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Effect of agroclimatic variability on land suitability for cultivating rubber *(Hevea brasiliensis)* and growth performance assessment in the tropical rainforest climate of Peninsular Malaysia

Mohd Hafiz Mohd Hazir[a,b,*], Radhiah Abdul Kadir[b], Emanuel Gloor[a], David Galbraith[a]

[a] *School of Geography, University of Leeds, Leeds LS29JT, UK*
[b] *Malaysian Rubber Board, 50450 Kuala Lumpur, Malaysia*

A R T I C L E I N F O

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A B S T R A C T

Climate change directly alters climate conditions and indirectly impacts land suitability for cultivating rubber. The Malaysian tropical rainforest climate with regular rainfall of about 2000–2500 mm per year and the average temperature of 26–28 °C provide a suitable condition for planting rubber commercially. There is doubt about how well rubber plants will perform in the future because of climate change. The main question of whether rubber is still appropriate for planting in Peninsular Malaysia must be answered conclusively as rubber requires an approximately 30 year investment in one cycle. This question is particularly relevant in Malaysia as its rubber production is dependent on smallholders. Smallholders contribute approximately 93% of natural rubber production and furthermore, 93% of the rubber land area in Malaysia is owned by smallholders. An agroclimatic map produced in this study will help smallholders in deciding whether to proceed with rubber or change to other valuable crops based on their specific location. In this study, we evaluate 21st century land suitability for cultivating rubber and assess its growth based on climatic data for the Historical (1970–2000), Early (2010–2040), Middle (2040–2070) and End (2070–2100) projections periods. We use the *Hevea* 1.0 static model for rubber tree modelling to calculate the agroclimatic indices and estimate 30 years' of actual rubber growth (girth) for all study periods. We find that climate change is predicted to have a positive impact on rubber-suitability in tropical rainforest in Malaysia climates at least until 2100. The End period, where the precipitation and temperature are projected to experience significant increases, becomes more favourable to rubber. The Perak region shows the highest increase in estimated rubber growth in the Early, Middle, and End periods by 16.3%, 31.9% and 39.4%, respectively. Among all regions, Kelang is predicted to be the most suitable area to plant rubber during the Early period as it has a potential estimated girth of up to 94.5 cm. Meanwhile, Johor is predicted to be the best place to cultivate rubber during the Middle and End periods with growth estimations of 97 cm and 99.5 cm, respectively. We indicate that about 32% of existing planted rubber area in Peninsular Malaysia is in Class 6 of land suitability to cultivate rubber.

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* Corresponding author.
E-mail addresses: gymhmh@leeds.ac.uk, mohdhafiz@lgm.gov.my (M.H.M. Hazir), radhiah@lgm.gov.my (R.A. Kadir), e.gloor@leeds.ac.uk (E. Gloor), d.r.galbraith@leeds.ac.uk (D. Galbraith).

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1. Introduction

Global climate change definitively affects land suitability for planting crops and the crops' growth performance. Climate change is currently altering environment conditions all over the world, and its impacts are well-known and undeniable (Letcher, 2009; Zommers and Alverson, 2018). Proof of increasing temperature phenomenon since 1850 and are predicted to be more serious in future has been shown by countless scholars from various established governments and independent organizations around the world by using real figures of historical data that have been formulated into climate modelling to predict future climate change impacts (Stocker et al., 2013; Stocker, 2014; Desler, 2016; Li and Fang, 2016; Barnett and Facey, 2016; UNFCC, 2017; Epeland and Kettenring, 2018, Rötter et al., 2018).

Agroclimatic information such as soil types, rainfall, temperature and sunshine are basic information that must be determined before any decision can be made on choosing the best crops to cultivate on particular lands. In Malaysia, an agroclimatic and crop zone classification has been developed by the Malaysian Meteorological Department and Malaysian Department of Agriculture as a guideline to any interested individual, company or organization. This classification became a decision support tool for making critical decisions on whether to cultivate perennial crops or not. This decision-making process is necessary because perennial crops, such as rubber, have long lifespans of 30 years and involve considerable investment. Global climate change will have great impacts on local climate systems, including in Malaysia. Increasing of temperature and rainfall reduction beyond the threshold crops requirement will greatly affect on the production (Yohannes, 2016). Therefore, understanding the impact of the predicted future climate change on rubber assists in deciding whether to replant with the same crop, such rubber, or change to more suitable crops. This reasoning also applies to new open areas of land regarding whether to start planting rubber or not. This study may provide information on which regions will be best for planting rubber and estimate its growth performance in Peninsular Malaysia. Growth analysis can provide useful insights into the influence of biotic as well as abiotic factors on rubber tree (Shorrocks et al., 1965; Chandrasekhar et al., 2005).

A marked temperature increase has been observed in Peninsular Malaysia over the last 46 years (1969–2015). The surface mean temperature was recorded as increasing by 0.24 °C per decade. The surface maximum temperature also significantly increased by 0.23 °C per decade while the surface minimum temperature increase was approximately 0.27 °C per decade. The climatic data also show that, for a shorter time frame beginning in 1990, increasing trends in rainfall were observed for Peninsular Malaysia (MESTECC, 2018). MESTECC (2018) projected the average annual air temperature for Peninsular Malaysia was projected to increase by 2.4–3.4 °C by 2030, and it may further increase to 4.8–6.4 °C by 2050 from a baseline of 25.4–26.3 °C. The positive trends of increasing of rainfall amounts from now until 2030 was projected across Peninsular Malaysia with a variation of 0.6–7.1%. Significant increases in average annual rainfall amount were predicted for the period of 2030–2050 of up to 10.6%. The historical average annual rainfall data range from 1891 mm to 3907 mm across Peninsular Malaysia (MESTECC, 2018).

Hevea brasiliensis is a native of the tropical rain forests of South America, where it grows under conditions of high humidity and growth well with many other species of wild trees, climbing plants and undergrowth. Meanwhile, the typical Peninsular Malaysia climate, with a regular rainfall of about 2000–2500 mm per year, a dry period about February to March (low yielding period from January to April), moderate yielding period in May to August (inter-monsoon season) and a wet spell about October to December (high yielding period from September to December), average temperature of 26–28 °C produces an equable warm humid atmosphere which seems admirably suited to planted monoculture of rubber (Edgar, 1960; Said, 2005; MRB, 2009). The rubber tree will thrive up to an altitude of 300 m above sea level, but above this trees are smaller, less vigorous, and produce less yield. It prefers a good stiff loamy soil with good subsoil drainage, but will thrive on clay, alluvial soils and even on hard gravelly soil. It will also grow on peat, provided the layer is not too deep, and drainage adequate. It cannot tolerate salt and will not grow on land liable to frequent flooding with sea-water (MRB, 2009). Said (2005) found that land productivity is strongly influenced by the number of tapping days not the tree productivity. The number of tapping days directly effect on rubber production. Even though on high yielding period, if there is flood occurrence because of extreme events, rubber tappers will not tap the trees. On the other hands, there also wintering season in low yielding period where the trees defoliated their leaves as a defence mechanism to reduce water loss. In this period, rubber tappers are not encouraging to tap the trees. It will cause the tree to get the disease known as tapping panel dryness, Brown Bast or dry bark.

The impacts of climate change on perennial crops such as rubber in tropical rainforest climates is still questionable for whether the conditions will become more favourable or less favourable. The climatic change in the Great Mekong sub-region was projected to be predominantly in the direction of higher suitability for rubber cultivation, and the expansion of the climatically optimal area was suggested to be minimal in the year 2070 (Golbon et al., 2018). Climate plays a major role in rubber tree distribution as suggested by Ray et al. (2016); among all the bioclimatic factors, precipitation and temperature contributed the most to explaining rubber tree distributions. However, Siwar et al. (2013) calculated rubber production would decline with a range of 10–30% due to negative impacts of climate change. The results for potential suitability classifications by Arshad et al. (2013) showed that all nine regions studied in Peninsular Malaysia were highly suitable for rubber cultivation with land indices ranging from 90 to 99 using mean monthly climatic data from 2002 to 2012. Ahmed et al. (2017) observed that suitable lands for plant rubber were more concentrated in the southern part of the Seremban district of Negeri Sembilan, Peninsular Malaysia by considering soil and rubber growth requirements. These authors also suggested that most of the existing rubber plantations are not located on optimally productive land, which may account for a low productivity. Considering the planting of rubber based on an evaluation of land suitability using 2007–2016 climatic data, Arshad (2017) showed that the Lancang and Durian soil series were the most suitable soils to cultivate rubber in Pahang.

The estimation of total land area suitable for cultivating rubber and identifying the best locations to plant rubber based on regions in this study has been made only to compare one period to another and for comparing regions to regions. In reality, even though certain regions are agroclimatically suitable for cultivating rubber, it is still not guaranteed that the owner of the land will grow rubber. There are many factors that may cause an owner to choose not to plant rubber in Peninsular Malaysia. The main potential reasons are because of the low natural rubber price and lack of tappers (MdLudin et al., 2016; Razak et al., 2016). The younger generation in Malaysia is not interested in being tappers as they can obtain a higher pay from other types of work. Rubber tappers also have become low class traditional job because it is not classified as a professional job (Hashim, 1998). Rubber smallholders currently are from older generations and their children have suggested that they do not want to be tappers; thus, as the land owner, they must hire people to tap rubber. However, the price is not competitive enough to cover the rubber smallholding maintenance costs and to share the profit with hired rubber tappers. The only reason rubber still planted in Malaysia is because of the government's role in offering a rubber replanting scheme to the smallholders and by continuing incentives to support their rubber smallholding maintenance costs, including of cost of living. In addition to the land usage conversion from rubber smallholdings to the commercial buildings, residential or industrials, Fox and Castella (2013) highlighted Malaysian smallholders most likely converted their rubber to other crops such as oil palm because driven by strong demand on the world market.

Rubber crops have had historical value in Malaysia for over a century, as it was first planted at a moderately large scale in the year of 1895 (Webster and Baulkwill, 1989). The rubber sector in Malaysia is championed by smallholders, as they hold 93% of the 1,083,480 total hectares' rubber-planted area and contributed approximately 93% of the 740,140 total tonnes of natural rubber production in 2017 (MRB, 2018). Smallholding in Malaysia is defined as farming below 40 ha (Fox and Castella, 2013; Hazir and Muda, 2018). The hypotheses in this study that will be evaluated are that the climate is a determinant factor for suitability to plant rubber and sustainability rubber growth in Peninsular Malaysia. The main objectives of this study are to assess the suitable area for cultivating rubber, estimate the crop's growth performance and evaluate the existing planted rubber area based on the Historical (1970–2000), Early (2010–2040), Middle (2040–2070) and End (2070–2100) agro-climatic periods. Assumptions were made that (a) soil effects on rubber are constant across a periodical time series and (b) the land use does not change from 1970 to 2100 as we used the Reconnaissance Soil Map of Peninsular Malaysia 2002 (Revised) as a based map (c) existing planted rubber area is constant across all agro-climatic periods as we used the Planted Rubber Area Map of Peninsular Malaysia 2015 as a based map. We removed water and urban areas from the map; hence, the total land area of Peninsular Malaysia is calculated approximately as 12,725,900 ha.

2. Methodology

2.1. Site study

Peninsular Malaysia, also known as West Malaysia (Fig. 1), is a part of Malaysia located near the Equator in between latitudes of 1°15′ N to 6°55′ N and longitudes of 100°30′ E and 104°18′ E. Peninsular Malaysia has a hot, humid tropical climate that can be described as a rainforest tropical climate with two main monsoon seasons and two inter-monsoon seasons. The northeast monsoon and southwest monsoon periods are based on location as the former varies between October and February and the latter from April to October; the latter is characterized by thunderstorms (Khatib et al., 2012). During the northeast monsoon, the exposed areas on the eastern part of the Peninsular Malaysia receive heavy rainfall. The southwest monsoon is a drier period for the whole country, particularly for the other states on the west coast of Peninsular Malaysia. In contrast, the two inter-monsoon seasons often result in heavy rainfall that usually occurs in the form of convective rains. During these seasons, the west coast is generally wetter than the east coast (Deni et al., 2010; Suhaila et al., 2010). The overall weather of Peninsular Malaysia is warm as the temperatures and humidity are high, but the mountains are slightly cooler all year with average recorded temperatures ranging from 21 °C to 32 °C (Wong et al., 2009).

2.2. Data sources

In this study, we utilized climatic data for the average annual precipitation (Supplementary material, Fig. A1) and annual mean air temperature (Supplementary material, Fig. A2) for Historical (1970–2000), Early (2010–2040), Middle (2040–2070) and End (2070–2100) periods, which were provided and published by National Hydraulic Research Institute of Malaysia (NAHRIM) (NAHRIM, 2016). Based on this report, NAHRIM produced 'ensemble average' realization hydroclimate projected data using validated and calibrated Regional Hydroclimate Model of 15 climate projections for the 21st century made possible through 3 different coupled land–atmosphere-ocean GCMs (ECHAM5 of the Max Planck Institute of Meteorology of Germany, CCSM3 of the National Center for Atmospheric Research (NCAR) of the United States, and MRI-CGCM2.3.2 of the Meteorological Research Institute of Japan) under 4 different greenhouse gas emission scenarios (B1, A1B, A2, and A1FI) that were dynamically downscaled at hourly intervals by the Regional Atmospheric Model MM5 over Peninsular Malaysia (RegHCM-PM); a hillslope scale was used to study the impacts of climate change on the hydroclimate regime over Peninsular Malaysia as a detail description explained in this report (NAHRIM, 2016). Thirteen watersheds (Batu Pahat, Johor, Muda, Kelang, Kelantan, Linggi, Muar, Pahang, Perak, Selangor, Dungun, Kemaman and Kuantan) and 12 selected coastal regions are shown as Fig. 1. This setup is the same as the NAHRIM study regions, and they were selected later to assess the impact of climate change on the suitable area for planting rubber and to analyse the growth performance of rubber. Fig. 2 shows the Planted Rubber Area Map of Peninsular Malaysia 2015 provided by Malaysian Department of Agriculture. This data will be use as a basis to analyse land suitability of existing planted rubber area. Indirectly it will indicate either Malaysia growth rubber at the correct places or not and what will happen in the next future.

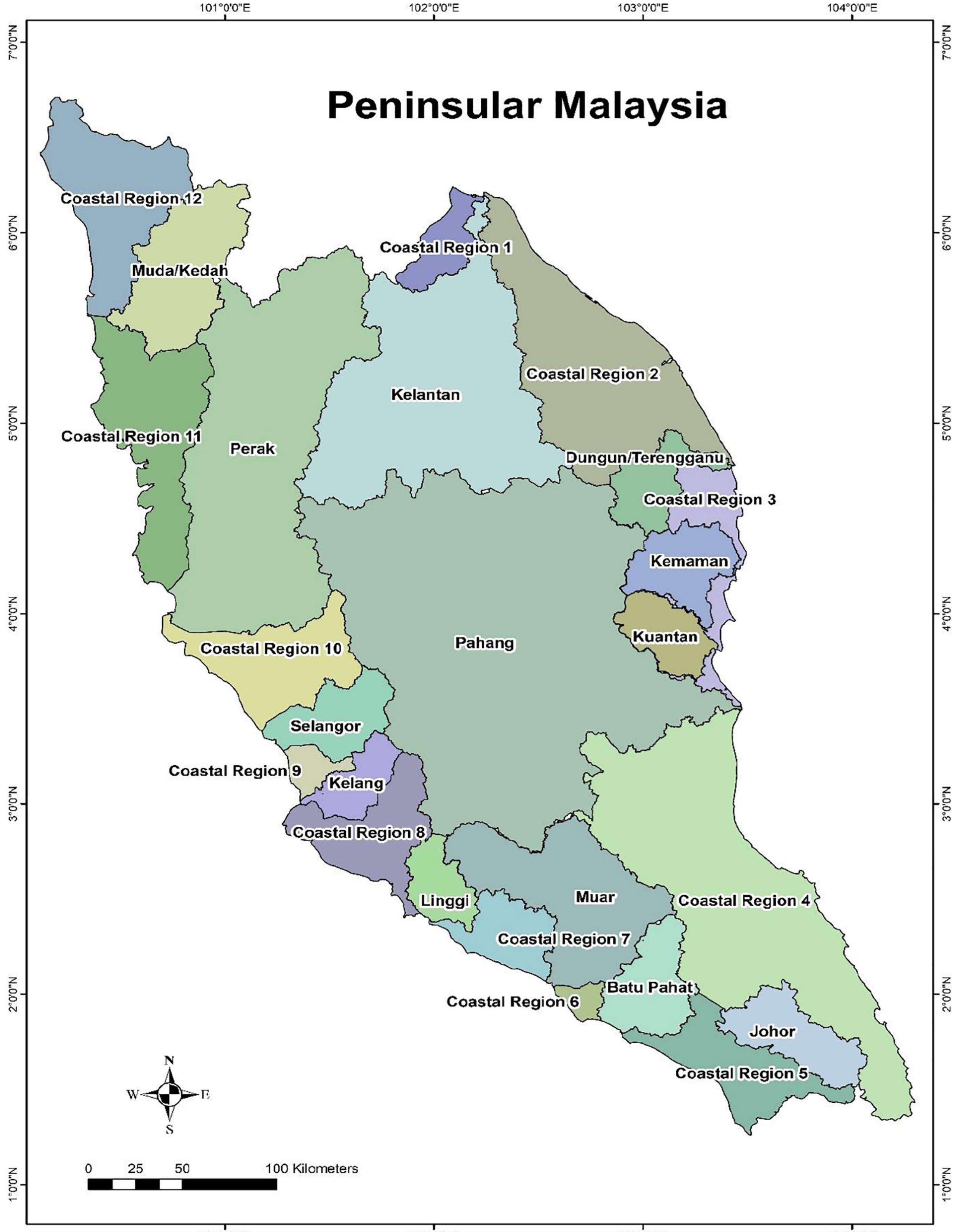


Fig. 1. The selected 13 watersheds and 12 coastal regions of Peninsular Malaysia.

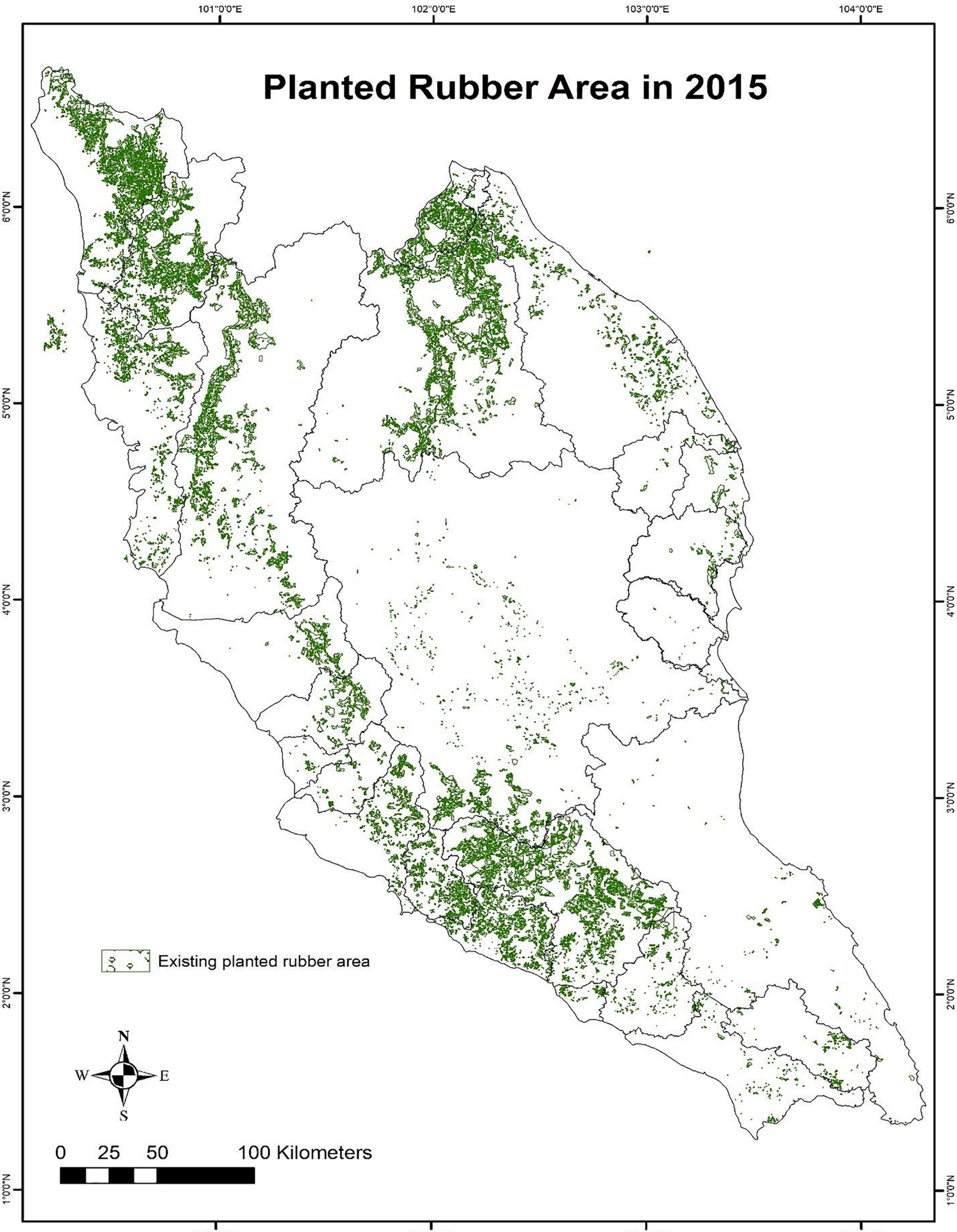


Fig. 2. Planted Rubber Area Map of Peninsular Malaysia in 2015.

2.3. Static and dynamic model

There are two types of mathematical models that have been implemented by previous researchers to predict the performance of rubber growth: static and dynamic (Abd Karim, 2006). The data collection process for the entire range of rubber tree related lifespans, practices and parameters is very time consuming and costly in nature. The dynamic model examples related to rubber can be found in Purnamasari et al. (2002) where the authors used the BEAM Rubber Agroforestry Model to examine the impact of uncertainty about prices and climate on decision variables. Meanwhile, Liu et al. (2019) adapted the Land Use Change Impact Assessment (LUCIA) model to simulate the effects of weed management on erosion in rubber plantations. In addition, Abd Karim (2006) used the STELLA Research Software Environment and Microsoft EXCEL and linked them to the current agroforestry model WaNuLCAS (Water, Nutrients, and Light Capture in Agroforestry Systems). Dynamic modelling such as STELLA introduces an approach to modelling that makes it a more practical, intuitive endeavour (Hannon and Ruth, 1994). However, in this study, we focus on the variability effect of soil and climate across Peninsular Malaysia on land suitability for planting rubber and rubber growth performance by comparing historical and future scenarios. Thus, we decided to proceed with the static model as it is a highly simplified model that only uses examples of annual precipitation and mean temperature as inputs. This choice was made because simpler models are more easily understood and have proved to be adequate for many purposes. The ultimate simulation model should be simple yet comprehensive enough to predict the growth of different varieties under any agro-climatic conditions (Abd Karim, 2006). The use of models in research programmes (Matthews, 2002) has the potential to increase efficiency by emphasizing process-based research rather than the study of site-specific effects.

2.4. Land suitability to cultivate rubber assessment and rubber growth performance estimations

This study implements the static modelling approach, namely, *Hevea* Version 1.0 introduced by Yahya (2008) to assess land suitability for planting rubber across Peninsular Malaysia and to estimate the actual growth (girth) of 30 years of planted rubber trees, with a planting density of 500 trees per hectare during different periods of climatic data. The assumption was made that the planting stocks (2-whorl budded stocks) are uniform for all planted areas (Yahya, 2008). Rubber trees were replanted every 30 years as previous research shows that this is the maximum limit when yields fall to an uneconomic level (MRB, 2009; Munasinghe and Rodrigo, 2018). Due to real-world practices and the land surface not being completely flat, the Malaysian Rubber Board recommended at least a maximum of 500 trees per hectare by following the basic rule where the distance between trees should not be closer than 2 m. We assumed that the standard distance between trees and rows are 4 m and 5 m, respectively. We decided to follow a common smallholder's practice where the tapping cost is not as important as ideally the trees should be tapped by the smallholders themselves. As mentioned in the introduction, 93% of rubber production in Malaysia is contributed by smallholdings. The estate sector needs to consider the tapping cost and balance this cost with the yield by reducing the numbers of trees by up only to 400 trees per hectare (MRB, 2009). In this study, we comprehensively measured the potential actual rubber growth variability based on soil and climate conditions (temperature, precipitation and sunshine) across Peninsular Malaysia. This static modelling consists of four main components as variables where the actual growth of rubber ($\mathrm{GR}_{\mathrm{actual}}$) is subjective by a Soil Index (SI), Climate Index (CL), Management Index (MGg) and Clone Index for growth (CIg), so that the actual growth ($\mathrm{GR}_{\mathrm{actual}}$) is expressed as:

$$GR_{actual} = GR_{max}(SI \times CL \times MGg \times CIg) \tag{1}$$

However, we are only concerned with environment variability, so we only consider Soil Index (SI) and Climate Index (CL) as variables. We assumed that rubber management completely follows the recommendations by the Malaysian Rubber Board and has no effect on rubber growth, thus the Management Index concludes as 1. The effect of rubber genotypes was not included in this study; thus, we generalized and assumed that a rubber tree was tapped after the girth reached 45 cm and showed no incidence of disease. Therefore, the Clone Index for growth also marked as 1. Thus, the formula was simplified as:

$$GR_{actual} = GR_{max}(SI \times CL) \tag{2}$$

The rubber tree maximum growth was derived from:

$$GR_{max} = \frac{2.37 \times TAge \times \varnothing}{22 + TAge + 3.7 \times 10^{-4} \times \left[\frac{TAge^2 \times D}{0.2 + 5 \times D}\right]^{1.35}} \tag{3}$$

where

GR_{max} in cm $TAge$ = Tree Age from time of planting (years) D = Tree density (number of trees per hectare) $\varnothing$
= 120 (a constant representing clonal growth performance)

As previously explained, we decided the maximum of lifespan of planted rubber tree is 30 years and that the density of planted rubber trees is 500 trees per hectare, so the GR_{max} is equal to:

$$GR_{max} = 162.8cm \tag{4}$$

Hence, the estimation of the actual rubber growth, $\mathrm{GR}_{\mathrm{actual}}$, of the rubber tree equation based on soil and climate variability is derived as:

$$GR_{actual} = 162.8(SI \times CL) \tag{5}$$

2.4.1. Soil index (SI)

Soil series have been mainly established in the past based on parent material and geomorphology (Paramananthan and Zauyah, 1986). Soil suitability classes for rubber based on the soil series have been identified and discussed in detail by previous researchers by considering the limiting factors on land to plant rubber (Chan and Pushparajah, 1972; Sys, 1975); Pushparajah and Amin, 1977; Ye, 1982). Ye and Chan (1992) discussed in detail four methods of soil suitability classification systems for *Hevea brasiliensis* cultivation. These authors suggested the Soil Suitability Evaluation System for Rubber using Land Qualities of 1982 (System 4) as they claimed it classifies soil suitability with the highest accuracy. However, in this study, we were dependent on the available Reconnaissance Soil Map of Peninsular Malaysia 2002 (Revised) (Supplementary material, Fig. A3) and the available soil series attributes. This map was created by the Malaysian Department of Agriculture and shared among Malaysian government agencies through the Malaysian Centre Geospatial Data Infrastructure (MaCGDI). Each polygon in the map represented either a single soil series or the combination of two or more soil series. In total, the map consists of 52 types of individual or grouping soil series across Peninsular Malaysia. We were using ArcGIS Desktop (ESRI [version 10.5], Redlands, CA) to process and analysed the data.

The metadata on this map were published and explained in detail on the MaCGDI website (http://mygdix.mygeoportal.gov.my/mygdiexplorer). Most of the available soil suitability classification systems for rubber cultivation are on individual soil series and hence are not suitable for associating two or more soil series. However, we found that the soils-rubber suitability for Peninsular Malaysia was based on the classification scheme by Wong (1986), where later it was adapted by the Malaysian Meteorological Services (MMS, 1993) and is compatible for use in this study. Three categories of suitability for rubber growing were introduced; hence, we followed the guidelines of Wong (1986). This system divided soil series into three classes: suitable soils, marginal soils and unsuitable soils. In this study, we converted the Soil Series Map into Soil-Rubber Suitability by giving a full mark of 3/3 for suitable soils, 2/3 for marginal soils and 1/3 for unsuitable soils. The soil index then was generated based on the list of 52 soil series. Fig. 3 illustrates the distribution of the suitable area to plant rubber based on the soil series information that had been converted into a soil index. The indices' range of 0.33–1.00 represents the Soil-Rubber Suitability, where 1.00 indicates a suitable soil to plant rubber. Table 1 shows the example of some common Malaysian soil series and categorizes these soils based on Soil-Rubber Suitability.

2.4.2. Climate index (CL)

Hevea brasiliens performs best in tropical lowland climates or those similar to its origin in the State of Para, Brazil. Thus, different climatic conditions would be expected to adversely affect the growth and production of rubber. In this model, the climate index is a function of sub-indices comprising precipitation (Pi), light (Li) and temperature (Ti) and is indicated as:

$$CL = f(\text{PrecipitationIndex}(Pi) \times \text{TemperatureIndex}(Ti) \times \text{LightIndex}(Li)) \tag{6}$$

2.4.2.1. Precipitation index (Pi). In this model, a precipitation index (Pi) is calculated based on the relationship between the relative girth and the amount of precipitation as per Yahya (2008), who found the highest R^2 (0.75) and is noted as follows:

$$Pi = \frac{1.037 \times P^{2.26}}{898.2^{2.26} + P^{2.26}} \tag{7}$$

where P = Precipitation in mm year^{-1}.

2.4.2.2. Temperature index (Ti). Yahya (2008) derived the equation that is justified to be best fit ($R^2 = 0.89$) based on the relationship between the yield of rubber and the monthly mean temperature; T (°C) shows an increase ranging from 24 °C to 28 °C, followed by a decline at or above 30 °C for the GT 1 clone. The equation was:

$$Ti = -0.0154T^2 + 0.8864T - 11.797 \tag{8}$$

where T values between 24 °C and 28 °C are assumed to be good for rubber plantations.

2.4.2.3. Light index (Li). In general, Malaysia receives approximately six hours of direct sunlight per day after a substantial amount of direct sunlight is blocked by clouds in the afternoons and evenings. In this study, the light index input is the average monthly amount of sunshine. The Li is expressed as follows:

$$Li = \frac{1.018 \times SS^{2.13}}{52.78^{2.13} + SS^{2.13}} \tag{9}$$

where SS = Sunshine in hours' monthly.

However, we did not have the sunshine data for the given period; thus, we generated the relationship among available climatic data and available historical sunshine values from various resources to predict the given sunshine value of the study period in the different regions. The monthly averages of maximum air temperature (T_{max}), minimum air temperature (T_{min}), mean air temperature (T_{mean}) and precipitation ($P_{monthly}$) were used to determine the daily estimated sunshine hours (SS_{daily}). The historical monthly data for all stations range from 1980 to 2016 were derived and extracted from the Malaysian Meteorological Department, World Meteorological Organization online database (https://data.un.org) and previous studies (Malaysian Meteorological Service, 1993; Khatib et al., 2012; Arshad et al., 2013; Arshad, 2017). Regression analyses were conducted to estimate the monthly sunshine hours

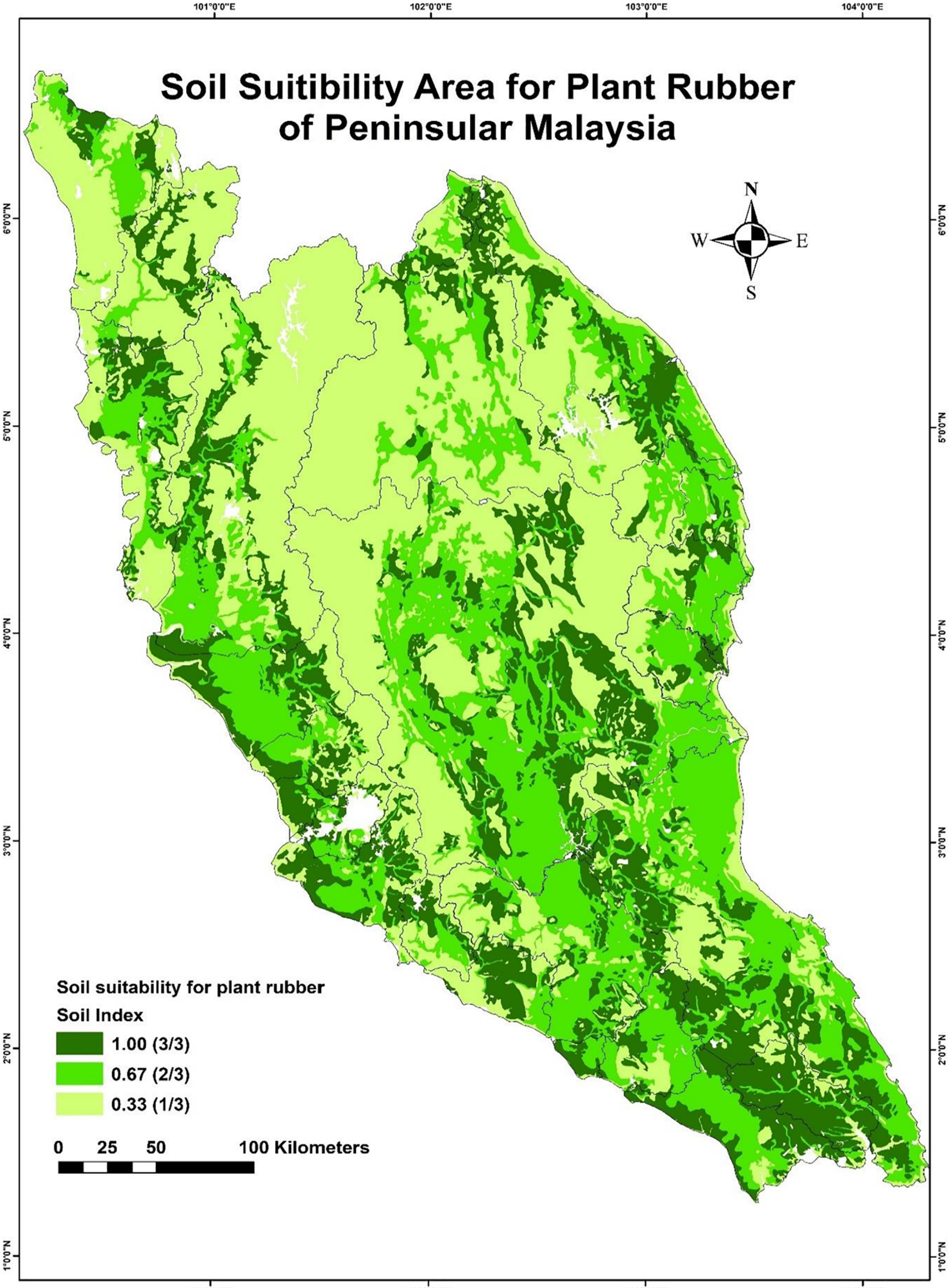


Fig. 3. Soil-rubber suitability map.

Table 1
Soil-rubber suitability for some common Malaysian soil series in Peninsular Malaysia.

No.	Soil suitability	Soil class/(index value)	Soil series
1.	Suitable soils	Class I (3/3 = 1.00)	i. Bungor-Durian ii. Selangor-Kangkong iii. Rengam-Jerangau iv. Kuantan
2.	Marginal soils	Class II (2/3 = 0.67)	i. Batu Anam ii. Kangar iii. Holyrood-Lunas iv. Kulai-Yong Peng
3.	Unsuitable soils	Class III (1/3 = 0.33)	v. Rudua-Rusila vi. Keranji vii. Linau-Sedu

by calculated average data from all months and stations. A relationship is most reliable when its R-squared value is at or near 1 (Landau, 2004). SPSS (IBM, 2017) software was used to determine the best regressions between SS_{daily} as a dependent variable and the other meteorological data as independent variables to obtain equations for estimating sunshine, $SS_{estimation}$ (Landau and Everitt, 2004).

We found that $P_{monthly}$ had a larger influence ($R^2 = 0.72$) on daily sunshine hours, SS_{daily} (Fig. 4), than maximum air temperature ($R^2 = 0.58$), minimum air temperature ($R^2 = 0.06$) or mean air temperature ($R^2 = 0.41$) (Fig. 5). The Pearson correlation coefficient result for SS_{daily} and $P_{monthly}$ was -0.832, which is a strongly statistically significant negative linear relationship ($p < .001$ for a two-tailed test). The results shown in Table 2 indicate that the exponential relationship produced a higher R^2 compared to the linear regression. This finding highlighted that temperature is a not a good predictor for sunshine in tropical rainforest climates compared to results published by Abd el-wahed and Snyder (2015), where the authors found that mean air temperature was a reliable indicator in determining sunshine by using linear regression in an arid climate. However, this result supports Yang et al. (2009), who obtained a high correlation by estimating the monthly sunshine based on precipitation in northern China. We decided to proceed in calculating the estimated sunshine using precipitation as an input and in determining the exponential relationship as per the equation below:

$$SS_{daily} = 8.5582e^{-0.02P_{monthly}} \tag{10}$$

where P_{monthy} = Monthly mean of precipitation in mm.

We modified Eq. (10) to obtain the estimation sunshine, $SS_{estimation}$ in an average of total monthly sunshine in hours month $^{-1}$ and input precipitation, $P_{annually}$ in annual average of total precipitation, mm yr^{-1}. Then, the resulting equation for $SS_{estimation}$ was derived as:

$$SS_{estimation} = 260.3119e^{-0.00017P_{annually}} \tag{11}$$

where $P_{annually}$ = Annual mean precipitation in mm.

Fig. 6 shows the results of average estimated average total monthly sunshine of the selected regions for all periods using Eq. (11).

2.5. Girth (circumference of rubber trunk) as the key variable for analysis

The rubber tree is exploited commercially for its latex by a systematic excision of the external tissues of the trunk specifically known as bark. Latex is typically contained in tubes and cells can be found in all organs of the plant which are collectively known as laticifers or most researchers referred as ‘latex vessel’ (Bryce and Campbell, 1917). Among all the latex vessel system, the number of latex vessel rings continues to be the most important single property highly related to yield. Latex vessel density is higher in rings near the cambium than in those in the outer bark. The more rapid the growth, the greater the frequency with which latex vessel rings are initiated and hence the larger their number (Gomez, 1982). It is well-known vigorous rubber trees will produce better yield

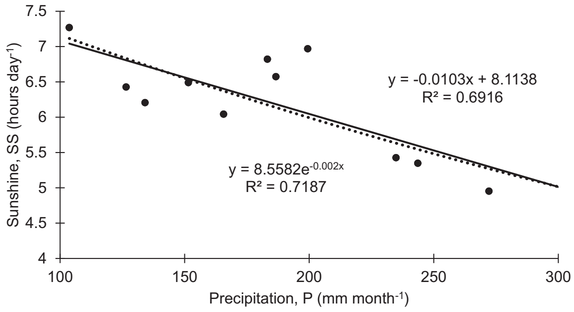


Fig. 4. The relationship between average daily sunshine and average monthly precipitation.

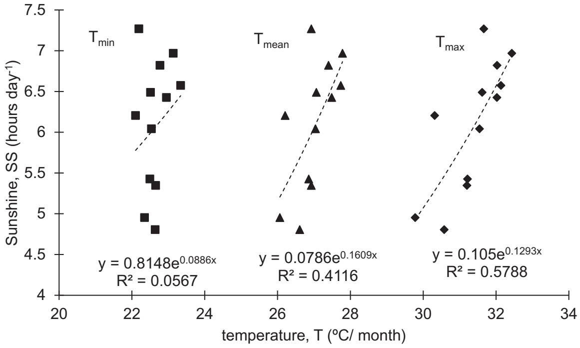


Fig. 5. The relationship between average daily sunshine and average monthly air temperature of a) minimum temperature, T_{min} b) mean temperature, T_{mean} and c) maximum temperature, T_{max}.

Table 2
Linear and exponential regression results.

Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Linear	0.692	22.429	1	10	0.001	8.114	−0.010
Exponential	0.719	25.544	1	10	0.000	8.558	−0.002

The independent variable is precipitation, $P_{monthly}$. The dependent Variable: Sunshine, SS_{daily}.

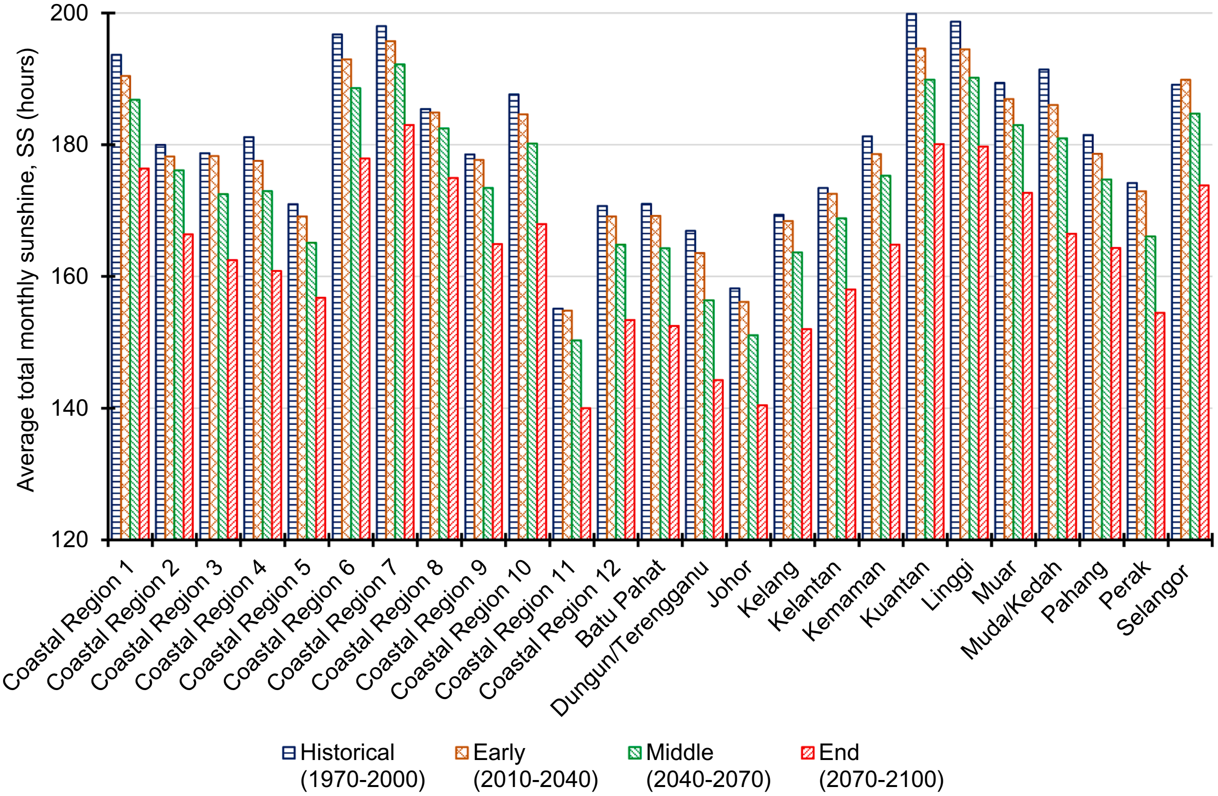


Fig. 6. Average estimated average total monthly sunshine of the selected regions for Historical (1970–2000), Early (2010–2040), Middle (2040–2070) and End (2070–2100).

regardless of any rubber clone. Bryce and Campbell (1917) demonstrated a positive correlation coefficient between the number of latex vessel rows and the thickness of the bark. Narayanan and Ho (1973) found to conform to a linear expression the relationship between yield and girth. The linear expression is related to some of the clonal characters. It is clear from the variations in the regression coefficients and intercepts that the linear relationship between yield and girth differs markedly between clones. Gomez (1982) also found that the constants of the linear expression are correlated with the total number of latex vessel rings, bark thickness and distance between consecutive latex vessel rings, but not with the density or diameter of either latex vessels or sieve-tubes. Mann et al. (1934) suggested there exists a very close relationship between the characters of girth, yield and the number of latex vessel rows. Growth can be measured in various parameters but girth or circumference measurement of the main trunk remains the most significant (Chandrasekhar et al., 2005). Girth and girth increment of trees are used in experimental work to assess the growth performance of new planting materials and the effects of cultural treatments on growth (Shorrocks et al., 1965). Practically, planters or smallholders are much easy to monitor girth rather than to count latex vessel ring.

Therefore, identifying when to start tapping or harvest the latex is a crucial decision. These trees are “tappable,” meaning that they are ready for latex collection by regular tapping of the tree bark (Vrignon-Brenas et al., 2019). The planters or smallholders wants to tap their rubber trees as soon as possible but yet the trees must be mature enough and will not affect their future growth (Gooding, 1952; Wycherley, 1976). Hunt (1983) and Vrignon-Brenas et al (2019) highlighted the aim is to start latex harvesting as early as possible with minimal retardation to optimize tree growth, particularly in girth. The immaturity period of rubber trees ranges from four to eight years before the conventional method of tapping is applied (Husin et al., 1986; Rayong, 2003; MRB, 2009). Thus, any reduction in immaturity period could bring early income. The effective approach to reduce immaturity period of rubber trees is by opening the trees for tapping at smaller girth. The earliest record to tap rubber tree using micro-puncture tapping system is when the girth reach 36 cm (Abraham, 1981, 1992; Kadir, 1988; Shiqiao et al., 2007). But then, premature tapping is limited by the effects on the long-term vigor of the tree and created new problem (Hunt, 1983; Xiao et al., 2003). Planters and smallholders still using conventional tapping system where the girth at least must 45 cm measured 170 cm height from ground or 150 cm from the bud union (Rayong, 2003; Chandrasekhar et al., 2005). Recent experience indicates that trees which have reached a girth of 43 cm and above can be brought into tapping, if required, with mild stimulation (Kadir, 1988). Gunasekara et al. (2007) studies showed that N, P, K, and Mg fertilization improved rubber tree growth and shortened the pre-harvest period. Basically, this immature phase ends when 50% of the trees in the plantation reach a girth of 50 cm measured 1 m above ground level (Vrignon-Brenas et al., 2019).

3. Result and discussion

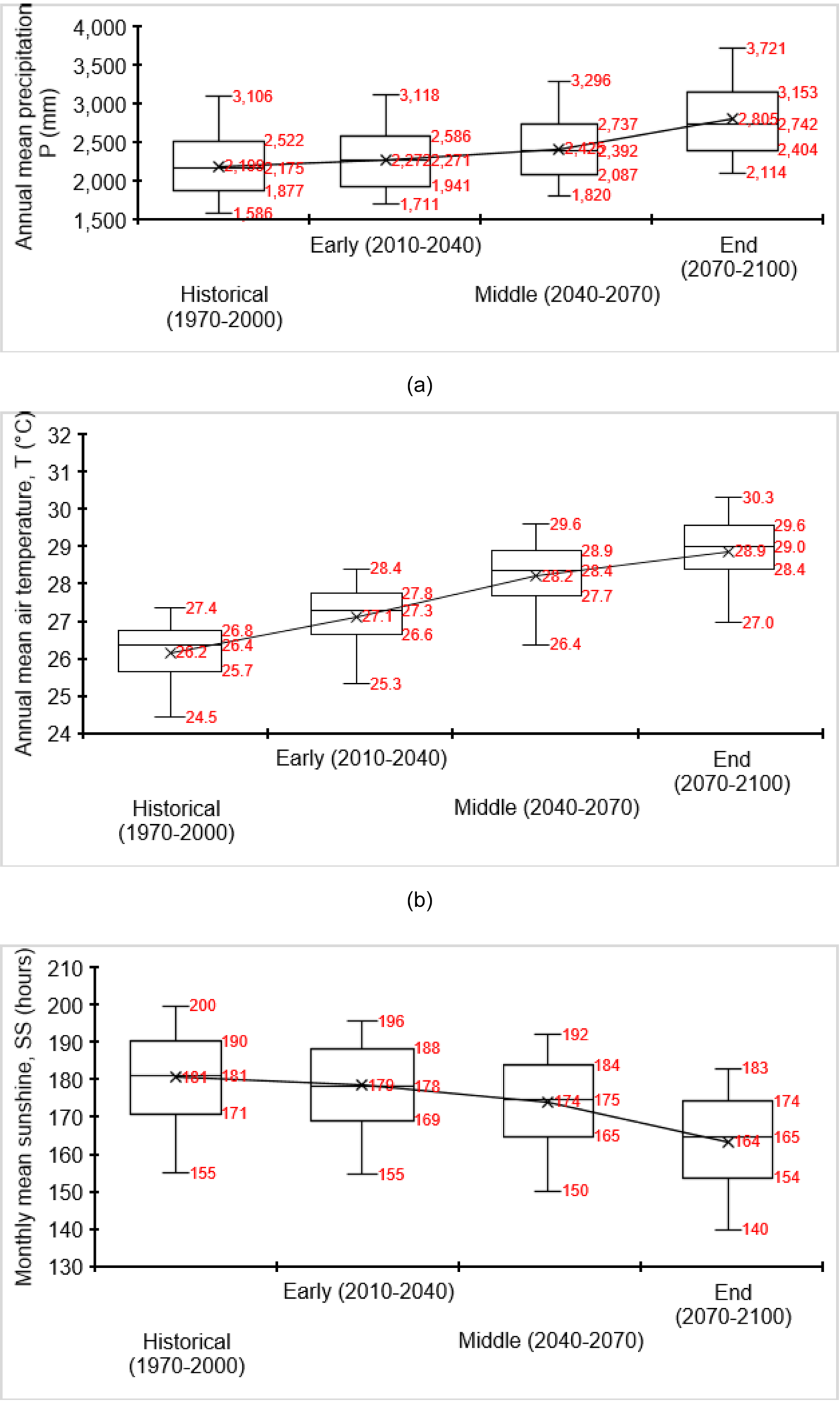
3.1. Precipitation, temperature and sunshine

Fig. 7 summarizes the climatic data of average annual precipitation, annual mean air temperature and average monthly sunshine of Peninsular Malaysia based on Historical (1970–2000), Early (2010–2040), Middle (2040–2070) and End (2070–2010) periods in the form of a boxplot. Visualization methods using boxplots enhance the understanding of sample data and help to make comparisons across data (Krzywinski and Altman, 2014). The parallel boxplots for the precipitation (Fig. 7(a)) illustrate growing trends along the cumulative years as the End period is predicted to have the most significant change among all periods, with a 27.6% increase compared to the Historical period. Peninsular Malaysia is estimated to experience a high mean air temperature in the future as shown in Fig. 7(b); the percent increases for the Early, Middle and End phases compared to Historical data are expected to be 3.4%, 7.6% and 10.3%, respectively. Meanwhile, in Fig. 7(c), sunshine, as we already expected, indicates a contradictory pattern as it has a negative relationship with precipitation. Peninsular Malaysia is predicted to encounter a 9.4% decrease in monthly hours of sunshine in the End period compared to the Historical period.

Site specific periodical changes of the Historical, Early, Middle and End phases for average annual precipitation, annual mean air temperature and average monthly sunshine across 25 regions in Peninsular Malaysia have been projected and presented in Supplementary material, Fig. A4. All regions indicate gradual increases in precipitation in the Early and Middle periods and then drastically escalations during the End period, except for Coastal Region 12 where the amount slightly drops by 1.3% during the Early period. The predicted increment for all regions varies by 17.1–45.4% during the End period. Dungun Terengganu, Coastal Region 1 and Coastal Region 2 are projected to receive and record higher precipitation amounts in the future. The average annual mean air temperature for Peninsular Malaysia may increase by 0.9–1.0 °C during the Early period, and then it may further increase to 1.9–2.3 °C during the Middle period and reach a peak to 2.5–3.0 °C during the End period. Coastal Region 8, Coastal Region 9 and Coastal Region 12 highlight the highest percentage of increases among the regions for the Early, Middle and End periods, respectively. The magnitudes of sunshine amounts are predicted to decrease near the end of the 21st century. All regions except Selangor show a declining pattern during the Early period; Selangor increases slightly at first by 0.4% but then follows the standard decrease trend. The other regions show a declines during the Early (−0,5% to −2.8%) and Middle (−1.6% to −6.3%) periods and then plummet during the End (−15.6% to −13.6%) period. Coastal Region 11 and Johor will be greatly impacted by lower sunshine amounts in each calculated period.

3.2. Climate index (CL) and soil index (Si)

The climate index, as a function of precipitation indices, temperature indices and soil indices, is successfully calculated using Eq. (6). The results in this study are quite interesting as they show that climate change impacts will alter conditions to become more favourable and more promising for rubber in tropical rainforest climates, especially in Peninsular Malaysia. Fig. 8 reveals the climate



(a)

(b)

(c)

(caption on next page)

Fig. 7. Boxplots of (a) annual mean precipitation, (b) annual mean temperature and (c) monthly mean sunshine based on Historical (1970–2000), Early (2010–2040), Middle (2040–2070) and End (2070–2100).

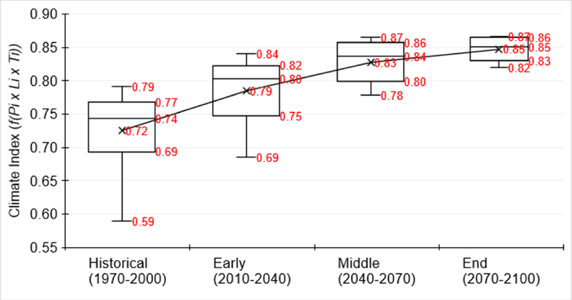


Fig. 8. Climate index data distribution during Historical (1970–2000), Early (2010–2040), Middle (2040–2070) and End (2070–2100) periods.

index data distribution during the Historical (1970–2000), Early (2010–2040), Middle (2040–2070) and End (2070–2100) periods in boxplot form. It also shows the improvement and narrowing of the range of climate suitability for rubber. The index value of 0–1 indicates the suitability of climate for planting rubber, as indices closer to 1 indicate a more favourable climate condition for rubber. The boxplot graph demonstrated the increment pattern for all studied periods. Among all periods, the End period is the most suitable climate condition to growing rubber, with a 18.1% enhancement in suitability from the Historical period across Peninsular Malaysia.

A Soil-Rubber Suitability map was successfully generated based on the soil series map that consists of 52 individual or combinations of soil series. The interaction between the climate index and soil index is translated into a suitability area for planting rubber map, otherwise known as a rubber agroclimatic map as shown in Fig. 9. We divided the suitability area to plant rubber into six classes. The indices below 0.3, or class 6, are considered as not truly suitable for planting rubber. The rubber growth estimation using Eq. (5) indicates that, after 30 years of planting rubber, the girth for a normal class 6 tree only reaches maximum of 48.8 cm and thus is still not ready to be tapped. Meanwhile, class 1 as an index value is more than 0.7, which is considered as the most suitable area to plant rubber. The estimated rubber growth for 30 years' lifespan of rubber in this class is more than 114 cm, and the yield will potentially be in an optimal state (Yahya, 2008). The rest of the classes ranged from 0.6 to 0.7 (class 6), 0.5–0.6 (class 5), 0.4–0.5 (class 4) and 0.4–0.3 (class 3).

3.3. Suitability area to cultivate rubber assessment and rubber growth performance estimations

A calculation of the total land area for each class from the suitable area to the plant rubber map in Peninsular Malaysia then was carried out. Fig. 10 shows the result of total land area for each class of the suitability land index for planting rubber in the 4 periods of Historical, Early, Middle and End. No changes in land area are predicted across all study periods for class 6 as this class also represents the largest area among all periods. The calculated land area for class 6 is 6,031,393.1 ha, or a cumulative 47.4% from the total land of 12,725,900.3 ha. During the Historical period, class 4 was the second major area including 2,088,843.6 ha or 16.4% from the available total land area. However, this class was projected to reduce by 14.4% during the Early period and then show a sharp decline during the Middle and End periods. The maximum rubber growth estimation for class 4 is approximately between 65.1 cm and 81.4 cm, which indicates the marginal conditions for planting rubber in this area.

The Class 1 rubber-suitability index is known as the best area to cultivate rubber stands and was the third largest land area during the Historical period. Class 1 is estimated to rise gradually during the Early (20.2%) and Middle (22.6%) periods and then remain constant until the End period. Class 3 (0.5–0.6) is recognized as a good category or area to plant rubber with an estimated potential rubber growth of 81.4–97.7 cm. This class performs very well as it rose gradually by up to 15.6% between the Historical and Early periods and then a sharp increase to 30% until the end of the Middle and End periods is projected. The second-best class indices range from 0.6 to 0.7 and an associated estimation of rubber growth of 97.7–114 cm is predicted to have a slight decrease from the Historical to Early period of 6.1–2.4% and then cease during Middle and End periods. Class 5 with the index of 0.3–0.4 only exists during the Historical period with a total land area of 453,841.9 ha. This class is less suitable for planting rubber as the growth is only borderline suitable between 48.8 cm and 65.1 cm.

The main question about the best location to plant rubber and how well rubber performs is answered in Fig. 11. Based on our observations, all areas in Peninsular Malaysia will experience an increase in the environmental suitability to cultivate rubber. We generalized the interaction of the soil and climate indices based on a site study of 25 regions. Then, by using Eq. (5), we assessed the rubber growth performance in each region. In this assessment, the Historical period is chosen as a benchmark and the estimated actual rubber growth (girth) for 30 years during this period is between 47.7 cm and 89.7 cm. The highest recorded region was Kelang, and the lowest girth was in Coastal Region 3. During the Early period, the increase in the estimated 30 years' rubber growth is predicted to be between 3.3% and 16.3% across Peninsular Malaysia. The highest estimated rubber growth is expected in Kelang at 94.5 cm, and the lowest girth will be in Coastal Region 3. This figure also shows a positive trend of estimated rubber growth during the Middle period as the range rose gradually between 5.8% and 31.8%. Perak region still holds as the highest increase in rubber

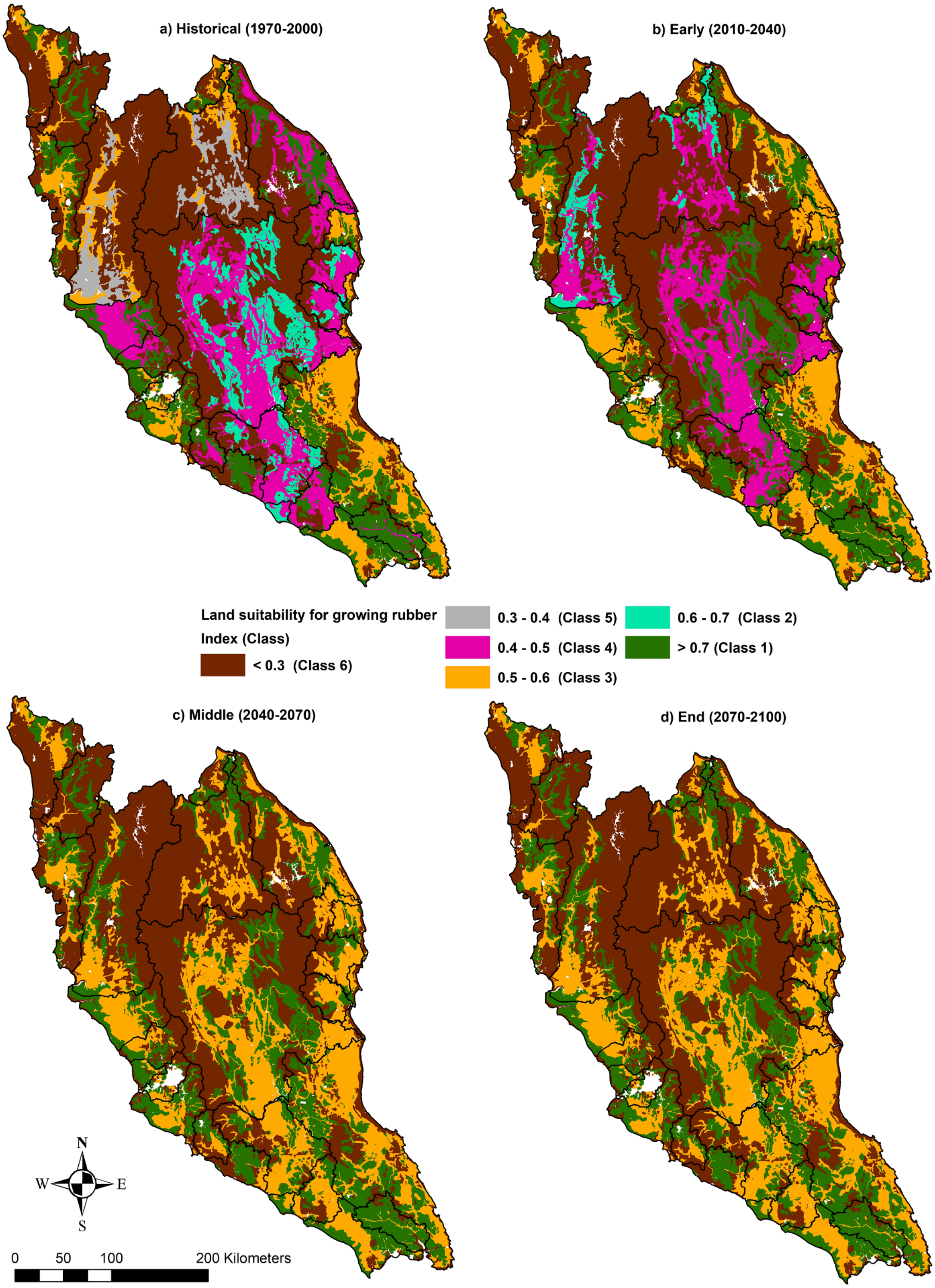


Fig. 9. Rubber agroclimatic map based on interaction of soil index and climate index of (a) Historical (1970–2000), (b) Early (2010–2040), (c) Middle (2040–2070) and (d) End (2070–2100) periods.

growth, but then Johor is identified the most suitable region during the Middle period because it has the highest girth of 97 cm. The highest increase during the End period is still expected in the Perak region while the lowest increase is located in Coastal Region 12. We can clearly identify the suitable areas to plant rubber from the graph. Johor, Muar, Kelang, Selangor, Batu Pahat, Kelantan,

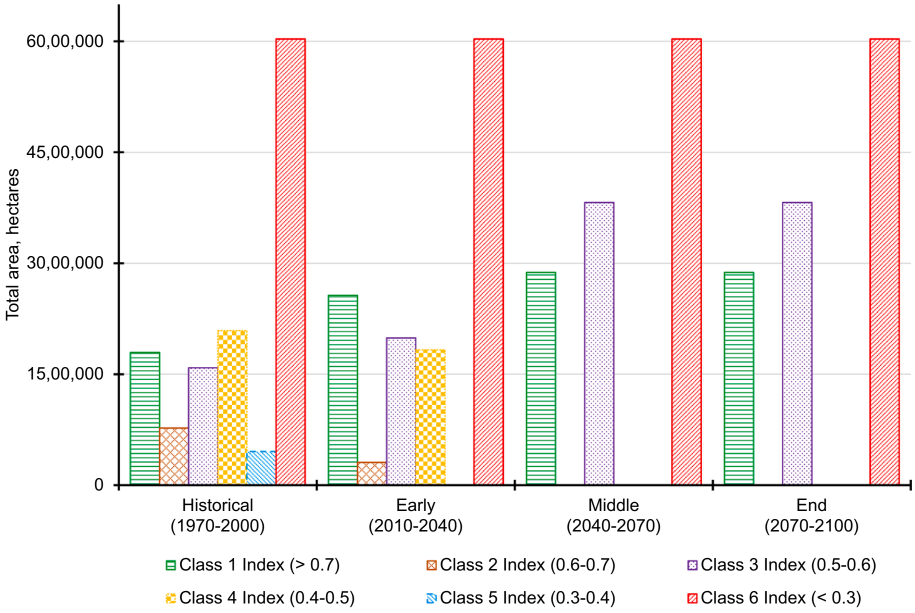


Fig. 10. Result of the total land area for each class of the suitability land index for planting rubber.

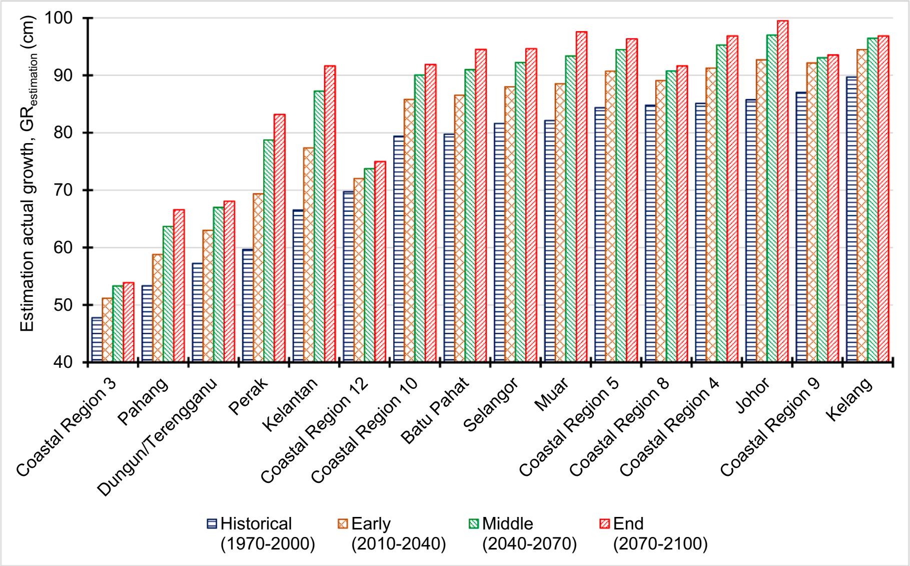


Fig. 11. Estimation of actual rubber growth performance for different period in different region.

Coastal Region 4, Coastal Region 5, Coastal Region 8, Costal Region 9 and Coastal Region 10 are estimated to perform well as their estimated rubber growths are more than 90 cm during the End period. Coastal Region 3, Dungun Terengganu and Pahang are shown to be unsuitable regions for planting rubber as their growth performances are lower all around for all periods. The rest of the regions are suitable, although the Historical and Early periods show lower growth performances for these regions as they then reach a peak at the Middle and End periods (Supplementary material, Fig. A6).

3.4. Evaluation of land suitability of existing planted rubber area in Peninsular Malaysia

The 2015 planted rubber area data was acquired from Malaysian Department of Agriculture. This data then overlay to the rubber agroclimatic map (Fig. 12). The total remaining planted rubber area in Peninsular Malaysia was approximately 963,101 ha. We assume there is no changes in existing planted rubber area across the study period. Our finding shows that, about 32% of present planted rubber area was in Class 6 suitability land to cultivate rubber. It is calculated approximately of 308,403 ha' rubber was planted at the most not suitable area to plant rubber based on the Historical period. The total rubber area in this class then predicted

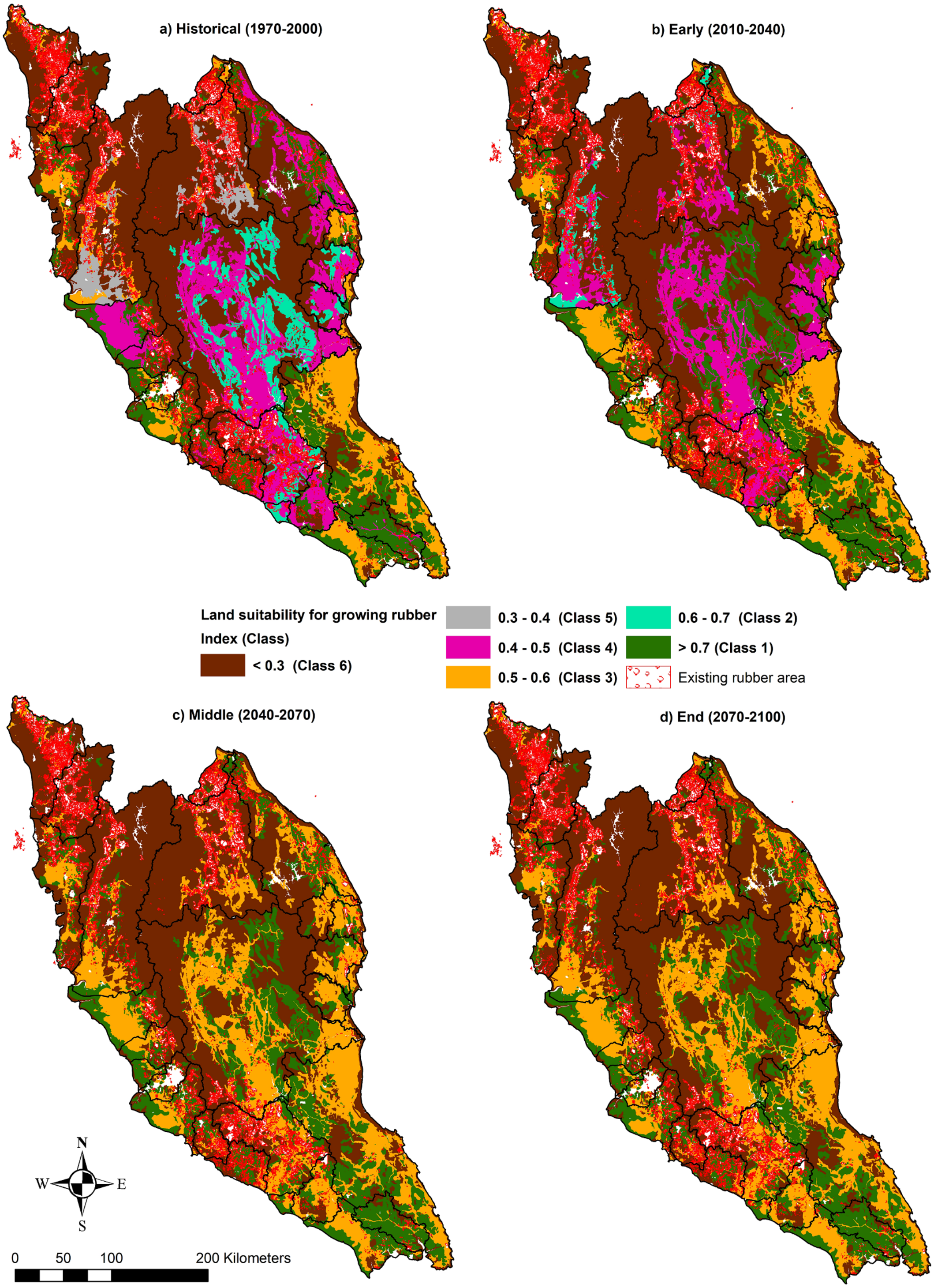


Fig. 12. Planted rubber area overlay to the rubber agroclimatic map of (a) Historical (1970–2000), (b) Early (2010–2040), (c) Middle (2040–2070) and (d) End (2070–2100) periods.

not to be changed in the future based on the result of Early, Middle and End periods. We suggested the land suitability to plant rubber at this area still the same in the future over the time because of low soil index suitability to growth rubber thus the land status still maintain in Class 6 to growth rubber. The consideration action must be taken at this region by replanting with the more suitable rubber clone or other valuable crops or do the remedial measures to upkeep the rubber production. The growing rubber region in Class 1 was calculated approximately of 212,066 ha during the Historical period. The amount then was increasing by 27% during

Table 3
Total planted rubber area based on land suitability class for growth rubber.

Land suitability class for growth rubber	Planted rubber area (Ha)			
	Historical (1970–2000)	Early (2010–2040)	Middle (2040–2070)	End (2070–2100)
Class 1	212066.2	256004.8	363804.0	363804.0
Class 2	43938.6	107799.2	–	–
Class 3	186199.1	115306.0	290893.6	290893.6
Class 4	135634.5	175587.6		–
Class 5	76859.1	–	–	–
Class 6	308403.5	308403.5	308403.5	308403.5
Total	963101.0	963101.0	963101.0	963101.0

Early period to 256,005 ha. Then it shows peak constantly to 363,804 ha during the Middle and End periods, respectively. This pattern indicates that agroclimatic condition become more favourable to growth rubber in the future as there are increasing pattern over the periods of Historical, Early and Middle. The same explanation for the Class 3 as it shows the same behaviour across the cumulative years. Total rubber area in Class 2 was calculated of 43,937 ha and 107,799 ha during Historical and Middle periods, respectively. There is no rubber growth region in Class 2 during Middle and End periods and it is suggested because of that area alter to the others class because of climate change effect. It has possibility to go up to the better class. The same trend goes for the Class 4 and Class 5. The details result of total planted rubber area for all land suitability class to plant rubber by different periods is explained in Table 3.

4. Conclusion

In conclusion, based on the static model results of *Hevea* Version 1.0, rubber can still be planted in Peninsular Malaysia into the future. Different climate change scenarios will alter the environment to be more favourable for cultivating rubber in future. We also conclude that the climate is a determinant factor for suitability to plant rubber and sustainability rubber growth in Peninsular Malaysia. Peninsular Malaysia is projected to experience a high mean air temperature, increases in precipitation and decrease in monthly hours of sunshine in future. Based on our results, all areas in Peninsular Malaysia will experience an increase in the environmental suitability to cultivate rubber. The highest estimated rubber growth is expected in Kelang and the lowest girth was in Coastal Region 3. We projected the suitable areas to plant rubber are Perak, Johor, Muar, Kelang, Selangor, Batu Pahat, Kelantan, Coastal Region 4, Coastal Region 5, Coastal Region 8, Costal Region 9 and Coastal Region 10 and estimated to perform well as their estimated rubber growths are more than 90 cm during the End period. Our study indicates that, about 32% of existing planted rubber area was in Class 6 of land suitability for growing rubber. It is calculated approximately of 303,498 ha' rubber was planted at lowest of land suitability to plant rubber. The tree productivity itself is lower than normal and additional of lower tapping days will drop the rubber production.

Although this study shows that climate change in the future will benefit rubber planting operations in tropical rainforest climates such as Peninsular Malaysia, the effects of extreme weather on rubber must be further explored (Hazir et al., 2018, 2019). Long dry spells, droughts and floods are common threats for any crops, including rubber. As a warning, the global climate change effect is predicted to increase dryness periods because of an associated predicted increase in warm days; indeed, droughts have become more common, especially in the tropics and sub-tropics since approximately 1970 (Hartmann et al., 2013). As mentioned by Cubasch et al. (2013), an extreme weather event is an event that is uncommon to a specific place and/or time of year and when a pattern of extreme weather persists for some time, such as a season, it may be then classified as an extreme climate. A local extreme weather occurrence period may not be seasonal as Peninsular Malaysia is close to the equator, but then it may still potentially damage the rubber tree ecosystem. Tan et al (2015) suggested that Malaysia's climate system is becoming wetter in wet season and drier in dry season. Hence the frequency and intensity of dynamic natural disasters such as floods and droughts are expected to increase. The adaptation of rubber may also differ because of the genotype and phenotypic plasticity of *Hevea brasiliensis*. This forest tree has become well adapted to plantation cultivation, unfavourable environmental conditions such as overheating of the soil surface, soil wash from the roots, and lack of water are inimical to growth, and may cause poor development or abnormal symptoms in young trees. Indeed, different climate projection if feed to the *Hevea* 1.0 model will produce significantly different result. Thus, site-specific research with real-time data collection is still needed to confirm the vulnerability to climate change of cultivated rubber in Peninsular Malaysia.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2019.100203.

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