmet Ali Dereli. 2020. “Development of a Land Suitability Model for Citrus Cultivation Using GIS and Multi-Criteria Assessment Techniques in Antalya Province of Turkey.” *Ecological Indicators* 117 (May): 106549. https://doi.org/10.1016/j.ecolind.2020.106549.

Tilman, David, Christian Balzer, Jason Hill, and Belinda L. Befort. 2011. “Global Food Demand and the Sustainable Intensification of Agriculture.” *Proceedings of the National Academy of Sciences of the United States of America* 108 (50): 20260–64. https://doi.org/10.1073/pnas.1116437108.

Tomlin, C Dana. 2012. *GIS and Cartographic Modeling*. Redlands, UNITED STATES: Esri Press. http://ebookcentral.proquest.com/lib/curtin/detail.action?docID=3238264.

Tzeng, Gwo-Hshiung, and Jih-Jeng Huang. 2011. *Multiple Attribute Decision Making: Methods and Applications*. 1st ed. London: London: Chapman and Hall/CRC. https://doi.org/10.1201/b11032.

USGS Earthexplorer. 2010. “Sarawak Topography Map.”

Ustaoglu, E., and A. C. Aydınoglu. 2020. “Suitability Evaluation of Urban Construction Land in Pendik District of Istanbul, Turkey.” *Land Use Policy* 99 (May). https://doi.org/10.1016/j.landusepol.2020.104783.

Verheye, Willy. 2002. “The FAO Guidelines for Land Evaluation.” *Encyclopedia of Life SUpport Systems (EOLSS-UNESCO)* II: 76–100.

Verheye, Willy. 2008. “Land Evaluation.” In *Land Use, Land Cover and Soil Sciences*, edited by Willy H. Verheye, 2:307. Oxford, United Kingdom: UNESCO-EOLSS Publishers.

Wahid, Omar, Nordiana Abd Aziz, Mohammed Ahmad Tarmizi, Harun Mohd Haniff, and Ahmad Kushairi Din. 2010. “Mapping of Oil Palm Cultivation on Peatland in Malaysia.” *MPOB Information Series*, no. MPOB TT No. 473: 3–6.

Walker, Joe. 2002. “Environmental Indicators and Sustainable Agriculture.” *ACIAR Monograph Series* 84: 323–32.

Weil, Ray R, and Nyle C Brady. 2017. *The Nature and Properties of Soils / Ray R. Weil, Nyle C. Brady.* Edited by Daryl Fox. Fifteenth. Harlow, England : Pearson.

Wetlands International. 2010. “A Quick Scan of Peatlands in Malaysia.” *Wetlands International-Malaysia: Petaling Jaya, Malaysia*. Vol. 1.

Wetlands International. 2020. “Scaling Up the Power of Wetlands: Wetlands International Strategic Intent, 2020-2030.” Wetlands International.

Wit, Paul De, and Willy Verheye. 2009. “Land Use Planning for Sustainable Development.” *Land Use, Land Cover and Soil Sciences–Land Use Planning*, 33–60.

Wong, Jack. 2018. “Sarawak Aims to Replant Additional 443,500ha of Oil Palm.” *The Star*, July 30, 2018. https://www.thestar.com.my/business/business-news/2018/07/30/sarawak-aims-to-replant-additional-443500ha-of-oil-palm/.

Wösten, J H M, A B Ismail, and A L M van Wijk. 1997. “Peat Subsidence and Its Practical Implications: A Case Study in Malaysia.” *Geoderma.* [Amsterdam. https://doi.org/10.1016/S0016-7061(97)00013-X.

Yalew, Seleshi G., Ann van Griensven, Marlous L. Mul, and Pieter van der Zaag. 2016. “Land Suitability Analysis for Agriculture in the Abbay Basin Using Remote Sensing, GIS and AHP Techniques.” *Modeling Earth Systems and Environment* 2 (2): 1–14. https://doi.org/10.1007/s40808-016-0167-x.

Yu, Jia, Yun Chen, Jianping Wu, and Shahbaz Khan. 2011. “Cellular Automata-Based Spatial Multi-Criteria Land Suitability Simulation for Irrigated Agriculture.” *International Journal of Geographical Information Science* 25 (1): 131–48. https://doi.org/10.1080/13658811003785571.

Yule, Catherine M. 2010. “Loss of Biodiversity and Ecosystem Functioning in Indo-Malayan Peat Swamp Forests.” *Biodiversity and Conservation* 19 (2): 393–409. https://doi.org/10.1007/s10531-008-9510-5.

Yusoff, Sumiani, and Sune Balle Hansen. 2007. “Feasibility Study of Performing an Life Cycle Assessment on Crude Palm Oil Production in Malaysia.” *International Journal of Life Cycle Assessment* 12 (1): 50–58. https://doi.org/10.1065/lca2005.08.226.

Yusop, Z, C H Chan, and A Katimon. 2007. “Runoff Characteristics and Application of HEC-HMS for Modelling Stormflow Hydrograph in an Oil Palm Catchment.” *Water Science and Technology*. Oxford. https://doi.org/10.2166/wst.2007.690.

Zabihi, Hasan, Anuar Ahmad, Iris Vogeler, Mohamad Nor Said, Morteza Golmohammadi, Behrouz Golein, and Mehrbakhsh Nilashi. 2015. “Land Suitability Procedure for Sustainable Citrus Planning Using the Application of the Analytical Network Process Approach and GIS.” *Computers and Electronics in Agriculture* 117: 114–26. https://doi.org/https://doi.org/10.1016/j.compag.2015.07.014.

Zadeh, L. A. 1965. “Fuzzy Sets.” *Information and Control* 8: 338–53.

Zen, Zahari, Colin Barlow, and Ria Gondowarsito. 2006. “Oil Palm in Indonesian Socio-Economic Improvement: A Review of Options.”

Zhou, Jiang, and Daniel L. Civco. 1996. “Using Genetic Learning Neural Networks for Spatial Decision Making in GIS.” *Photogrammetric Engineering and Remote Sensing* 62 (11): 1287–95.