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Assessing the Suitability of Oil Palm (*Elaeis guineensis*) Production in Peninsular Malaysia based on Soil, Climate and Land Use

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ABSTRACT

In recent years, palm oil production has grown rapidly as a result of rising demand. Oil palm plantations have been established on thousands of acres to meet this demand. The objective of this study is to assess the suitability of oil palm production as driven by soil, climate, and land use. The land suitability assessment (LSA) method was adopted in this study. We use geospatial techniques of overlay mapping as a suitable land suitability assessment method, in which the evaluation criteria are recorded as superimposed layers. A land suitability map is produced by integrating these layers into a single layer. The method is also applied to delineate available areas for growing oil palm in Peninsular Malaysia. The findings revealed that suitable soil areas for oil palm production are extensively found in the selected regions of Peninsular Malaysia, in states like Selangor and some parts of Kedah, Kelantan, and Terengganu with clay loam and sandy loam soil properties, while in the southern region like Melaka, moderate suitability for oil palm production was found due to the domination of clay soil in the area. Highly suitable areas were estimated (mean annual water deficit <150 mm) to be 3688254.00 ha (29.54%) of the total land area; suitable areas (mean annual water deficit <250 mm) were 6540669.00 ha (52.38%); moderately suitable areas were (mean annual water deficit <400 mm) 2227500.00 ha (17.84%), and unsuitable areas (mean annual water deficit >400mm) for oil palm production as a result of poor water availability was 31104.00ha (0.25%). The Land Use Land Cover Map of Peninsular Malaysia revealed the suitable areas to cover an average of 10885001.46 ha (82.45%), water bodies 1239505.58 ha (9.39%), built-up areas (unsuitable areas) 1051544.34 ha (7.96%), and bare surface areas are also not suitable areas for oil palm production at 26509.73 ha (0.20%). This study recommends that oil palm plantations be expanded into areas with highly suitable soils and climates.

INTRODUCTION

West and southwest Africa is home to the oil palm (Elaeis guineensis), mainly in the region between Angola and the Gambia 10°N and 10°S and extending to a 200-300 km coastal belt from approximately 15°N to 15°S (Paterson et al. 2013). In the case of this species, guineensis refers to the name of the area where it was found, not the country now known as Guinea (Verheye 2010, Paterson et al. 2013, Nambiappan et al. 2018, Abubakar et al. 2021, Abubakar et al. 2022a, 2022b). The Bogor Botanical Garden in Indonesia is believed to have been the first to plant oil palm in Southeast Asia in 1848 (Nambiappan et al. 2018). In Malaysia, the first commercial plantation was established in 1917 at Tennamaran Estate in Kuala Selangor (Basiron 2007, Dunn et al. 2011, Nambiappan et al. 2018). The main product of the crop is vegetable oil, and it is grown mainly for industrial purposes (Verheye 2010). Oil palm requires a suitable climate for optimum production (Abubakar et al. 2021). Temperatures between 27 and 28°C are optimal daily, with maximums of 30-32°C on a monthly basis and minimums of 21-24°C (Verheye 2010, Zainal et al. 2012, Paterson et al. 2013, Abubakar et al. 2021). In the coldest month, the minimum temperature should be > 18°C (Abubakar et al. 2022a, 2022b). Seedling growth ceases at temperatures < 15°C, and when temperature drop below 18°C growth is stopped (Verheye 2010, Zainal et al. 2012, Paterson et al. 2013). There should be at least 85% relative humidity in the air (Verheye 2010, Oettli et al. 2018). In addition, solar radiation should be at least 16 or 17 MJ m^{-1} d^{-1} (Oettli et al. 2018). A typical requirement for oil palms is 150mm of rain per month, with an annual rainfall of 2000-2500mm, and a dry period of no more than 2-3 months (Verheye 2010, Paterson et al. 2015). Oil palm can be grown on a wide variety of soils (Verheye 2010, Paterson et al. 2013, Rhebergen et al. 2016, Pirker et al. 2016; Abubakar et al. 2021). A well-drained, deep soil is essential for palm trees (Paterson et al. 2013, Abubakar et al. 2022a, 2022b). Low-elevation tropical lowlands are the primary growing areas for the crop where the original vegetation cover of these areas was dense rainforests (Verheye 2010). Physical soil properties are more important in oil palm plantations than soil fertility (Verheye 2010). Soil physical properties, such as soil moisture, are more important than nutrient supply, which can be corrected by fertilizer application (Verheye 2010). The best place for planting the crop is on the flat or gently undulating ground (Verheye 2010, Paterson et al. 2013, Abubakar et al. 2022a, 2022b). Oil palm is a very lucrative crop and a high-yielding oil plant (Corley & Tinker 2008, Castiblanco et al. 2013). It is economically the most efficient of all oil crops because of its ease of establishment, low costs, and high output (Dislich et al. 2017). Palm oil and other products derived from oil palm are found in a variety of products such as lipstick, pizza dough, instant noodles, shampoo, ice cream, detergent, margarine, chocolate, cookies, biodiesel, soap, packaged bread. The product is also found in frying fats, biscuits, snack foods, bakery products, cosmetics, candles, pharmaceuticals, and supermarket goods, etc. (Nagaraj 2009, Teoh 2010, Sutton & Kpentey 2012, Castiblanco et al. 2013, Paterson & Lima 2018). Oil palm is highly produced by the following countries: Indonesia, Malaysia, Nigeria, the Democratic Republic of Congo, the Ivory Coast, Brazil, Colombia, Costa Rica, and Ecuador (Corley & Tinker 2003, Paterson et al. 2013, Abubakar et al. 2022a, 2022b, Abubakar et al. 2022a, 2022b). Indonesia and Malaysia, palm oil accounts for over 85% of global demand (Varkkey et al. 2018, Rahman 2020, Ayompe et al. 2021). Among the major palm oil export destinations are India, China, the European Union (EU), the United States (USA), Pakistan, Bangladesh, Nigeria, and the Philippines etc. (Kushairi et al. 2018, 2019, Maluin et al. 2020, Abubakar et al. 2022a, 2022b).

Over the past few decades, oil palm production has witnessed a sharp rise, particularly in terms of the area that has been produced and the amount of oil produced (McCarthy & Cramb 2009, Sayer et al. 2012). National export revenues have increased significantly due to the expansion of the oil palm industry, particularly during the Asian financial crisis of the late 1990s, and today it dominates the landscape in Malaysia (Khiabani & Takeuchi 2020). Oil palm production has increased in recent years due to a rise in global demand for fats and oils (Abazue et al. 2015). In Malaysia, rapid oil palm plantation expansion began in 1980 when the expansion reached 1.0 million ha and subsequently reached 2.9 million ha in 1991, 3.1 million ha in 1998, 3.8 million ha in 2004, 4.9 million ha in 2010, and 5.9 million ha in 2019 (Malaysian Palm Oil Board 2020). Recent years have seen stiff competition for plantation land in Peninsular Malaysia, where acres of land have been taken over by oil palm plantations (Koh & Wilcove 2008, McCarthy & Cramb 2009, Koh et al. 2011, Shevade & Loboda 2019, Charters et al. 2019).

The distribution of oil palm is restricted by climate on a large scale; nevertheless, local factors such as terrain and soil texture may also have an impact (Paterson et al. 2015, Rhebergen et al. 2016, Abubakar et al. 2022a, 2022b, Paterson 2021a, 2021b). Monitoring land use changes and observing the transition from forests to plantations and evaluating the effects of these changes in Malaysia could benefit from the use of remote sensing (Vadivelu et al. 2014). The first step in oil palm plantation is a land-suitability evaluation (He et al. 2011, Vasu et al. 2018). Several methods and theories have been employed since the early twentieth century to evaluate soils. A number of these include; Land capability classifications (LCC) (Klingebiel & Montgomery 1966), the Storie index (SI) (Storie 1978), the FAO land suitability assessment (FAO 1976), the parametric method (Sys et al. 1991), Land Suitability Evaluation, and GIS-based multi-criteria analysis, to name a few examples (Elsheikh et al. 2013, Nguyen et al. 2015). Biophysical suitability evaluation methods are used to examine the physical state of the environment for a certain crop (Pirker 2015, 2016, Rhebergen et al. 2016, Vasu et al. 2018, Khiabani & Takeuchi 2020, Jaroenkietkajorn & Gheewala 2021, Abubakar et al. 2022a, 2022b).

Because of the rapid growth of oil palm trees' vegetation cover and their spectral similarity to other land covers such as natural forests and rubber plantations, mapping the distribution of oil palms using optical satellite remote sensing, particularly the image-based approach, is a difficult task (Gutiérrez-Vélez & DeFries 2013, Li et al. 2015, Torbick et al. 2016). In this study, geographic information systems (GIS) are used to evaluate land suitability for oil palm production and assess the land available for oil palm cultivation in Peninsular Malaysia using soil, climate, and land use data. Using data from the literature, we explain the agro-ecological conditions and develop environmental criteria that determine whether or not a region is an ideal place to grow oil palms. Identifying suitable land for oil palm cultivation as well as determining its yield is imperative for policymakers and entrepreneurs. In addition, this study will assist investors and the government in exploring suitable areas left for oil palm expansion in Peninsular Malaysia.

MATERIALS AND METHODS

The Study Area

Located between longitude 99° and 105° east, the study area stretches between latitudes 1° and 7° north (Fig. 1). Malaysia is bordered on the North by Thailand; on the East by the South China Sea; on the South by the Strait of Johore; and on the West by the Strait of Malacca and the Andaman Sea, with a total boundary length of 2,068 km (Zulkifli et al. 2020). The Highlands, floodplains, and coastal zones dominated the region with a total land area of 132,000 km^2 (Abubakar et al. 2022a, 2022b). Peninsular Malaysia experiences a tropical climate all year round that is warm and humid (Sarkar et al. 2020). There is a temperature range of 25° to 32°C in the region (Abubakar et al. 2022a, 2022b). There are two monsoon seasons in the region: the southwest monsoon from May to September and the northeast monsoon from November to March, which is associated with high rainfall (Wong et al. 2009). Annual rainfall varies between 2000 and 4000 mm in the region (Muhammad et al. 2020, Abubakar et al. 2022a, 2022b).

Land Suitability Assessment

In Malaysia, as in many other countries around the world, land suitability maps are used to plan land use and identify areas that can grow crops at the lowest possible cost to the economy and the environment through land suitability assessments (LSAs) (Bandyopadhyay et al. 2009, Olaniyi et al. 2015, Mugiyo et al. 2021). Assessing the suitability of a piece of land for agriculture or determining whether it is suitable for its intended use is called land suitability assessment (Olaniyi et al. 2015). In general, land suitability assessments are conducted on locations based on their biophysical and ecological characteristics to assess their potential for agriculture (Olaniyi et al. 2015, Doula et al. 2017). To determine land and crop production suitability indexes, land features and site-specific comparisons with crop requirements are considered (Rhebergen et al. 2016).

In this study, geospatial overlay mapping is used to assess land suitability, where the criteria for evaluating the suitability of a site are recorded as layers overlaid one over the other (Malczewski 2004). A land suitability map is then produced from these layers by integrating them into a single data layer. The method we used allowed us to define

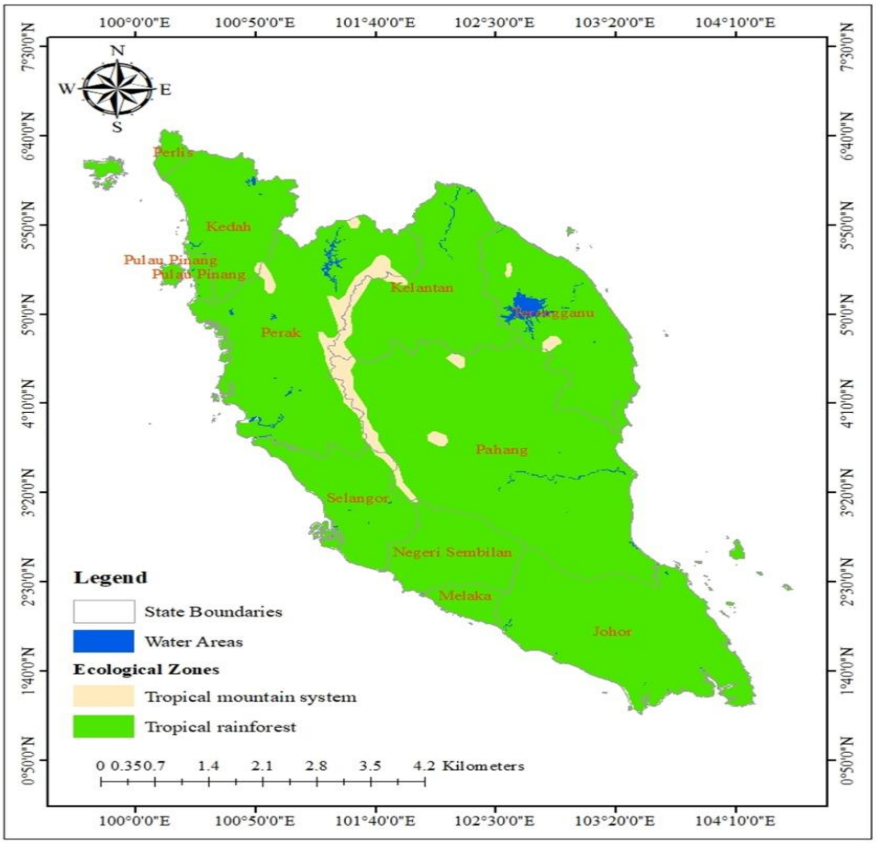

Fig. 1: Study area map.
Source: A Malaysian administrative map is adopted and modified, in 2022.

Table 1: Biophysical parameters indicating suitability for oil palm production.

Criterion	Suitability Class 4 (Highly suitable)	Suitability Class 3 (Suitable)	Suitability Class 2 (Moderate)	Suitability Class 1 (Unsuitable)
Mean annual rainfall (mm)	1700-2875	1450-1700	1000-1450	<1000
Annual mean temperature (°C)	>22	22-20	20-18	<18
Slope (°)	0-8	8-16	16-50	>50
Elevation (m)	0-1500	>1500	>1500	>1500
Mean annual water deficit	<150	<250	<400	>400
Soil texture	Clay loam	Sandy loam	Clay	Sandy
Solar radiation MJ M^{-2} day^{-1}	>16	16 - 21	< 21	> 21

both the suitable and the available locations in Peninsular Malaysia for oil palm cultivation. Based on mean annual water deficits, we identified climatically suitable oil palm production areas (Rhebergen et al. 2016). Oil palm yields are significantly affected by water scarcity (Corley & Tinker 2003, Rhebergen et al. 2016).

Rhebergen et al. (2016) argued that determining and grouping areas with similar climatic conditions for the production of oil palm can be accomplished by using mean annual water deficits. The authors further stated that generally, oil palm production is not feasible in areas with water deficits greater than 400 mm per year. In oil palm plants, it is assumed that the critical water deficit is 200 mm a year, after which growth and yield begin to suffer (Corley & Tinker, 2003). This assumption led us to define four categories of water deficit based on Olivin's suitability assessment methods (1968). An oil palm production feasibility study in Ghana by Rhebergen et al. (2016) utilized a similar approach. A water deficit approach, developed by Olivin (1968), and van der Vossen (1969) was used in this study to determine soil, climate, and land use suitability for oil palm production in Peninsular Malaysia.

i. Highly suitable zones with a mean annual water deficit of <150 mm;
ii. Moderate: zones with mean an annual water deficit of <250 mm;
iii. Suitable: zones with mean an annual water deficit of <400 mm; and
iv. Unsuitable: zones with mean an annual water deficit of >400 mm

Nonetheless, we categorized biophysical constraints into suitable and unsuitable areas based on climatic conditions (Table 1). After water deficit, rainfall, solar radiation, temperature, slope, and elevation are the most significant factors that influence oil palm yields (Paramananthan 2003). Rhebergen et al. (2016) argued that the amount of solar radiation suitable for oil palm production cannot be determined precisely because it is difficult to isolate its effect from other factors affecting production. When there is at least >16 MJ^{-2} day^{-1} of solar radiation per day, oil palm grows best (Oettli et al. 2018). In addition to reducing stomatal aperture and leaf temperature, excessive solar radiation can slow the rate of carbon dioxide absorption (Paramananthan 2011). Photodamage can also occur to the palms when they are exposed to high levels of solar radiation (Kasahara et al. 2002). Costly management interventions can only modify elevation out of these constraints.

In addition, this study examines protected areas and land uses, including national parks, forest reserves, world heritage sites, wetlands, and wildlife. A protected area is defined as geographical space, recognized, dedicated, and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values (Najihah et al. 2018). Population counts (people), settlement points, and light levels at night distinguish urban settlements from rural ones. Table 2 presents the data type and sources for this study.

Data Collection (Table 2)

Data Processing

Sentinel 2A Image Preprocessing

During the Level-2A processing, top-of-atmosphere (TOA) Level-1C, orthoimages are classified and atmospheric corrections are applied. Level-2A's main output is an orthoimage Bottom-Of-Atmosphere (BOA) corrected reflectance product. Level-2A output image products were resampled and generated with an equal spatial resolution for all bands (10 m, 20 m, or 60 m). There are three separate folders in the standard distributed product containing all resolution envelopes:

- 10m: containing spectral bands 2, 3, 4, 8, a True Color Image (TCI), and an Aerosol Optical Thickness (AOT) and Water Vapour (WV) maps resampled from 20 m.

Table 2: Data type and sources.

Data	Variable	Unit/Format	Resolution	Period/year	Source
Land Cover	Ecological Zones	- /Shapefile	-	-	https://data.review.fao.org/map/catalog/srv/eng/catalog.search#/metadata/74bab234-3a1e-442d-93cf-0b34859e9a60 Accessed 07/06/2022
Urban extent	Urban places	- /Shapefile	-		https://sedac.ciesin.columbia.edu/data/set/grump-v1-urban-extents/data-download
Rainfall	Average monthly rainfall	mm month^{-1}/Raster	30 arc-seconds (~ 1km)		https://www.worldclim.org/ Accessed 20/06/2022
Temperature	Minimum, maximum, and mean temperature (monthly) The temperature of the coldest month	^{o}C/Raster	30 arc-seconds (~ 1km)		https://www.worldclim.org/ Accessed 15/06/2022
Solar radiation	Average monthly solar radiation	kJm^{-2}day^{-1}	30 arc-seconds (~ 1km)		https://www.worldclim.org/ Accessed 15/06/2022
Digital Elevation Model (DEM) of Shuttle Radar Topography Mission (SRTM)	Elevation	Meters (above sea level)	3 arc-seconds (~ 100m)	2008	https://srtm.csi.cgiar.org/srtmdata/ Accessed on 20/06/2022
Soil Properties	Soil type	Unit/Shapefile	-	2012	https://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/ Accessed 18/06/2022
	Soil texture	%/Raster	30 arc-seconds (~ 1km)		
Sentinel 2A	Satellite Imagery	-/Raster	10m		https://scihub.copernicus.eu/dhus/#/homeAccessed 12/02/2022
Protected area	Protected areas	- /Shapefile	-	-	https://www.protectedplanet.net/country/MY Accessed 18/06/2022
Population	Inhabitants' population	-/Raster	30 arc-seconds (~ 1km)		https://sedac.ciesin.columbia.edu/data/collection/gpw-v4 Accessed 13/07/2022
MODIS Terra NDVI data (MOD 13)	NDVI	Raster	1km		Land Processes Distributed Active Archive Center (LP DAAC), NASA. Accessed 18/02/2021

- 20m: containing spectral bands 2-7, the bands 8A, 11, and 12, a True Color Image (TCI), a Scene Classification map (SCL), and an AOT and WV map. The band B8 is omitted as B8A provides more precise spectral information.
- 60m: containing all components of the 20 m product resampled to 60 m and additionally the bands 1 and 9. The cirrus band 10 is omitted, as it does not contain surface information.

A tool known as Sen2Core in SNAP software was used in the preprocessing (Pałas & Zawadzki 2020). Combined with a scene classification module, Sen2Cor uses state-of-the-art atmospheric correction techniques tailored to the Sentinel-2 environment (Muller-Wilm et al. 2013, Skakun et al. 2022). However, the scene classification algorithm allows the detection of clouds, snow, and cloud shadows and the generation of a classification map, which consists of three different classes for clouds (including cirrus), together with six different classifications for shadows, cloud shadows, vegetation, not vegetated, water and snow (Hughes & Hayes 2014, Zekoll et al. 2021).

The preprocessed images were imported to ArcGIS for layer stacking. Band 4, band 3, and band 2 were used respectively to obtain the natural color combination 432.

The image was then mosaic using the mosaic operator to the new raster tool.16-bit unsigned was used for the pixel type, the mosaic operator was set to maximum and a mosaic color map was set to match. The image was then clipped using the respective shape file of the states.

Image Classification

The unclassified images were subjected to clustering of similar spectral signatures for different LULC classes in ArcGIS. Four temporary classes were generated (water bodies, built-up areas, bare surfaces, and vegetation). Field sampling was done with the help of high-resolution (Google Earth Imagery) using the printed (unsupervised) map. The information generated using high-resolution images includes areas that have mixed clusters like water bodies and vegetation, built-up areas, cropland, etc. During the data collection, different feature identifiers (IDs) were generated for all the land uses, and the data was collected from on-screen digitization and photographs of the identified land uses.

As part of supervised classification, it is essential to identify the types of information that are relevant to the image (e.g., land cover types). Based on the reflectances for each information class, the software system develops a statistical characterization (see Table 3). The signature analysis stage involves deriving a characterization of the reflectance on each band, such as the mean or the range, or it may involve analyzing the variances and covariances of all bands systematically. As soon as a statistical characterization is obtained for each information class, a classification decision is made based on which signature the image most closely resembles based on the reflectance of each pixel. Table 3 presents the description of land cover categories used

A supervised maximum likelihood classification (MLC) method in ArcGIS was used, creating training samples from the acquired data generated from the Google Earth imagery to create the classes required for the LULC map.

Table 3: Detailed descriptions for each land cover category.

LULC Type	Description
Water Body	Lakes, ponds, rivers, wetlands, and reservoirs
Built-Up Area	Transportation, business, and residential services
Vegetation	All types of plants, including parks, playgrounds, trees, grasslands, forests, and shrublands
Bare Surface	Landfills, open spaces, and bare soils

Accuracy Assessment

The process of classification requires the assessment of accuracy. In the investigation area, the objective is to determine if pixels were grouped into the appropriate feature classes. However, one basic accuracy measure is the overall accuracy, which is calculated by dividing the correctly classified pixels (sum of the values in the main diagonal) by the total number of pixels checked.

Overall accuracy (%) = (correctly classified pixels/total number of pixels) …(1)

1. In addition to the overall accuracy, each class can also be classified with an equal degree of accuracy. Further, we need to determine how the accuracy is distributed across the categories because the overall accuracy doesn't indicate how it is distributed. The overall accuracy method, however, considers these categories as having equivalent or similar accuracy even though the categories could have dramatically different accuracy values. To determine the accuracy of individual categories, there are two methods available (Bharatkar & Patel 2013).
2. Therefore, Users' accuracy is calculated by dividing the number of correctly classified pixels by the total number of pixels classified in a LULC class – The percentage of correctly classified classes is of concern to users (Bharatkar & Patel 2013).

$$\text{User's accuracy (\%)} = \frac{\text{Correctly classified pixels}}{\text{Classified total pixels}} \quad \ldots(2)$$

For a particular LULC class, The producer's accuracy is the ratio between correctly classified pixels and reference pixels (Bharatkar & Patel 2013, Rwanga & Ndambuki 2017).

$$\text{Producer's accuracy (\%)} = \frac{\text{Correctly classified pixels}}{\text{Reference total pixels}} \quad \ldots(3)$$

Therefore, the Producer's accuracy (%) = (Correctly classified pixels/Reference total pixels) (Bharatkar & Patel 2013).

A summary of each classification's accuracy is shown below;

- Commission error = 1 - user's accuracy
- Omission error = 1 - producer's accuracy
- The kappa coefficient (K) can be computed as follows,

$$K = \frac{P_0 - P_c}{1 - P_c} \quad \ldots(4)$$

Where P_0 = Proportion of units that agree = overall accuracy

P_c = Proportion of units for expected chance agreement

Therefore, The general range for Kappa values is if K

< 0.4, a poor kappa value; while, if 0.4 < K< 0.75, is a good kappa value and if K > 0.75, it is an excellent kappa value (Bharatkar & Patel 2013).

The accuracy assessment was carried out using ArcGIS pro 2.4 in which a stratified sampling method was used.

Data Analysis

The data used in this study was preprocessed and corrected in the ArcGIS environment. Raster grid data is a subset to the extent of Peninsular Malaysia's boundaries using the administrative map of the country. Inverse distance weighted (IDW) interpolation was used to generate maps of rainfall and temperature. To accomplish this, ArcGIS Spatial Analyst was used. The climatic data were organized in Microsoft Excel, saved as a comma-separated value (CSV), and imported as points into ArcGIS, where they were interpolated to generate climatic element maps. A map of the study area was used to delineate the Digital Elevation Model (DEM) of the area from Shuttle Radar Topographic Mapper (SRTM) data in the ArcGIS environment. To georeference the maps, WGS 1984 coordinates were used. After that, the DEM was used to generate the slope map for the area.

One of the most efficient and inexpensive methods for estimating evapotranspiration (ET) is remote sensing, which offers regional and global coverage efficiently and economically (Anderson et al. 2012, Weiss et al. 2020), especially when combined with meteorological data (Salmon et al. 2015). The direct measurement of actual evapotranspiration (AET) is very rare globally (Bates et al. 2008). Based on meteorological data describing climate variations and land use data describing vegetation changes, an alternative solution would be to predict ET variations by using mathematical models (Yang et al. 2008). Whatever the method applied, the spatial scale of the computed value depends on the method used to estimate the ET (Liou & Kar 2014). Climate station-based techniques are rare and produce point estimates, but with the use of the coordinate point of each station, it can be applied in the geographical information system (GIS) to assess the spatial and temporal variation of ET (Hengl et al. 2012). Satellite remote sensing methods are capable of estimating the biophysical properties of land from one pixel up to the regional scale with a certain degree of accuracy (Liou & Kar 2014).

Crop Coefficient ET Estimation Methods

As defined by Jensen et al. (1990), crop coefficients are derived from experimental correlations between actual ETs measured from a specific crop and ETs from a reference crop. To calculate reference ET, one must calculate weather data for a defined reference crop, such as alfalfa or grass, and then use the crop coefficient (Kc) to calculate the ET for a specific crop (Allen et al. 2005, Anapalli et al. 2020).

An important method for managing irrigation water is to estimate AET using the crop coefficient (Kc) (Kamble et al. 2013). ETc estimates derived from the Kc method can differ significantly from actual crop ETc estimates (Allen et al. 2005)

According to Allen et al. (2005) and El-Shirbeny et al. (2014), the crop coefficient (Kc) is a dimensionless number (usually between 0.1 and 1.2) used to calculate the actual evapotranspiration (AET). Using satellite data, Kamble et al. (2013) estimate Kc by evaluating NDVI and the relationship between NDVI and Kc.

$$K_C = \frac{1.2}{NDVI_{dv}}(NDVI - NDVI_{mn}) \qquad \ldots(5)$$

Therefore, where; 1.2 is the maximum Kc, $NDVI_{dv}$ is a difference between the minimum and maximum NDVI value for vegetation and $NDVI_{mn}$ is the minimum NDVI value for vegetation (El-Shirbeny et al. 2014).

To calculate monthly potential evapotranspiration, we converted solar radiation into water equivalents for each month based on latitude and year (Hargreaves & Samani 1982). To better reflect potential evapotranspiration (ETP), we included more climatic variables. Using the Hargreaves equation, we estimated ETP (Rhebergen et al. 2016):

$$ETP = 0.0023 \times Ra \times (T - t)^{0.5}0(t_m + 17.8) \qquad \ldots(6)$$

Where:

ETP = Evapotranspiration in mm/day

Ra = Expressed as water equivalent, extraterrestrial solar radiation (mm/day)

T-t = Monthly maximum and minimum temperature difference (°C)

tm = Means air temperature (°C)

Water requirements for crop modeling have been estimated using this method (Kra & Ofosu-Anim 2010). As opposed to Penman-Monteith, this method requires less data (Allen et al. 1998), and similar results are produced by both methods (Hargreaves & Allen 2003). A monthly difference was calculated between the mean maximum and minimum temperatures in the study area using WorldClim climatic variables to generate the ETP layer (Läderach et al. 2013).

A mean annual water balance was calculated from ETP (Surre 1968). All monthly negative water balances were added up to calculate the annual water deficit. A total of 28 meteorological stations provided data on rainfall. There are some stations on commercial palm plantations, while others are on smallholder plantations. Within the oil palm belt, production sites have various rainfall (mm $month^{-1}$) distributions. Based on our suitability assessment and Surre's method (1968), we calculated the average annual water deficits for each site. We identified potential oil palm production areas on potentially available land by combining land use data. The maps we used for land suitability excluded protected areas and urban settlements.

The normality test is conducted to determine if climatic data is normally distributed. Empirical probability distributions can be used to analyze normally distributed data. The commonly used test of normality is the Anderson-Darling (A-D) statistic, defined as:

$$A_n^2 = \int_{-\infty}^{\infty} |F_n(x) - F(x)|^2 \Psi(x) f(x) d(x) \quad \ldots(7)$$

Where:

$$\Psi(x) = {}^{n}/_{F(x)\{1-F(x)\}}$$

n = Data points totaled for the study;

F(x) = distribution function of the fitted distribution;

f(x) =density function of the fitted distribution;

$$F_n = \frac{i}{n}$$

i = The cumulative rank of the data point.

A-D statistics are generally considered to be more useful than K-S statistics because they can account for tail distributions as well as main distributions. This normality test is based on the following hypotheses (Anderson- Darling normality test):

$H_{0:}$ Data is from the population with a normal distribution;

H_1: Data is not from a population with a normal distribution;

Data distributed normally can be assessed by the Anderson-Darling p-value. Therefore, if the distribution fits the data, the A-D statistic will be small and the associated p-value will be greater than the chosen alpha-level (0.05 and 0.10). AddinSoft Xlstat software was used to analyze the data using the Anderson-Darling Normality test.

SPSS 22 version and Microsoft Excel software were used to compute Mann-Kendall and Sen's slope trend analysis.

We calculated Actual Evapotranspiration, or AET, by combining Kc (from satellite images) with ET (from meteorological station observations). To conduct the analysis, ArcGIS was used.

$$AET = K_C \times ET \quad \ldots(8)$$

Where;

AET = Actual evapotranspiration [mm d^{-1}],

Kc = Crop coefficient [dimensionless],

ET = Reference evapotranspiration [mm d^{-1}].

The difference between AET and PET was used as an agricultural water deficit

Water deficit was generated herein to reflect the agricultural water deficit (AW_D) using the following formula

$$AW_d = PET - AET \quad \ldots(9)$$

Where; AW_D: is the Evapotranspiration deficit defined as the difference between potential water demand (PET) and the actual water supplied (AET) for vegetation. Agriculture experiences more water stress when PET is larger. Agricultural water stress is commonly measured using PET as the measure of crop water stress (Yin et al. 2022).

RESULTS AND DISCUSSION

Land Use Areas Suitable for Palm Production

Fig. 2 presents the Land Use Land Cover Map of Peninsular Malaysia showing suitable areas for oil palm production to cover an average of 10885001.46ha (82.45%), water bodies (1239505.58ha (9.39%), built-up areas (unsuitable areas) 1051544.34ha (7.96%), and bare surface areas that are also areas not suitable for oil palm production (26509.73ha (0.20%). Consequently, many vegetation areas, some of which are sensitive to environmental issues, have been cleared as a result of oil palm spread. Land conversion for oil palm cultivation impacts land use in varying ways, focusing on current land conversion and future land demand projections. In the future, this will be beneficial to the industry. A range of land use options was explored to minimize the pressure on land to be opened up for development and minimize monoculture dependence (Basiran & Ja'afar 2022).

Oil palm plantations are continuously being expanded in

Table 4: Statistics of Land Use Land Cover areas suitable for oil palm production.

Land use Land cover	Area (ha)	Percentage (%)
Vegetation (Suitable)	10885001.46	82.45
Water bodies	1239505.58	9.39
Built-up area (Unsuitable)	1051544.34	7.96
Bare surface	26509.73	0.20
Total	13202561.11	100.00

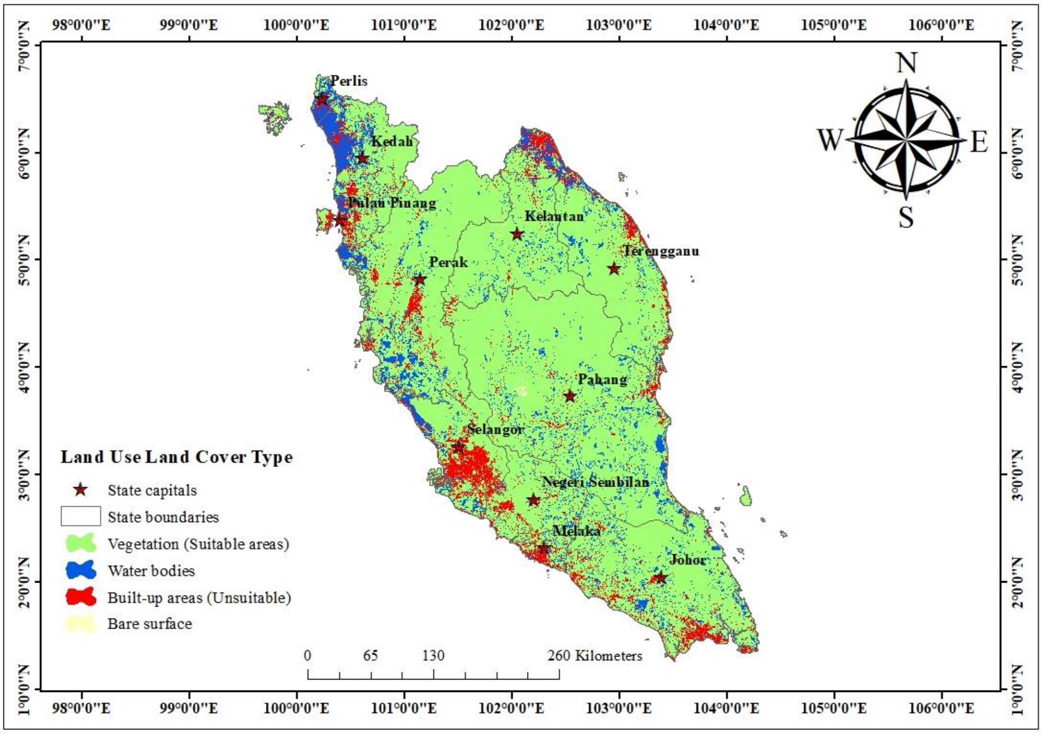

Fig. 2: Land Use Land Cover Map showing Suitable areas for Oil Palm production in Malaysia Peninsular.

Malaysia and Indonesia, and as a result, are accountable for over 85% of global palm oil demand (Tang & Al Qahtani 2020). The growth in the planted area in Peninsular Malaysia from 1975 to 2020 is shown in Fig. 3. Oil palm was planted on

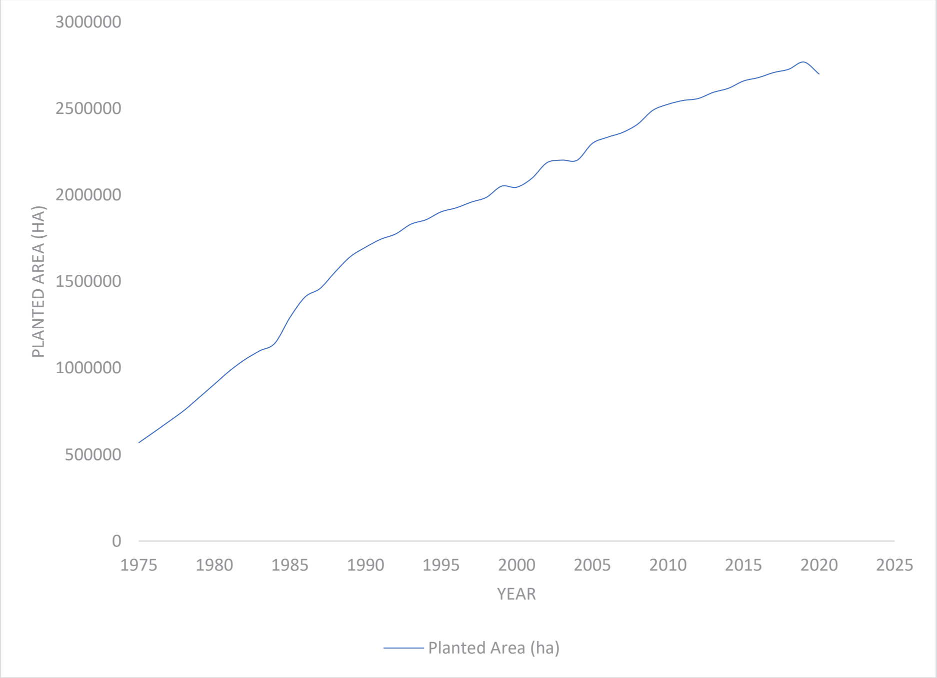

Fig. 3: Oil Palm area planted in Peninsular Malaysia (1975-2020).

2,769,003 hectares in Peninsular Malaysia in 2019 (see Fig. 3) and this was projected to be 4,560,479 hectares, 3,489,022 hectares, and 5,930,442 hectares for the years 2040, 2080, and 2100, respectively (Abubakar et al. 2022). It is unclear whether Malaysia will be able to achieve this target given its ongoing economic and political uncertainties.

The Tennarmaram Estate was the first to commercially plant oil palm in 1917 (Abubakar et al. 2022). A crop diversification program carried out by the government in the 1960s eventually led to the planting of oil palms on a large scale (Teoh 2000). Growth in planted areas of oil palm revealed that in 1975, 1976, and 1977, planted areas of oil palm covered about 568561 ha, 629558 ha, and 691706 ha, respectively. While the areas increased in 2018, 2019, and 2020 to 2,727,608 ha, 2,769,003 ha, and 2,700,004 ha, respectively (see Fig. 3) (Malaysian Palm Oil Board 2020). Oil palm plantations expanded rapidly in 2019 but slowed in 2020 as global economic growth slowed. In 2020, oil palms occupied 5.865 million hectares, down 0.6% from 5.900 million hectares in 2019 (Malaysian Palm Oil Council 2022). This might be on account of an increasing shortage of manpower and the economic impact of COVID-19. The Sabah and Sarawak parts of Malaysia offer greater land availability for the expansion of oil palm plantations. Sabah and Sarawak started developing their oil palm industries in the 1970s as Peninsular Malaysia expanded its oil palm planting in the late 1950s and early 1960s (Khiabani & Takeuchi 2020). In Fig. 3, we see how planted areas have increased over the last several decades.

In a rapidly growing economy such as this, protected areas are crucial to oil palm production (Kanniah et al. 2015). As one of the world's most biodiverse countries, Malaysia is home to some of the oldest rainforests in the world (see Fig. 4). With a GDP of USD 296.2 billion at present, the economic growth rate of Malaysia is 36th in the world (Tulayasathien & Tejapaibul 2017). With almost half of Malaysia's forest cover disappearing since the 1940s, Malaysia's rapid economic growth is negatively impacting the environment. The charismatic Malayan Tiger has also declined rapidly in this region (*Panthera tigris* Jacksoni) (Ten et al. 2021). The wild population has decreased by 10% since 1950 to only 300 individuals (Holzner et al. 2021).

There are 13.2% of protected areas in Peninsular Malaysia. The federal government or the state government

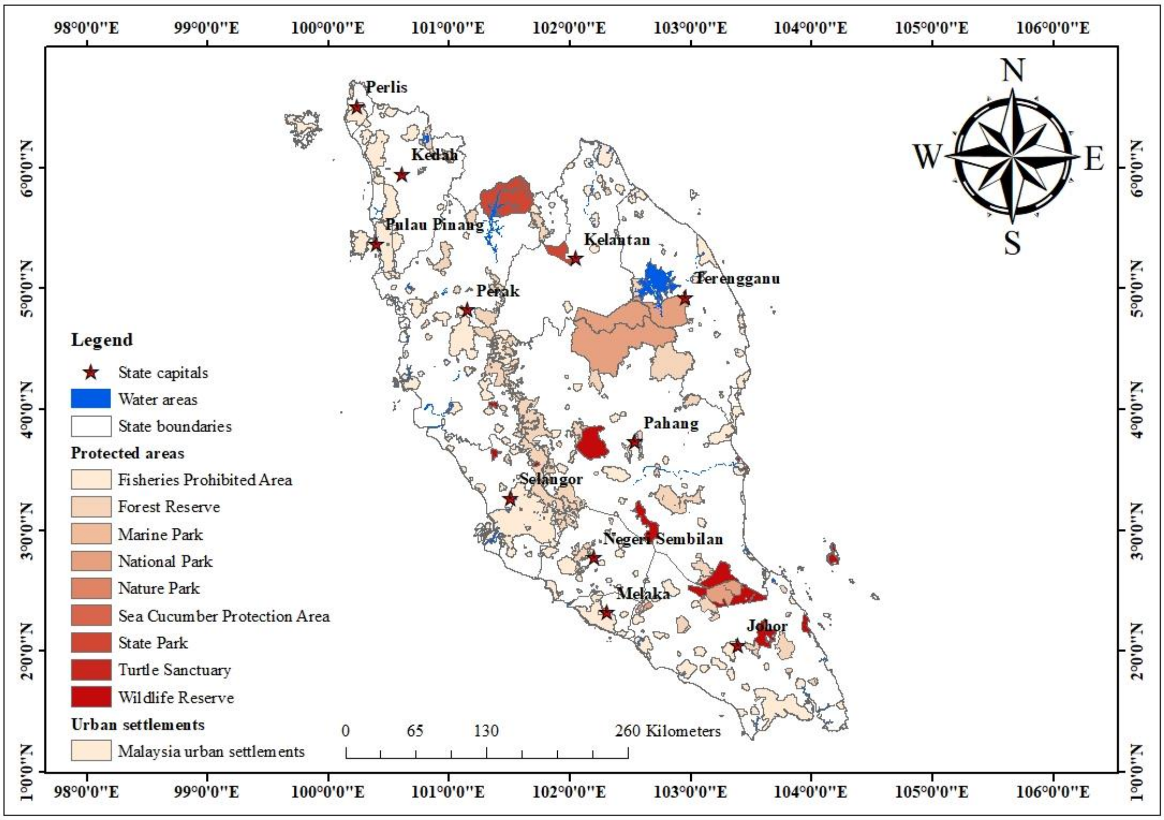

Fig. 4: Potential area for oil palm expansion excluding settlement and protected areas.

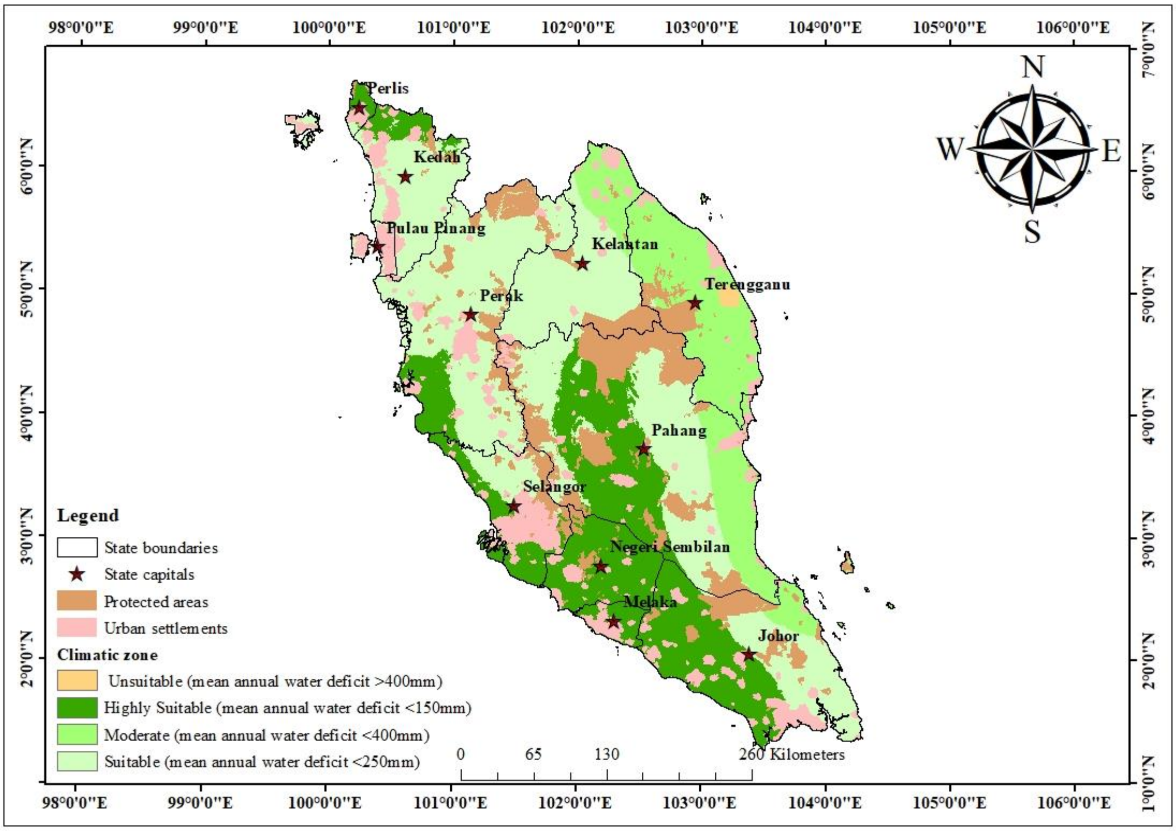

Fig. 5: Climatic zone (water deficit) suitable for oil palm production in Malaysia Peninsular.

manages protected areas (Najihah et al. 2018). At present, there is no system of national protected areas. Land and forest are deemed state matters by Malaysia's constitution, so establishing protected areas is a challenge (Schwabe et al. 2015). In addition to natural resources, states view them as revenue streams to fuel development (Hezri & Nordin Hasan 2006). Fisheries-prohibited areas, forest reserves, marine, and national parks, sea cucumber protection areas, turtle parks, turtle sanctuaries, and wild reserves are the major protected areas in Peninsular Malaysia and could be among the most suitable land left for oil palm production.

Many lowland forests (Fig. 4) have been cleared to expand oil palm production. Concerns have been raised about how future oil palm developments will affect environmental quality, especially for the remaining forest land (Basiron & Weng 2004, Ferdous Alam et al. 2015, Tang & Al Qahtani 2020).

Climatic Zones Suitable for Palm Production

Highly suitable areas were estimated (mean annual water deficit <150mm) for oil palm in Peninsular Malaysia to be 3688254.00 ha (29.54%) of the total land area (Fig. 5).

These areas were found mostly around the north-central and northwestern parts of the Peninsular. Suitable areas (mean annual water deficit <250mm) was 6540669.00 ha (52.38%), moderately suitable areas were (mean annual water deficit <400mm) 2227500.00 ha (17.84%) while unsuitable areas (mean annual water deficit >400mm) for oil palm production as a result of poor water availability was 31104.00 ha (0.25%) (Table 4). However, moderate and unsuitable areas for oil palm production in Peninsular Malaysia were decreased compared to Murphy et al. (2021) and Paterson (2020) projections as a result of increasing cultivation, which poses a negative environmental impact, threatening sustainability. The results of this study demonstrate that Malaysia's oil palm production may be threatened by climate change. On a broad scale, climate change will affect the distribution of oil palm production.

Furthermore, Malaysia has a humid and tropical climate (Abubakar et al. 2021). Mountains and complex interactions between land and sea greatly influence the climate (Abubakar et al. 2022a, 2022b). However, recent years have seen a

Table 5: Statistics of Climate suitability (water deficit) for oil palm production.

Climatic Zone (Water deficit)	Area [ha]	Percentage [%]
Highly Suitable (mean annual water deficit <150 mm)	3688254.00	29.54
Suitable (mean annual water deficit <250 mm)	6540669.00	52.38
Moderate (mean annual water deficit <400 mm)	2227500.00	17.84
Unsuitable (mean annual water deficit >400 mm)	31104.00	0.25
Total	12487527.00	100.00

rise in mild climate-related disasters. The socio-economic status of the country was significantly impacted by floods and droughts (Abubakar et al. 2021). Landslides caused by excessive rainfall and strong winds caused minimal damage to hills and coastal areas. (Abubakar et al. 2021). As a function of the area covered by biodiversity, Malaysia is the second-richest country in Southeast Asia, after Indonesia, with 0.2% of the world's landmass. According to the 2001 Global Diversity Outlook, Malaysia is one of twelve countries with mega-diversity (Abdul Rahman 2018).

Soil Properties Suitable for Palm Production

On the west coast of the Peninsular, suitable soil is primarily found for oil palm cultivation in a state like Selangor and some parts of Kedah with clay loam and sandy loam soil properties, while in the southern region like Johor, moderate suitability of oil palm production was noticed due to the domination of clay-soil in the area. However, sandy soil is only found in a very small area and is not suitable for the production of oil palm (Fig. 6). Kome et al. (2020) argued that climate in the coastal plains of southwest Cameroon did not pose a serious constraint on oil palm production, but oil palm production, however, is limited by soil physical characteristics (primarily clayey texture and poor drainage) and soil fertility.

The impact of climate on soil structure is complex (Várallyay 2010). It is raindrops, surface runoff, and filtrating water that have the greatest direct impact on aggregate destruction. In particular, climate change is contributing to more intense, frequent, and heavy rainstorms, especially during heavy rains and thunderstorms (Ashton-Butt et al. 2018). Changes in vegetation patterns and land use practices cause indirect influences. It is possible to boost fertility by

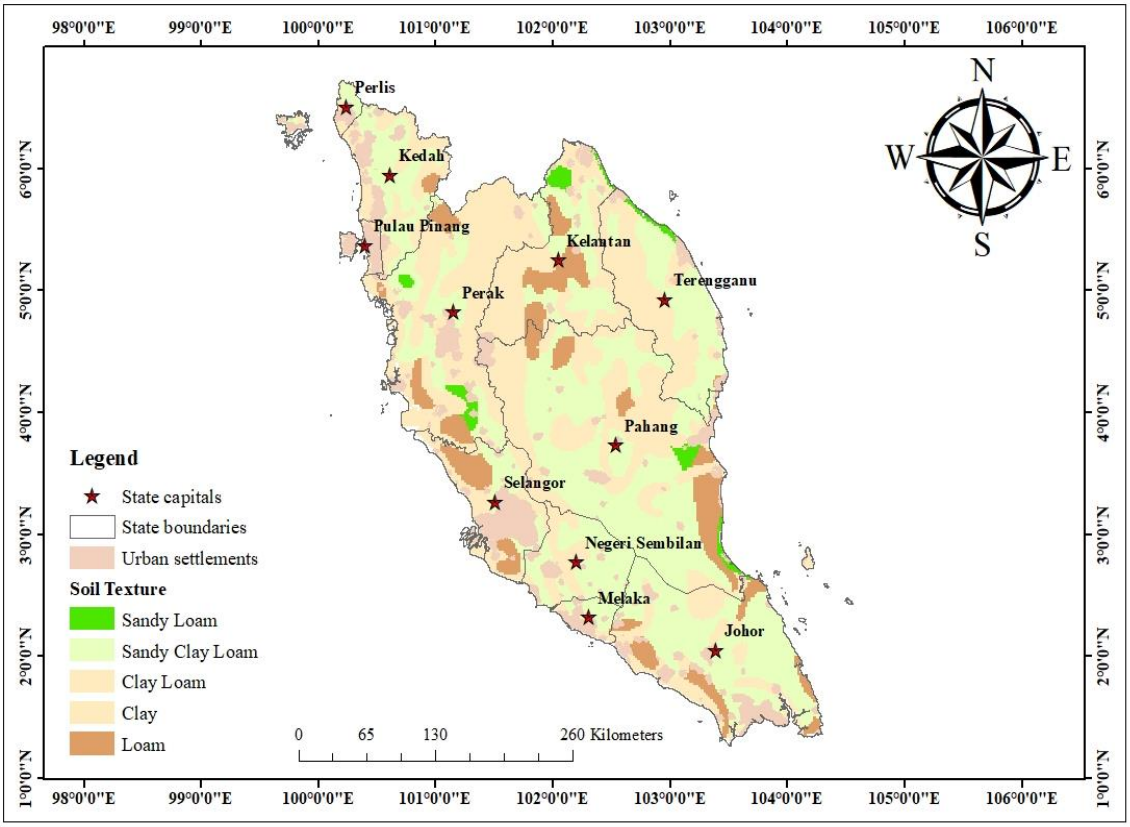

Fig. 6: Soil texture of Peninsular Malaysia showing areas suitable for oil pal production.

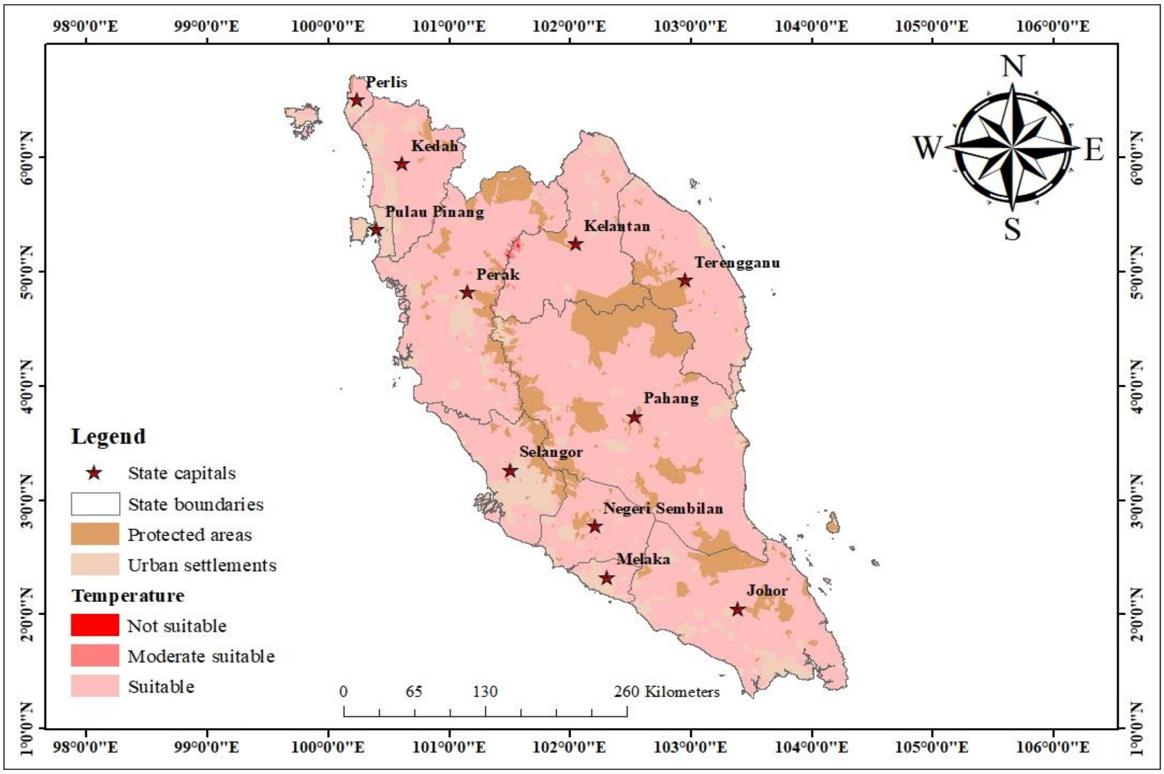

Fig. 7: Climatic zone (Temperature) suitable for oil palm production in Malaysia Peninsular.

using mineral fertilizers and crop residues (Fu et al. 2021). As most soils in the oil palm belt drain well, drainage criteria were not considered in the assessment. Fertile soils are found in the valleys (Annan-Afful et al. 2005); high rainfall periods often cause flooding and water-logging, so they often require costly drainage to avoid flooding (Rhebergen et al. 2014).

Fig. 7 and Table 6 reveal the climatic suitability areas (ha) for oil palm production in Peninsular Malaysia under the influence of temperature (degrees Celsius). Unsuitable areas cover about 6318.00ha (0.05%), moderately suitable areas 95337.00ha (0.76%), while the suitable areas cover a large area of about 12385872.00ha (99.19%).

Table 6: Statistics of Climate suitability (Temperature) for oil palm production

Climatic Zone (Temperature in degree Celsius)	Area (ha)	Percentage (%)
Temperatures <18	6318.00	0.05
Temperatures 18 – 20	95337.00	0.76
Temperatures >18	12385872.00	99.19
Total	12487527.00	100.00

The uplifted edges are found at elevations <1500 asl which cover 12396321.00 (99.45%) and has mean monthly minimum temperatures above >18^{o}C, which signifies suitability for oil palm production in the area (Fig. 7, 8 and Table 5, 6), while the unsuitable areas are at elevation >1500 covers an average area of 68283.00 (0.55%) (Table 7). Slope suitable areas (Fig. 9 and Table 9) reveal the areas with suitable slopes, estimated within the limits for oil palm at 12192606.00ha (99.83%). Almost all slopes >50, 12192606.00ha (99.83%) in the study area were removed from climatically suitable areas for oil palm cultivation. In suitable climate zones, the oil palm belt has undulating terrain with slopes between 0 and 30 degrees. Rendana et al. (2022) disclosed that a gently sloping flank or a low gradient slope margin would be a suitable place to plant oil palm. Urban settlements and protected areas were excluded

Table 7: Statistics of Elevation suitability for oil palm production

Elevation (degrees)	Area (ha)	Percentage (%)
Elevation 0 - 1500m	12396321.00	99.45
Elevation > 1500m	68283.00	0.55
Total	12464604.00	100.00

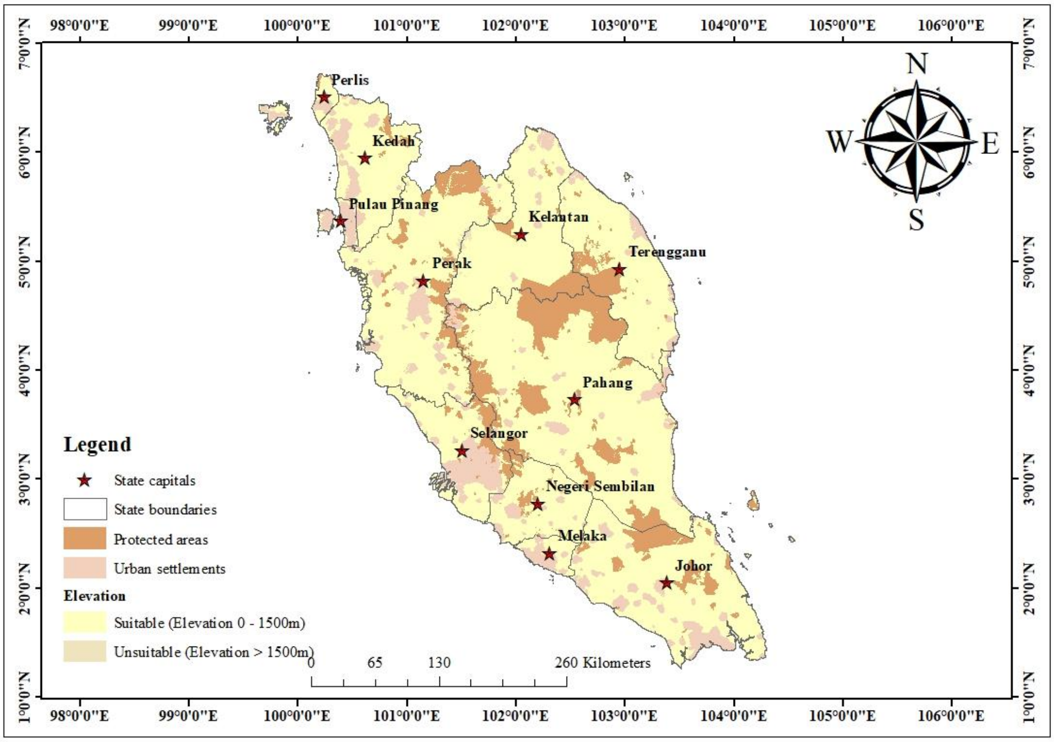

Fig. 8: Elevation areas climatically suitable for oil palm production in Peninsular Malaysia.

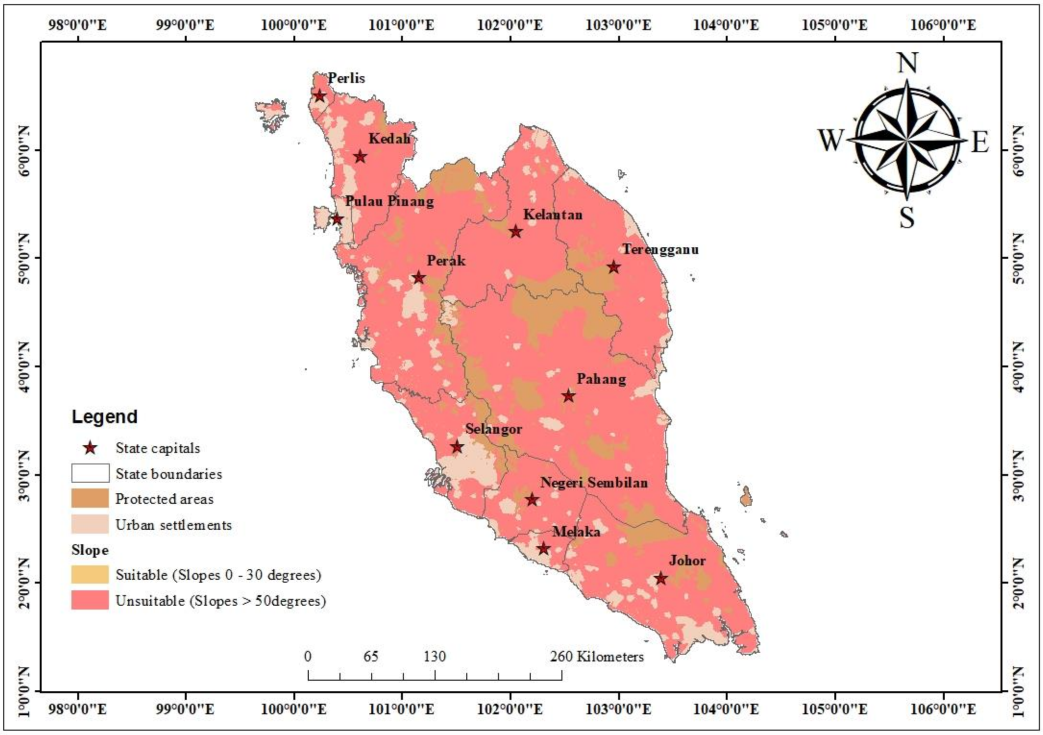

Fig. 9: Slope map showing areas that are climatically suitable for oil palm production in Peninsular Malaysia.

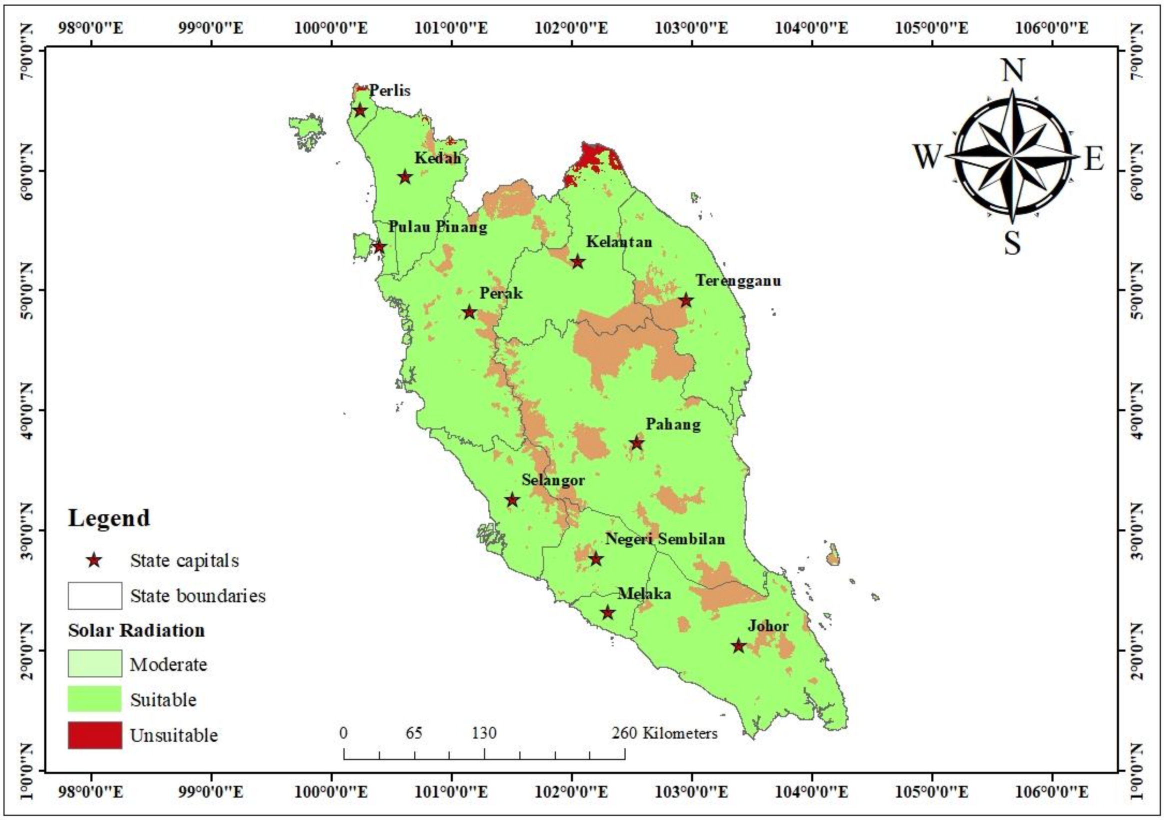

Fig. 10: Solar radiation zones climatically suitable for oil palm production.

from this calculation. Oil palm cultivation has declined due to a shrinking amount of suitable land (Fig. 9). Montgomery et al. (2016) argued that the reduction in agricultural land value has been caused by urbanization and industrialization

Fig. 10 depicts the climate suitability (Solar radiation MJ M^{-2} day^{-1}) area. Within the limits for oil palm production, suitable estimated solar radiation is 12399561.00ha (99.30%), moderate suitable 81.00ha (0.00%), and unsuitable 87885.00ha (0.70%) (Table 8). Fig. 11 presents the annual variation in the monthly average of daily solar radiation, while Fig. 12 presents the mean annual variation of solar radiation at the oil palm plantations region in Peninsular Malaysia.

Table 8: Statistics of climate suitability (Solar radiation) for oil palm production.

Climatic Zone (Solar radiation in MJ M^{-2} day^{-1})	Area (ha)	Percentage (%)
Moderate Suitable (Solar Radiation)	81.00	0.00
Suitable (Solar Radiation)	12399561.00	99.30
Unsuitable (Solar Radiation)	87885.00	0.70
Total	12487527.00	100.00

Climate, Land and Soil Suitability Analysis

To guide governments and policymakers in making decisions, a basic methodology was used to evaluate how much reasonable and accessible land is available in Peninsular Malaysia for oil palm cultivation. The results give a bedrock to the conversation of the ongoing debate on the development of oil palm in the nation and underline the significance of assessing the climatic elements that decide the ongoing and future production of oil palm in the country. Findings from the study reveal that a larger area was found to be suitable for oil palm production in Peninsular Malaysia than that identified by Abubakar et al. (2022). The observed differences may be explained by different methods for determining suitability, although climate variability is

Table 9: Statistics of slope suitability for oil palm production.

Slope	Area [ha]	Percentage [%]
Slopes 0 – 30	20331.00	0.17
Slopes > 50	12192606.00	99.83
Total	12212937.00	100.00

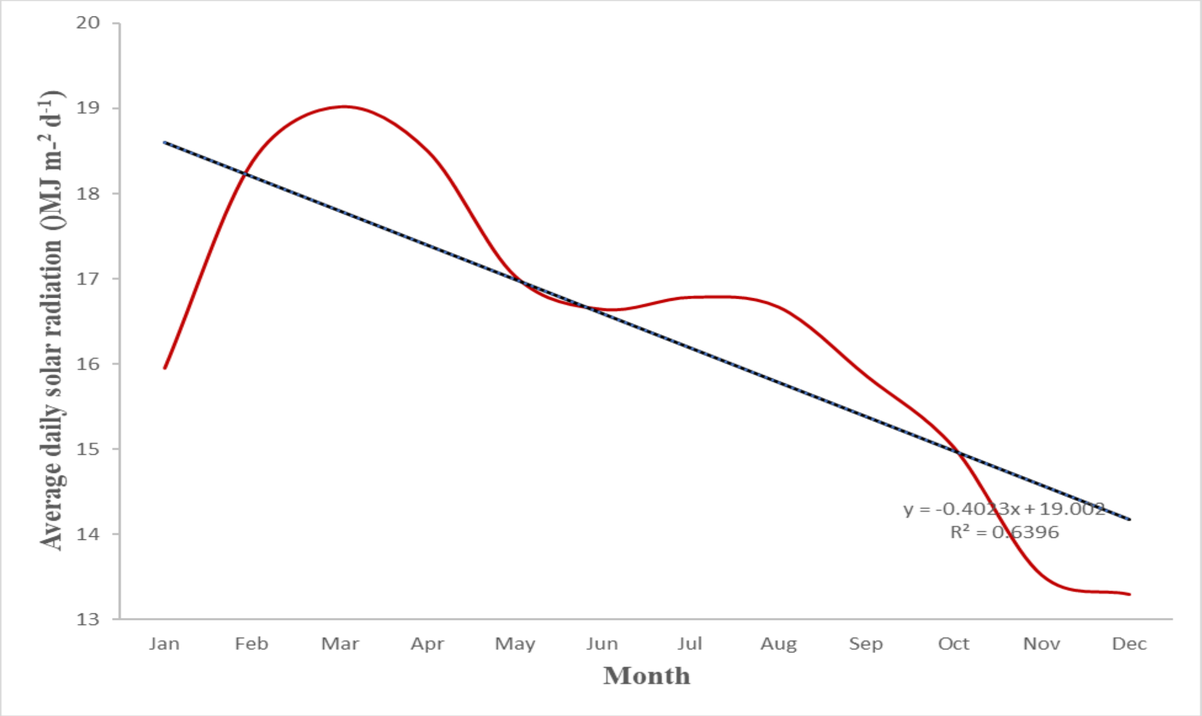

Fig. 11: Annual variation in the monthly average of daily solar radiation at oil palm plantations region in Peninsular Malaysia.

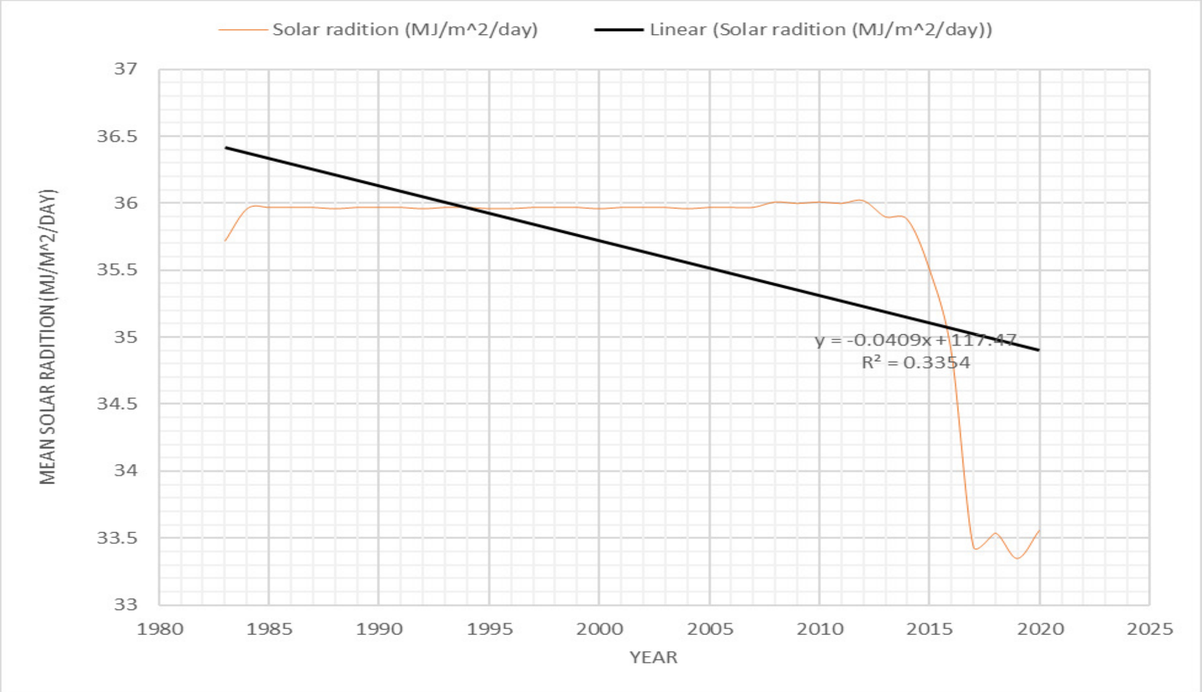

Fig. 12: Mean Annual variation of solar radiation at oil palm plantations region in Peninsular Malaysia from 1983 to 2020.

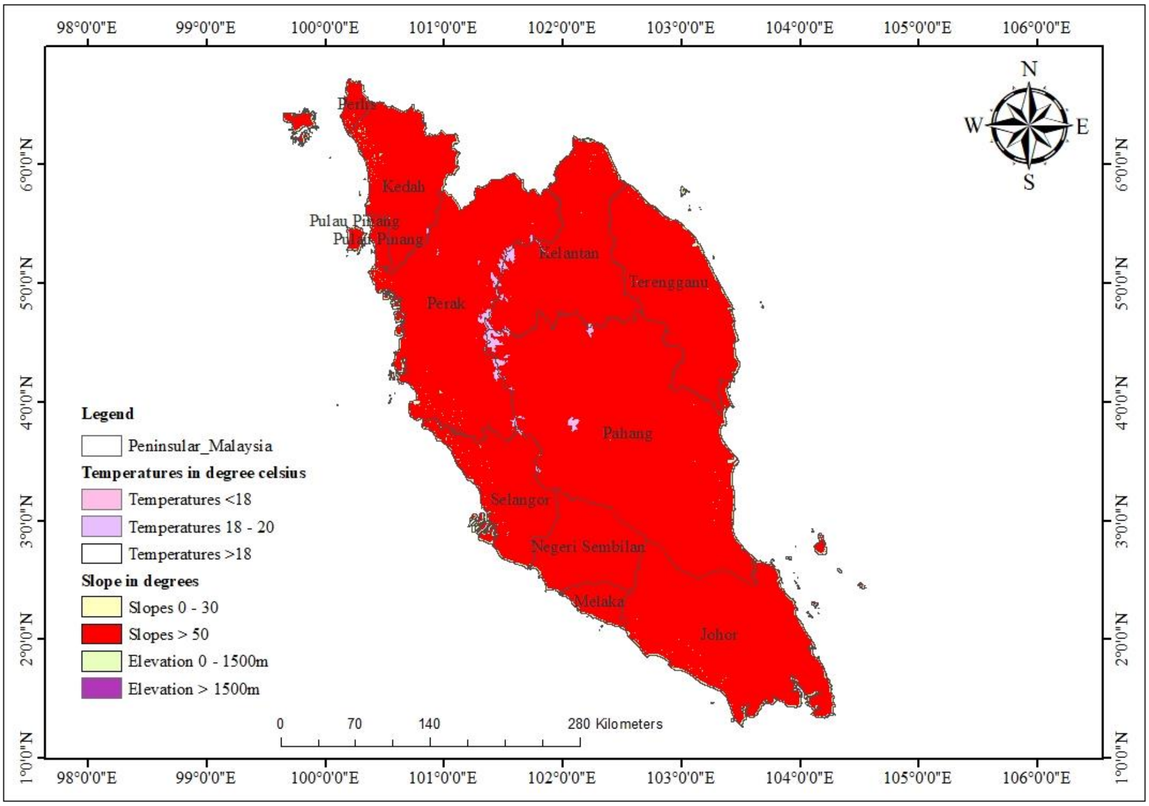

Fig. 13: Combine temperature, slope, and elevation map showing areas climatically suitable for oil palm production in Peninsular Malaysia.

another factor. Fig. 13 shows the combined temperature, slope, and elevation map showing areas climatically suitable for oil palm production in Peninsular Malaysia.

The data on climate, soil, and land use for this study were more detailed than those that were used by Rhebergen et al. (2016). Oil palm production can be made more sustainable with improved knowledge of environmental parameters. Remote sensing and GIS methodologies can explain observed changes in evapotranspiration and water deficit (Mustafa et al. 2011). A land suitability assessment would greatly aid in enhancing and validating the suitability analysis by simulating and analyzing oil palm production under varying climate conditions. The oil palm belt climate has changed dramatically from the early 1980s to the present (Abubakar et al. 2022a, 2022b). The country experienced an increase in temperature from 1980 to 2020 while rainfall remained stable (Abubakar et al. 2021). The WorldClim climate data for 1960–2000 is also used to assess temporal variations in climate. The eco-physiological constraints imposed by the climate determine the distribution ranges of species. Oil palm may not colonize unsuitable sites due to factors like soil properties and biotic interactions (Pareek 2017).

Due to the varying spatial scales at which each factor acts, the interrelationships among these factors can be complex (Murphy et al. 2021). The presence of oil palm plantations in climatically suitable areas can change over time due to other factors becoming more important at the local level (Paterson et al. 2015, Abdul Rahman 2018). It is more important to consider topography and soil texture on a finer scale, as well as nutrient content. Plantations of oil palm are expected to experience significant impacts due to climate change (Paterson et al. 2015, Sarkar et al. 2020).

Over the last four decades, most areas of Malaysia have seen an increase in surface temperature of 2.7-4.0^{o}C (Jegasothy et al. 2021). Since the 1970s, precipitation in Peninsular Malaysia has also increased (Loo et al. 2015). With increased trends in daily maximum rainfall along Peninsular Malaysia's west coast since the mid-1970s, northeast and southwest monsoon rainfall have increased dramatically (Cramb 2020, Kuttippurath et al. 2021). A longer dry spell was also observed during this period. From 1969-2009, Malaysia's average surface temperature rose from 0.6 to 1.20^{o}C and is predicted to rise from 1.5 to 2°C by 2050 (Paterson et al. 2015). A greater degree of fluctuation may be experienced in rainfall and river flows (Paterson et al. 2015). Daily minimum precipitation in Peninsular Malaysia is expected to fall by 32 to 61%, while maximum precipitation is expected to rise by 51% in Pahang, Kelantan, and Terengganu (Alam et al. 2011). There will be an increase of 10% in rainfall in Kelantan, Pahang, Terengganu, and the northwestern coast, and a decrease of 5% in Johor and Selangor, causing risks and uncertainty for oil palm farmers (Othman et al. 2016).

Agriculture's Role in Malaysia's Economic Development

A significant role has been played by agriculture in Peninsular Malaysia's recent economic transformations (Murad et al. 2008, Austin & Baharuddin 2012). In the years between 1997 and 2010, Malaysia was hit by numerous regional and global economic crises, which were alleviated by agriculture (Olaniyi et al. 2013). Therefore, in Malaysia, the growth in agricultural productivity will mainly be achieved through intensification, among other initiatives, as indicated by the previous and future economic plans (Ming & Chandramohan 2002, Abdullah et al. 2009, Nordin et al. 2014, Varkkey et al. 2018). In accordance with the Malaysian National Economic Development Plans, the National Physical Plan (NPP) was formulated through the Malaysian Town and Country Planning Act 1976 (Kassim 2012). Land suitability maps that are not updated regularly would make this task difficult for agencies. This study found coastal Selangor to be one of the highly climatic suitable areas for the production of oil palm (Fig. 5). The suitability of this area might expose the area to potential environmental degradation from agricultural intensification.

How Climate Change Affects Oil Palm Production in Peninsular Malaysia?

Despite falling from 6.0% of GDP in the 1970s to 3.1% in 2021 (World Bank 2022). Malaysia's development relies heavily on the agriculture sector (Wong 2007, Islam & Siwar 2012, Matahir & Tuyon 2013). There are a variety of subsectors within the sector, such as rubber, livestock, forestry, logging, fisheries, aquaculture, pepper, cocoa, pineapples, coconuts, tobacco, tea, etc. The oil palm industry dominated Malaysian agriculture in 2014, which accounted for 36.6% of the total agricultural production (Sarkar et al. 2020). After Indonesia, Malaysia has the second-highest palm oil production and exports (Abubakar et al. 2022a, 2022b). With 39% of global production and 44% of exports, Malaysia dominates palm oil production and exports (Alam et al. 2015). As a result, Malaysia's economy benefits greatly from oil palm cultivation and production.

Floods, droughts, heat stress, and heavy precipitation are all effects of climate change on crop production. Malaysian oil palm production has decreased due to the direct and indirect impacts of climate change (Paterson & Lima 2018). According to Zainal et al. (2012), Net revenue from oil palm production is significantly affected by climate change. Tropical countries are suffering from adverse effects of climate change on oil palm production (Paterson et al. 2015, 2017).

In addition, Paterson & Lima (2018) predicted that if temperatures exceeded 2°C and rainfall decreased by 10%, oil palm production would decrease by 30% in Malaysia. Oil palm production will be unsuitable beyond 2050 due to the unsuitable climate (Paterson, 2019a, Paterson 2020). Paterson (2019a) predicts a significant decline in oil palm production. The climate change effect on oil palms is expected to worsen between 2070 and 2100 (Paterson 2019b). Oil palm production may not be sustainable based on this projection. Due to climate intensity and severity, climate change can have considerable impacts on oil palm production. Oil palm plantations can become susceptible to diseases and pests if the land is dry or degraded, or if temperatures rise (Akinci et al. 2013).

The Contribution of Oil Palms to National Development

In terms of net contribution to gross national income (GNI), the palm oil industry is ranked fourth in the country with RM53 billion (Mahat 2012). Over the next decade, oil palm will dominate the nation's economy, contributing RM178 billion to the nation's GDP in 2020 (Mahat 2012). Since rubber and tin are being replaced by diversifying the economy, the government has been able to sustain the success of this industry. The oil palm sector was successfully developed as a result of this decision. The Malaysian government decided to promote oil palm plantations as a new agricultural commodity in 1955, in accordance with a World Bank mission recommendation (Teoh 2002). The narrow economic base was widened and diversified to grow the economy more efficiently. To expand palm oil exports, industrial estates are being established and palm oil estates are being expanded. Diversification initiatives were taken to develop manufacturing and expand the export of palm oil (Teoh 2002, Rasiah & Shahrin 2006). By creating wealth for the nation, the palm oil industry changed the economic landscape for the better, as well as alleviating poverty among the poor (Majid Cooke 2012). The Second Malaya Plan (1961-1955) clearly emphasized rural development and poverty alleviation as government priorities (Fredericks 2012). The poverty rate among agricultural farmers was 68.3% in the 1970s. A new program to alleviate poverty in rural areas was launched in the 1960s through the planting of oil palms. As a result of the government's rural development programs and newly opened lands, three rural development agencies were established to encourage the establishment of large plantation areas, including The Federal Land Development Authority (FELDA), the Federal Land Consolidation and Rehabilitation Authority (FELCRA), and the Rubber Industry Smallholders Development Authority (RISDA) (Teoh 2002, Yap et al. 2021).

Oil Palm Production Opportunities in Peninsular Malaysia

The competitiveness and advantages of palm oil have made it one of the leading sources of vegetable oils (Mekhilef et al. 2011). According to several studies, oil palm has done well in the global market for oils and fats for several reasons (Ming & Chandramohan 2002, Basiron & Balu 2004, Burri 2012, Von Giebler 2013, Goh et al. 2016, Mat Yasin et al. 2017, Kushairi et al. 2018). Palm oil is less expensive than other vegetable oils (Carter et al. 2007, Zimmer 2010). There was an increase of 7.9% in palm oil consumption over the past 40 years, compared to a growth of 5.6% in soy oil over that same period (Abazue et al. 2015). In comparison to other crops, palm oil has the highest productivity per acre (Murphy et al. 2021). The sustainability of palm oil cannot be matched by other vegetable oils, since it has a long lifespan of 25 years and it consumes significantly less energy during production. In comparison to other oil-producing crops, it requires less land and produces more oil per hectare (Sumathi et al. 2008, Lam et al. 2009, Levang et al. 2016). Among the facts that cannot be contested are the high productivity of oil palm, it's commercial profitability at large scales, and the growing demand for palm oil (Sheil et al. 2009). Oil palm profitability makes it an attractive investment for development and wealth creation in Malaysia, by offering a route out of poverty. There are also potential markets for palm oil and allied products as it is used in food products, detergents, cosmetics and, to a small extent, biofuel. Over half of all packaged products consumed by Americans contain palm oil, despite it being a minor component of the American diet. It is possible to improve incomes and quality of life through the development of oil palms if they are well-planned and managed (Meijaard & Sheil 2013). Throughout Peninsular Malaysia, oil palm cultivation is suitable due to the climate and soil conditions (Paterson & Lima 2018, Abubakar et al. 2022a, 2022b). Peninsular Malaysia continues to expand its oil palm production area (Shevade & Loboda 2019). Over 20% of the land is covered by oil palm plantations, and new plantations are being established throughout the region (Shevade & Loboda 2019). Historically, Peninsular Malaysia has been a resource-based economy dominated by plantations, including oil palm plantations that have replaced natural forests (Shevade & Loboda 2019). Finally, the market for palm oil is global and demanding, whereas the climate and soils in Peninsular Malaysia are highly suitable for oil palm cultivation.

CONCLUSION

In this study, we assess the suitability of oil palm production as driven by soil, climate, and land use in Peninsular Malaysia. To determine suitable and available land for oil palm production, remote sensing and GIS overlay were found to be useful methods. To handle digital spatial data, this method was found to be more flexible and accurate. The GIS in this study proves a powerful combination to apply for climate, soil, and land-use suitability analysis. The study shows that good soils and climatic conditions in Malaysia remain one of the most important factors in oil palm cultivation. Recent decades have seen Malaysia's oil palm plantations expand due to suitable soil and climate. In terms of delineating oil palm production sites, combining LSA with GIS enhances policymakers' and planners' decision-making capabilities. The northeastern part of central Peninsular Malaysia is home to the most suitable soils for oil palm production, particularly those in Selangor and Kedah, and Kelantan Terengganu, with clay loams and sandy loams, whereas in the southern regions, such as Melaka, clay soil dominates the area, which makes it moderately suitable for oil palm production. For further research, additional aspects including irrigation schemes, market infrastructure, and socioeconomics should be considered. Further suitability analysis will be possible due to soil databases and land information systems that include information on soil types, soil fertility, terrain, current land use condition, climate, slope, vegetation cover, soil erosion, and land unit maps. For further research, however, irrigation facilities, market infrastructure, and socioeconomic factors should be considered.

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