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Rubber leaf fall phenomenon linked to increased temperature

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ABSTRACT

Understanding phenological responses of vegetation to temperature have become increasingly important as the global climate changes. We examined how changes in temperature may be associated with the occurrence of rubber leaf fall, a new phenomenon affecting many rubber (*Hevea brasiliensis*) plantations. Spatial and temporal characteristics of the start and end of the rubber season for six study areas from four major rubber-producing countries were investigated using satellite imagery and 10 years of surface temperature data from 2010 to 2019. These study areas were Palembang (1154 ha) in South Sumatra, Indonesia; Medan (2667 ha) in North Sumatra, Indonesia; Ratnapura (581 ha) in Sri Lanka; Johor (195 ha) in Malaysia; Kedah (803 ha) in Malaysia; and Tboung Khmum (2421 ha) in Cambodia. Our results showed that there was a significant upward trend in average mean temperature for Palembang, Medan, Ratnapura and Johor, and that these trends were associated with a statistically significant difference in rubber defoliation and refoliation events. This shift also coincides with the reported occurrence of Rubber Leaf Fall disease from these study areas. In contrast, no change in temperature trends or phenological shift was identified for the two other study areas, and the disease was not reported in these areas. Overall, warming resulted in delayed phenological timing in most locations. While additional research is required to exclude alternative explanations, there is a strong possibility that climate change is responsible for the emergence of the new Rubber Leaf Fall disease.

1. Introduction

The rubber tree (*Hevea brasiliensis*) is a perennial plant originating from the Amazon River basin in Brazil. During the 19th century, rubber trees were widely distributed and grown in Southeast Asian countries, making the region the world's largest producer of natural rubber (Ahrends et al., 2015; Priyadarshan, 2017). Today, smallholders account for more than 75% of the world's natural rubber production (Douangsavanh et al., 2008; Fox and Castella, 2013). More than 40,000 products, including tyres and medical equipment, are made from the latex harvested from rubber trees (Mooibroek and Cornish, 2006). Sustainable production of natural rubber is crucial to the livelihood of the smallholder growers and global economic development.

Natural rubber production is highly vulnerable and exposed to unpredictable weather events and disease outbreaks. For example, in Hainan Island, China, rubber trees are exposed to frequent typhoon disturbances and chilling injuries (Chen et al., 2012). In 2008, a cold snap killed over 2.6 million rubber trees in the area (D. Qi et al., 2016). In South and Central America, the South American leaf blight, caused by the fungus *Microcyclus ulei*, has resulted in severe losses (Guyot and Le Guen, 2018). It was the primary reason for cultivation failure during the mid-1930 s and the implementation of quarantine measures that have remained ever since (Furtado et al., 2019; Langford, 1945). Other diseases, for example, foliar diseases caused by the fungi *Corynespora* and *Oidium*, have resulted in up to 45% yield loss (Liyanage et al., 2016; Umoh and Fashoranti, 2018). In general, diseases in rubber are estimated to reduce yield by more than 25% (Yin et al., 2019).

A novel leaf disease outbreak, known as Rubber Leaf Fall, was recently detected throughout rubber plantations in the major production areas. This phenomenon is characterised by out-of-season leaf fall, beyond the normal 'wintering' which occurs annually in the dry season. North Sumatra reported the outbreak in 2016, while South Sumatra and Malaysia reported it in late 2017. Cameroon reported the outbreak in the following year, 2018. In 2019, Thailand, India and Sri Lanka also recorded an outbreak of what was considered the same leaf fall disease. Following that, Papua New Guinea and Vietnam reported an outbreak in 2021. Available estimates have shown that the outbreak has now affected thousands of hectares of rubber plantations in Indonesia

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(380,000 ha), Malaysia (5000 ha), Thailand (52,000 ha) and Sri Lanka (4000 ha) (Rubber Research Institute of Sri Lanka RRISL, 2020).

The canopy reduction from the dropping of leaves in these affected areas generally ranges from moderate to severe. The health of the rubber trees is severely affected, resulting in a substantial reduction in latex yield (Pinizzotto, S A Kadir et al., 2021a). In severely affected areas, the affected tree canopy density can be reduced up to 90% (Ismail and Gohet, 2020). As a result, growers eventually notice a marked reduction in tree health and latex yield (Pinizzotto, S A Kadir et al., 2021a). The affected areas currently have an estimated yield loss of between 15% and 50% (Ismail and Gohet, 2020; Pinizzotto, Kadir et al., 2021b). While the primary cause is unknown, rubber research institutions suspect multiple fungal infections of the leaves as a potential cause of concern. There have been reports that the causal agent of the current outbreak belongs to the fungus genus *Pestalotiopsis* (Nyaka Ngobisa et al., 2018) or *Neopestalotiopsis* (Pornsuriya et al., 2020), a group which are known as endophytes of rubber and other plants (Gazis and Chaverri, 2010), but not considered highly pathogenic.

An outbreak of disease results from the interaction between the host, the pathogen, and the environment, a concept known as the Disease Triangle (McNew, 1960; Scholthof, 2007). Unless there has been a change in the host or virulence of the pathogen, disease outbreaks may be associated with changes in the climate that weaken the host or favour the pathogen (Garrett et al., 2016). The pathogens reported to be associated with Rubber Leaf Fall, in addition to other foliar pathogens of rubber, have been present for many years throughout the world's rubber plantations. While it is possible that the virulence of the pathogens has suddenly changed, exploring this would be difficult as it requires access to viable pathogen cultures dating to the time when rubber was established. Likewise, although there are a range of rubber cultivars commercially propagated, given rubber trees typically take seven years to mature and there are mixtures of cultivars throughout the production areas, it is unlikely that significant changes in the hosts can account for Rubber Leaf Fall. Therefore, we explored the third side of the disease triangle by studying the weather of affected and unaffected rubber plantations through long-term monitoring of rubber phenology. As phenology is a key indicator of plant responses to climate (Bertin, 2008; Parmesan and Yohe, 2003; Root et al., 2003), analysing the relationship between rubber phenological responses and climatic factors may provide insights into understanding Rubber Leaf Fall.

Phenological studies in rubber have been primarily focused on foliage seasonality: the annual defoliation known as 'wintering' and subsequent refoliation. This is because latex production drop during these periods. Latex production requires an adequate supply of foliar photoassimilates (Silva et al., 2012) which cannot occur during periods of leaf loss. Previous studies have demonstrated that temperature plays a significant role in rubber phenology (Azizan et al., 2021; Liyanage et al., 2019; Zhai et al., 2017).

In this study, we used rubber phenology to inform disease management strategies, a method that is particularly effective for foliar diseases (Guyot and Le Guen, 2018; Rivano et al., 2016; Vanegas-Gutiérrez et al., 2020; Zhai et al., 2017). Most plants, including rubber, may become more susceptible to disease during the developmental stage (Develey-Rivière and Galiana, 2007). This study investigated how temperature may be associated with the recent rubber leaf fall disease by examining the shift of rubber phenological events at six study areas in four major rubber producing countries. Four of these study areas had experienced Rubber Leaf Fall, while the phenomenon has not been reported for the other two areas. Using remote sensing data of mature rubber tree plantations, seasonality was modelled to determine interannual rubber phenological events over a ten-year period. This was then compared to the corresponding ten-year temperature data. This assessment enabled us to determine if temperature has changed over time and to detect any possible abrupt changes in the phenology. Finally, we evaluated the influence of temperature on the rubber phenology at each study area. This study provides an excellent opportunity to advance our understanding of rubber phenological response to climate change and inform the ongoing effort against the current Rubber Leaf Fall outbreak.

2. Methodology

2.1. Study area

Six plantations were selected as study areas in four major rubber-producing countries: Indonesia, Malaysia, Cambodia and Sri Lanka. Two study areas were located in both Malaysia and Indonesia, while Cambodia and Sri Lanka had one study area each (Table 1). The study area selection criteria were the rubber tree age, plantation size, cloud cover, and satellite and ground data availability. Out of six study areas, four reported an outbreak of novel Rubber Leaf Fall, while the other two did not have an outbreak based on ground information data for the study period. The locations of these study areas are presented in Fig. 1. The study areas were carefully chosen to ensure there were only rubber trees, making them homogeneous to avoid mixed pixel effects when using satellite images.

The six selected study areas are located within 12° of the equator and have a tropical climate that generally experiences hot and humid conditions all year round. Table 1 shows the geographical data of the study areas and their climatic parameters using the nearest respective weather station.

2.2. Method overview

The overview flowchart of our method is presented in Fig. 2. The flowchart is divided into five sections: (1) input; (2) processing; (3) output; (4) data analysis and statistics; and (5) research objectives. We used phenological data and temperature as the two primary inputs. The processing of the data is explained in detail in the following subsections. All the primary analyses conducted in this study are introduced in the data analysis and statistics subsection.

2.3. Phenological data

We used time-series satellite data to analyse the phenological events in the study area. The details of satellite data selection, pre-processing, composite and development of NDVI time series are discussed in subsection 2.3.1. Subsection 2.3.2 explain the derivation process of two rubber phenological events; the start of season (SOS) and the end of season (EOS) from the NDVI time-series data. The overall flow of the processes involved adopts the method established by Azizan et al. (2021).

2.3.1. Satellite data

This study used multi-series satellite data from the Moderate Resolution Imaging Spectrometer (MODIS). We retrieved two image datasets from MODIS instruments on-board the Terra and Aqua satellites over a 10-year period from 2010 to 2019. The extracted image datasets from the two sensors were used to derive the primary dataset for the phenological metrics. The data downloaded are 8-day composite data of surface reflectance, 250 m spatial resolution, and corrected for atmospheric effects. This dataset consists of two bands; red (0.620–0.670 μm) and near-infrared (0.841–0.876 μm). After preprocessing, these two datasets were combined using maximum value composite (MVC) to cater for the missing data. The missing data resulted from the frequent presence of clouds in the study areas due to the tropical climate. Three software, namely ArcGIS 10.7.1, ENVI 5.5 and R 4.0.2, were used to perform the preprocessing steps. Table 2 summarises the details of the image datasets used in this study based on the location of the study areas.

From the MVC layer, we computed the normalised difference vegetation index (NDVI) based on the red and near-infrared bands (Rouse et al., 1973). Previous phenological studies using remote sensing data had effectively utilised NDVI in their analysis (Pan et al., 2015; Wu et al.,

Table 1
Geographical and climatic parameters of study areas.

Parameters	Medan, Indonesia	Palembang, Indonesia	Johor, Malaysia	Kedah, Malaysia	Ratnapura, Sri Lanka	Tboung Khmum, Cambodia
Plantation area (ha)	2667	1154	195	803	581	2421
Number of rubber clones planted	8	> 200	62	9	10	10
Latitude	3.1904°	-2.9496°	1.7833°	6.0633°	6.7100°	11.9523°
Longitude	99.2480°	104.5171°	103.9224°	100.6276°	80.2215°	105.6122°
Average Altitude (m)	62	31	37	68	102	77
Annual mean temperature (°C)	27.1	27.3	27.9	27.0	27.0	27.5
Annual sunshine hour (hour)	1587	1677	2030	2455	2615	2650
Annual rainfall (mm)	2263	2623	2160	2375	2500	1000
Rainy season	August – December	October – March	March – December	April – December	April – December	May – November
Dry season	January – July	April – September	January – February	January – March	January – March	December – April

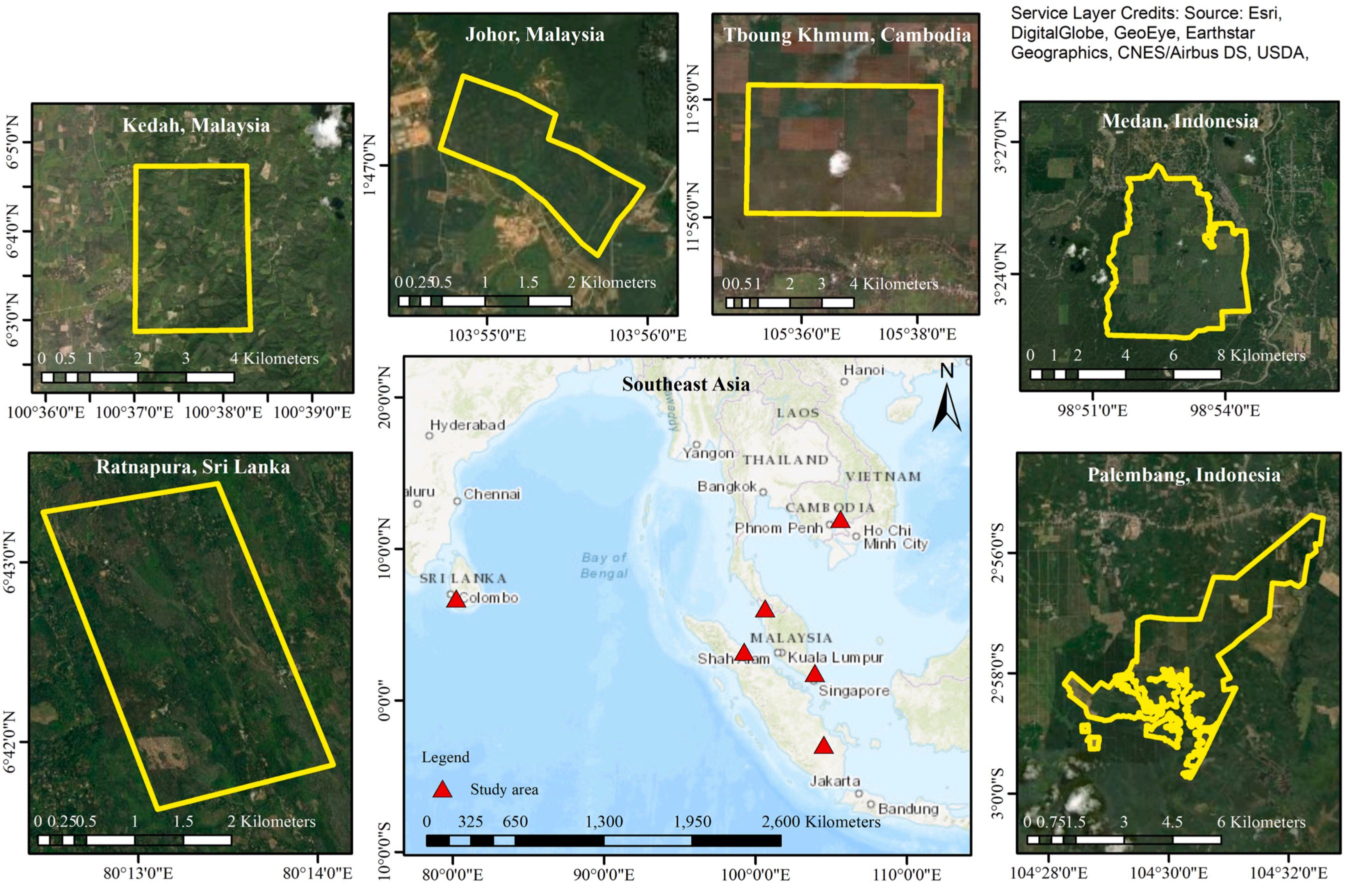

Fig. 1. The geographical location of the six rubber plantations analysed in this study.

2017). The vegetation index has also demonstrated an ability to reflect the greenness and health status of the vegetation (El-Gammal et al., 2014; Ozyavuz et al., 2015). In this study, we utilised the NDVI to study the phenology of rubber, particularly during the defoliation and refoliation phases.

2.3.2. *Phenological metrics*

Using the NDVI time series for each study area, we modelled the rubber seasonality using TIMESAT, a free software package designed to analyse satellite time-series seasonality to monitor the vegetation (Eklundh and Jönsson, 2015). TIMESAT has been widely used as a tool for phenology parameter extraction (Benzouaï et al., 2020; Diem et al., 2021; Pang et al., 2021; Qi et al., 2021; Stanimirova et al., 2019; Sun et al., 2021).

In TIMESAT, we applied the Asymmetric Gaussian smoothing technique to the NDVI time series before extracting the rubber phenological metrics. The smoothing filtered out the noise and removed spikes mainly due to atmospheric disturbances (Ghosh and Mishra, 2017) while preserving the seasonal curve (Ulsig et al., 2017). We selected the Asymmetric Gaussian smoothing method for the analysis because it is less sensitive to missing data and noise than the other smoothing methods available (B. Tan et al., 2011). Seasonal phenological metrics were extracted from the NDVI time-series at pixel-wise level whenever TIMESAT recognised an entire season. This study extracted the two most critical phenological metrics: (1) start of the season (SOS) and (2) end of the season (EOS). The SOS marks the start of the rubber season, which refers to the refoliation of rubber trees, and it is a period when the NDVI values begin to rise significantly. In contrast, the EOS marks the rubber

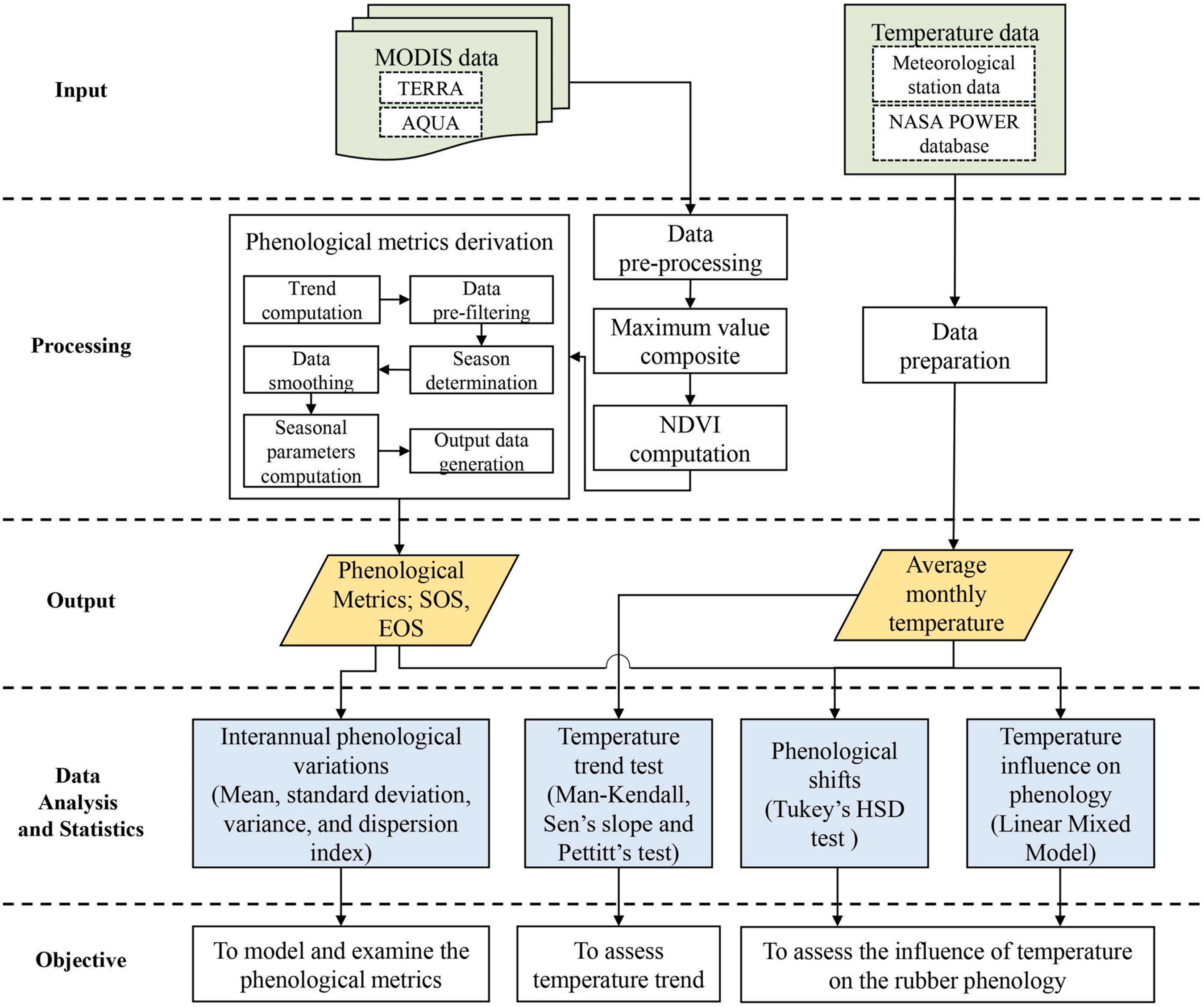

Fig. 2. Research methodology flowchart.

Table 2
Information on the image datasets used for each study area.

Study area	MODIS Platforms	Products	Tile Number	Timeframe	Number of images
Palembang	Terra	MOD09Q1	h28v9	2010–2019	460
	Aqua	MYD09Q1			460
Medan	Terra	MOD09Q1	h27v8	2010–2019	460
	Aqua	MYD09Q1			460
Tboung Khmum	Terra	MOD09Q1	h28v7	2010–2019	460
	Aqua	MYD09Q1			460
Ratnapura	Terra	MOD09Q1	h25v8	2010–2019	460
	Aqua	MYD09Q1			460
Johor	Terra	MOD09Q1	h28v8	2010–2019	460
	Aqua	MYD09Q1			460
Kedah	Terra	MOD09Q1	h28v8	2010–2019	460
	Aqua	MYD09Q1			460

season's end when rubber trees start to defoliate, with NDVI values dropping significantly. This characteristic is unique to rubber compared to other plantation crops, where mature rubber trees above five years of age experience annual wintering.

These two phenological metrics were determined by the thresholds of seasonal amplitude in TIMESAT (Stanimirova et al., 2019). Both the SOS and EOS values are used to define phenological profiles and to interpret the results (Schwieder, 2018). Furthermore, these measurements also demonstrate a link between the NDVI and rubber phenology, with NDVI values reflecting canopy cover of rubber plantations in the study. Overall, TIMESAT generated the SOS and EOS values of nine rubber growing seasons from the 460 NDVI input values for each pixel at each study area.

2.4. Temperature data

This study used 10-years of surface temperature data from 2010 to 2019 to study the changes in temperature trends. Two climate data sources were selected: available meteorological stations and online agro-climate archive data. The online climate data were obtained from the NASA Langley Research Center (LaRC) POWER Project. The database provides daily meteorological information globally at 1 ° latitude by 1° longitude grid (Aboelkhair et al., 2019; Negm et al., 2018) and has been compared favourably with local weather station data (Monteiro et al., 2018; White et al., 2011).

We used the available in situ meteorological station data for the Palembang study area. For the other study areas, where the meteorological station was located far away from the study areas or where data was not accessible, the temperature data were obtained from the NASA POWER database. All the data downloaded were at daily intervals. We prepared the average monthly temperature to evaluate temperature trends over a decade. We used monthly temperature instead of mean annual temperature because it is more effective in determining the timing of the phenological events (Fu et al., 2014). In addition, we computed the 90-day average daily temperature as an input in developing the model to estimate the timing of phenological events. The 90-day period before the start and end of rubber phenology was used in the analysis. It is a critical preseason period that influences plant phenology, as reported by several studies (Cho et al., 2017; Ren et al., 2017).

2.5. Data analysis and statistics

We conducted a trend analysis of the temperature data for the period under study to identify and assess any significant trends and changes. The Mann-Kendall test (Kendall, 1948)was used to detect and assess the significance of monotonic trends in the time-series data, while the Theil-Sen test (Sen, 1968; Theil, 1950) was used to estimate the slope. When a significant monotonic trend was detected, we conducted a Pettitt change point test to detect a shift in the central tendency of the time-series temperature data (Pettitt, 1979). The results provide critical information when an abrupt change has occurred. The interannual SOS and EOS values extracted at each pixel from TIMESAT were used to calculate the seasonal mean. We computed the overall mean, standard deviation, variance, and dispersion index for each phenological metric using the seasonal mean derived from each study area. We then calculated the length of the season (LOS) as the difference between the overall SOS and EOS. The 10-year seasonal means were plotted for each phenological metric of the study areas. We assessed and discussed any substantial advance or delay for values recorded more than one standard deviation for each study area.

To understand how temperature changes have affected the phenology of the rubber trees in the study areas, we divided the SOS and EOS into two periods; before and after the change-point. These two periods were selected based on the Pettitt change point test results (Das, 2019; Rahmani et al., 2015; Yang and Tian, 2009). In our study, the period before the abrupt change refers to the growing season of 2010/11–2014/15. On the other hand, the period after the abrupt change refers to the growing season of 2015/16–2018/19. The division was conducted to observe the effect of temperature on rubber phenology before and after the abrupt change. From this point onwards, we refer to these periods as P1 (before the change-point) and P2 (after the change-point). We then used the boxplots to represent the phenological distribution data corresponding to the P1 and P2 before performing the Tukey's honestly significant difference (HSD) test (Abdi and Williams, 2010). This test determines the significance of differences between the means values of these two periods. It is hypothesised that any shift in the rubber phenology will produce significant results.

In order to investigate the influence of temperature on the selected rubber phenological metrics (SOS and EOS), a linear mixed-effects (LME) model (Pinheiro and Bates, 2000) was fitted using the lmer function in the lme4 package (Bates et al., 2015). In the LME model, the predictor variables preseason temperature corresponds to the fixed effects, and the pixels correspond to the random effects. The random effect of the pixels in the model enables us to account for inter-pixel variations. The two predictor variables were used to estimate the SOS and EOS models. For all the LME model analyses, the assumptions of a mixed model, such as homogeneity of variance, normality of error, and linearity, were evaluated. The final model is the most parsimonious model, selected based on the Akaike Information Criterion (AIC) and validated by plotting model residuals.

All the data processing and statistical analyses, except where mentioned, were performed in the R statistical software (R Core Team 2013). The related packages used in R were obtained from The Comprehensive R Archive Network (http://cran.r-prject.org).

3. Results

3.1. Phenological characterisation

Table 3 summarises the overall mean for the SOS and EOS phenological metrics, standard deviation, variance, and dispersion index. These variables are presented in day of year (DOY), except for the dispersion index, which is dimensionless and length of season (LOS), which is presented as number of days. Based on the overall mean of the SOS, Tboung Khmum experienced an early SOS around DOY 60, followed by Johor (DOY 70), Kedah (DOY 74), Ratnapura (DOY 76), and Medan (DOY 78). The overall mean of the EOS for Tboung Khmum, Johor, Medan, Kedah, and Ratnapura is at DOY 30, 36, 39, 44, and 48, respectively. The overall mean of the SOS and EOS in Palembang are in DOY 230 (18 August) and DOY 183 (2 July), respectively. Amongst all the study areas, Medan had the lowest standard deviation, variance, and dispersion index for SOS. While for the EOS, Tboung Khmum recorded the lowest standard deviation and variance. In most cases, the dispersion index of EOS is higher than SOS. The overall mean for the LOS ranged between 318 and 344 days, and the average LOS for the study areas was 332 days.

The seasonal mean of the SOS and EOS of each study area is presented in Fig. 3. There were substantial (> one standard deviation) advances and delays in the SOS and EOS in several seasons in the study areas. There was an advanced SOS for the year 2011/12 at Ratnapura by 33 days and 2016/17 at Palembang by 20 days, and delayed SOS for the year 2016/17 at Ratnapura and Kedah by 44 and 26 days, respectively. In the case of EOS, it was advanced in 2010/11 at Medan (16 days) and at Ratnapura (24 days), in 2011/12 at Medan (11 days) and Johor (39 days), and in 2013/14 at Ratnapura (24 days). The EOS was delayed in 2012/13 at Ratnapura (29 days), in 2015/16 at Tboung Khmum (20 days) and in 2018/19 at Kedah (51 days). We linked the observed advances and delays to the preseason temperature data, literature, and past plantation records to understand and address the possible reasons for these incidents.

3.2. Temperature trend

The 10-year average monthly temperature data of the study areas showed variation in the temperature range. Fig. 4 shows the average monthly temperature time series and the linear trend for all the study areas. Tboung Khmum recorded the highest fluctuation in the data, ranging from 25 ºC to 33 ºC. On the other hand, the temperature in Medan had the lowest range among all the study areas, ranging from 23 ºC to 25 ºC. Other study areas fall in the moderate temperature range between 24 ºC and 28 ºC.

Table 4 presents the Man-Kendall, Sen's slope and Pettitt change point test results for all the study areas. The Man-Kendall test reveals significant monotonic trends for the average monthly temperatures data at four study areas; Palembang, Medan, Ratnapura and Johor. These study areas have an increasing temperature trend, with Sen's slope between 0.00296 and 0.00781. Based on the Sen's slope values, there was an average monthly temperature increase of 0.008 °C, 0.003 °C, 0.005 °C, and 0.004 °C for Palembang, Medan, Ratnapura and Johor, respectively. However, no significant trend was detected in the average monthly temperature data in Tboung Khmum and Kedah.

The Pettitt change point test conducted on temperature data from Palembang, Medan, Ratnapura and Johor showed several abrupt changes between March 2014 and February 2015. Fig. 5 illustrates the four change-points detected in four study areas' temperature data with significant monotonic trends, and it also depicts the two periods (P1 and P2).

Table 3
The overall mean, standard deviation, variance and dispersion index of the SOS and EOS for the study areas. All values in units of day-of-year (DOY).

	SOS				EOS				LOS
Sites	Overall mean	Standard deviation	Variance	Dispersion Index	Overall mean	Standard deviation	Variance	Dispersion Index	Overall mean
Palembang	230	13.21	174.58	0.76	183	12.84	164.91	0.90	318
Medan	78	4.50	20.27	0.26	37	10.77	116.01	3.15	324
Tboung Khmum	60	9.52	90.63	1.51	30	9.16	83.89	2.83	334
Ratnapura	76	26.94	725.68	9.56	44	18.53	343.40	7.85	333
Johor	70	10.95	119.87	1.72	49	20.34	413.73	8.45	344
Kedah	74	12.31	151.47	2.06	51	21.96	482.10	9.41	343

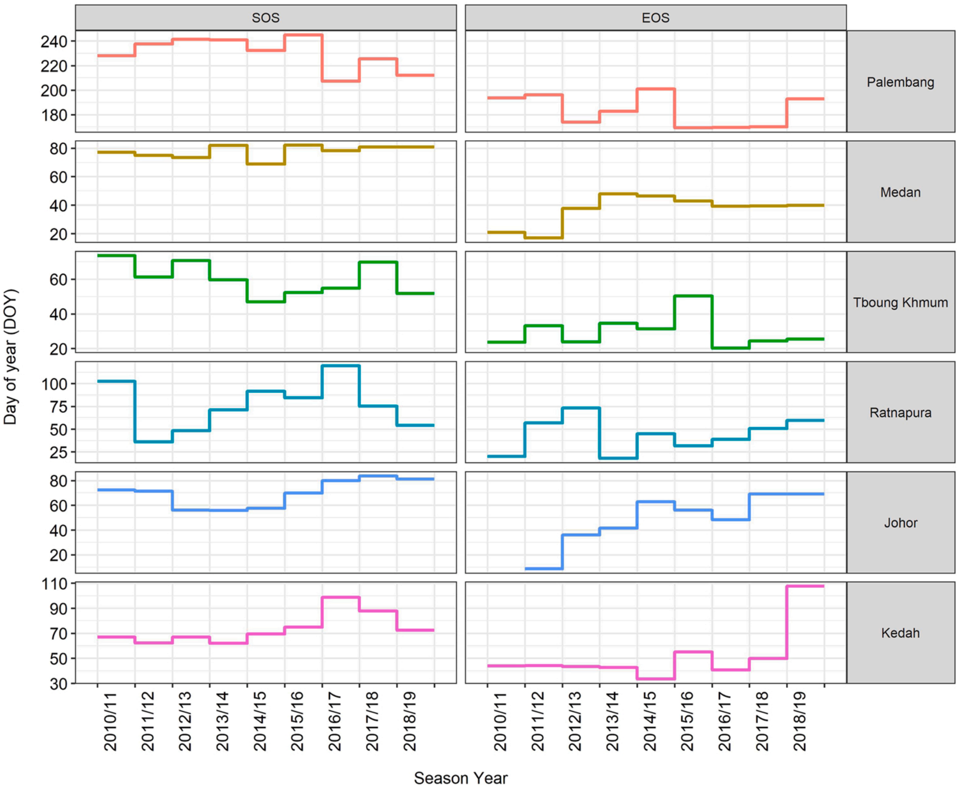

Fig. 3. The interannual variations of SOS and EOS based on average values of each seasonal year for all study areas. Numbers in the bracket represent the overall mean of the study areas' SOS and EOS of all growing seasons. The x-axis represents the growing season. For example, 2010/11 is the growing period from 2010 to 2011.

3.3. Phenological response to abrupt change

We used data from the P1 period as a basis for comparison with the P2 period to evaluate any significant changes in the SOS and EOS after the abrupt change. The boxplots in Fig. 6 show the distribution of the phenological metrics for the P1 and P2 period for all the study areas. Based on the Tukey's HSD results, with a p-value less than 0.05, significant differences between the P1 and P2 period were observed in Palembang, Medan, Ratnapura and Johor (Table S1). Both the SOS and EOS showed similar results. On the other hand, results from two study areas (Tboung Khmum and Kedah) did not significantly differ between the two periods.

3.4. Relative influence of temperature on the SOS/EOS

The LME models in Figs. 7 and 8 illustrate the relationship between temperature and the phenological metrics, SOS and EOS. The best model for the SOS and EOS for all the study areas was the random intercept mixed models (with fixed slope) chosen based on the lowest AIC value. It was determined that the DOY for the SOS and EOS increased with a rise in temperature for all the study areas, except in Palembang. The results indicate that an increase in temperature causes a delay in the SOS and EOS. All the final pixels from the six study areas used in this analysis show a consistent trend, although some study areas may have more pixels (i.e. Medan and Tboung Khmum) than others (i.e. Ratnapura and Johor).

Table 5 summarises the resulting model equations for the SOS and EOS of all the study areas. The models for all study areas were significant at a p-value less than 0.05 except for Ratnapura. All the study areas except Palembang have a positive temperature coefficient, ranging between 1.39 and 31.99. Generally, the positive temperature coefficient suggests that an increase in temperature delays the SOS/EOS dates. For instance, for Tboung Khmum, a one degree Celsius increase in temperature delayed the SOS and EOS by approximately 1.39 and 2.77 days, respectively.

4. Discussion

Our study has demonstrated the robustness of remote sensing methods to study rubber phenology. All of study areas in our research

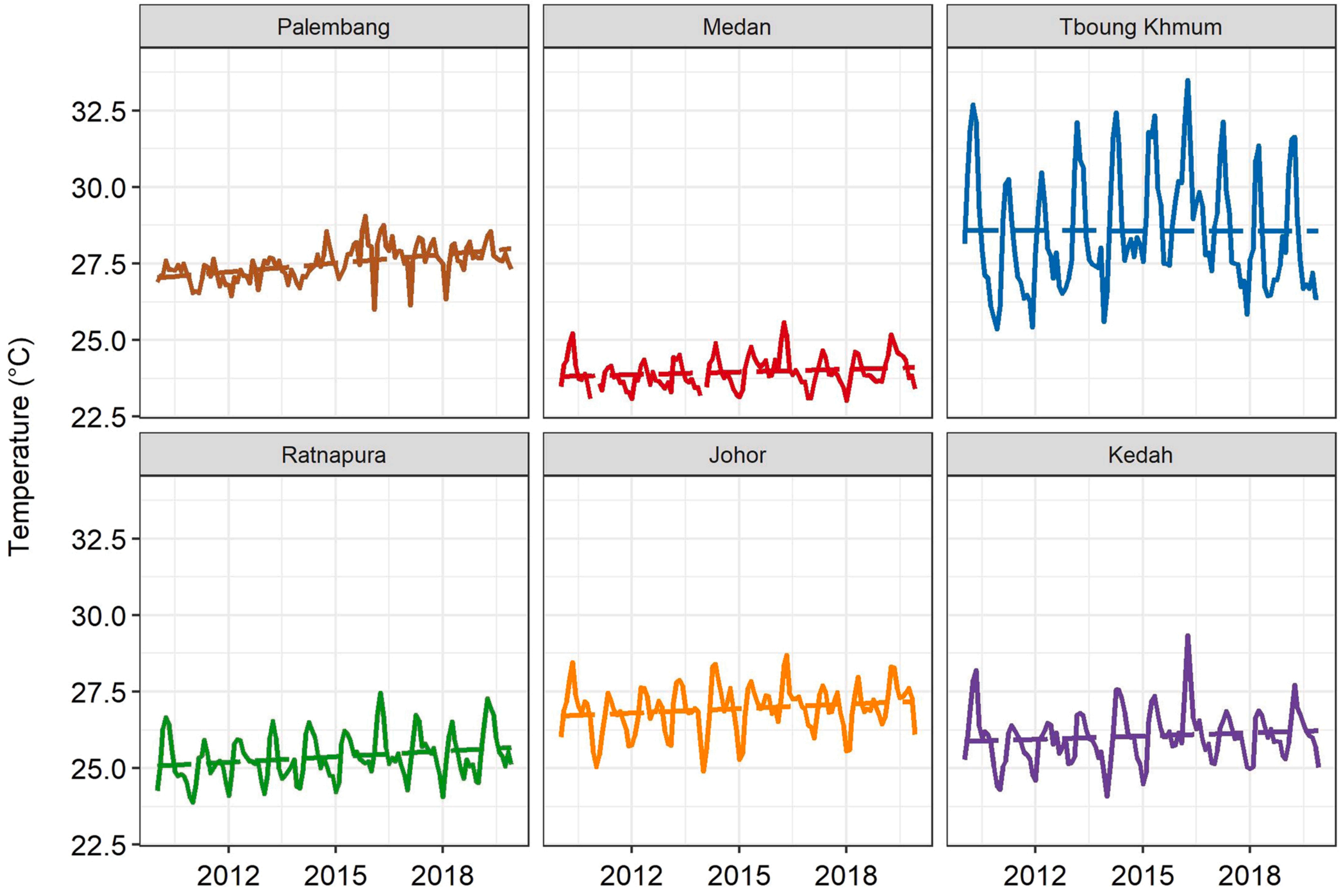

Fig. 4. 10-year average monthly temperature and the linear trend for all study areas.

Table 4
Man-Kendall, Sen's slope and Pettitt change point test result for all study areas.

Study area	Man-Kendall's p-value	Sen's slope value	Pettitt change point test result
Palembang	0.0000 * *	0.00781	t = 54 (June 2014)
Medan	0.0251 * *	0.00296	t = 62 (February 2015)
Tboung Khmum	0.8117	-0.00106	-
Ratnapura	0.0148 * *	0.00465	t = 62 (February 2015)
Johor	0.0555[a]	0.00347	t = 51 (March 2014)
Kedah	0.2064	0.00257	-

[a] statistically significant at $p < 0.1$, and * *statistically significant at $p < 0.05$

are situated near the equator, where the climate is ideal for the growth of rubber trees. The geographical locations of the rubber plantations influence the timing of the phenology. The locations determine the seasons, and we know that rubber wintering is associated with the dry season (Mohd Hazir et al., 2018; Verheye, 2010). Of the six study areas, we analysed only Palembang is located in the southern hemisphere, thus causing the SOS and EOS to be later in the Julian calendar, around July and August.

In contrast, the rest of the study areas are in the northern hemisphere and have the SOS and EOS between January and March. Priyadarshan (2017) has observed that the timing of rubber phenological events is affected by the latitudinal position of plantations. Plantations north of the equator have different rubber phenological timing than south of the equator. All the overall SOS and EOS values fall within the corresponding locations' dry season, verified from the phenological metrics of SOS and EOS extracted from the remote sensing data.

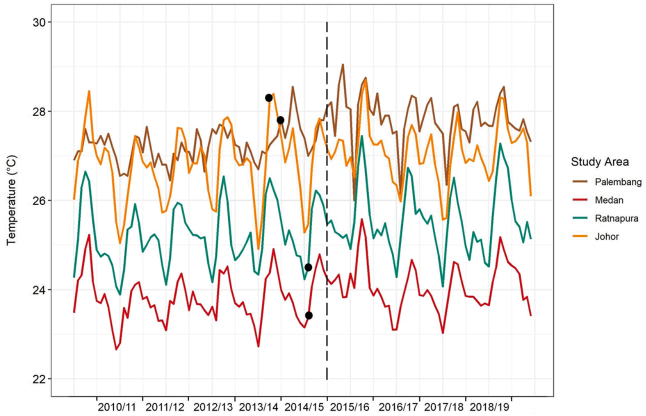

Fig. 5. The change-points in temperature trend of four study areas. The black coloured circle indicate the change-point. The x-axis represents the growing season, for example 2010/11 is the growing period from 2010 to 2011.

It has previously been demonstrated that remote sensing phenological metrics are highly correlated with ground data (Liang et al., 2011; Rodriguez-Galiano et al., 2015). Azizan et al. (2021) have also demonstrated the close alignment of phenological metrics data derived from MODIS data to higher spatial resolution data (Sentinel-2B) when no ground data is available for validation. In this study, using linear mixed-effects (LME) models, we found that the start of season (SOS) and end of season (EOS) timing of all study areas corresponded to reported ground data. It was also found that wintering occurs later for plantations located further north. The estimated average length of season (LOS),

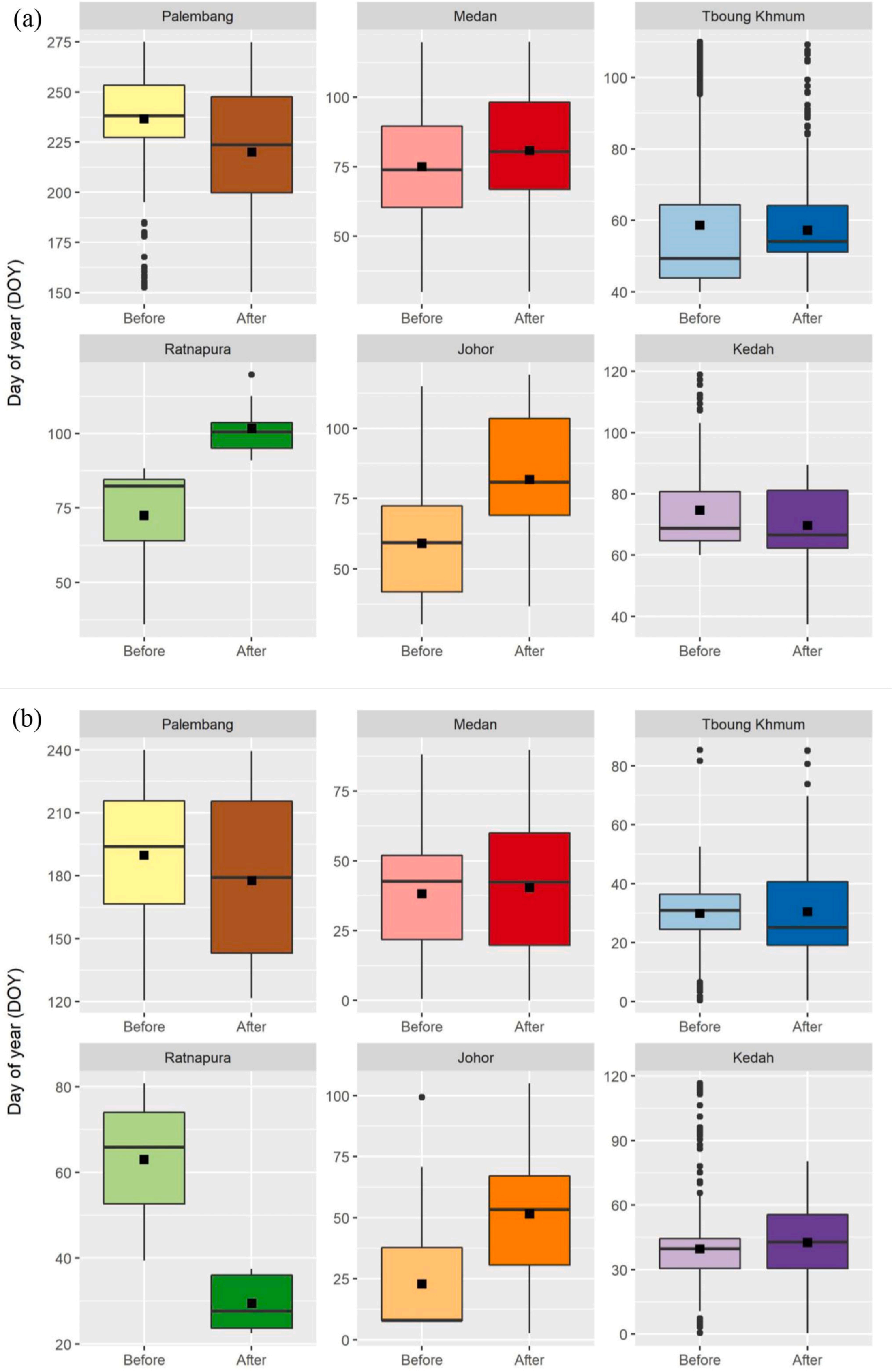

Fig. 6. Boxplots of the (a)SOS and (b)EOS for P1(before the change-point) and P2 (after the change-point) for all the study areas. The bold black square around the boxplot indicates the study area with statistically significant Tukey's HSD test results at a p-value of 0.05.

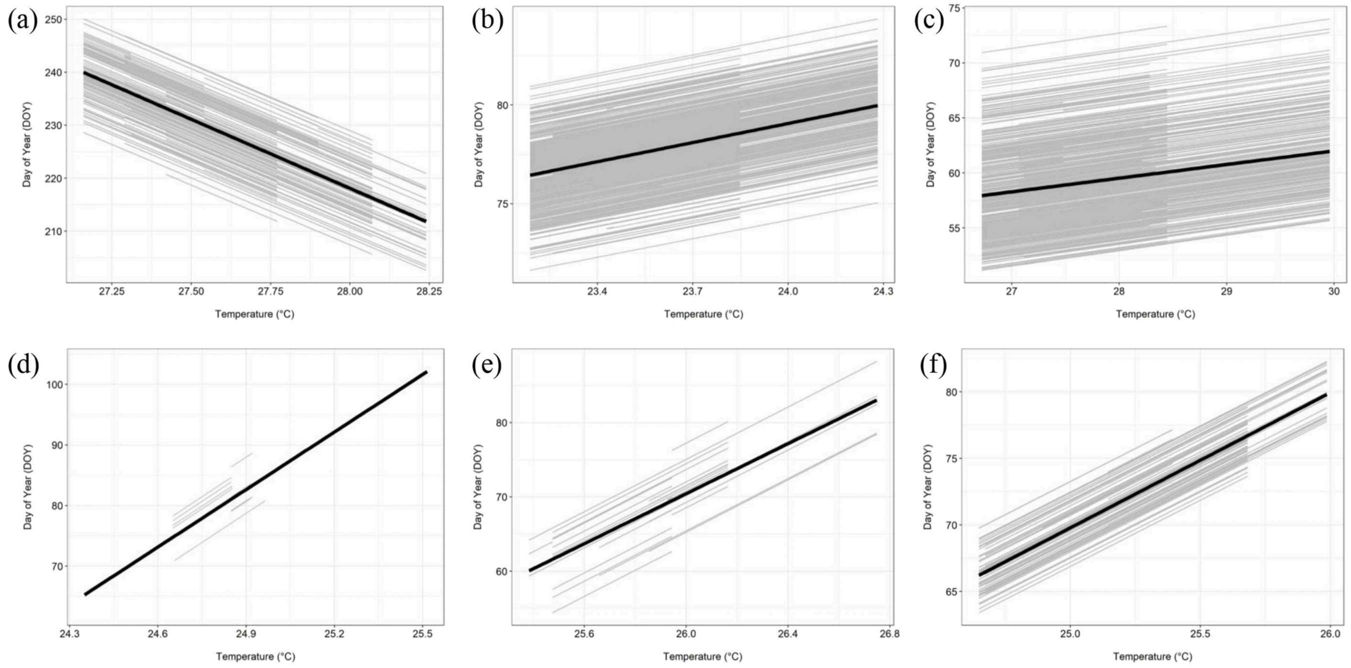

Fig. 7. The linear mixed model of the SOS for (a) Palembang; (b) Medan; (c) Tboung Khmum; (d) Ratnapura; (e) Johor and (f) Kedah. The grey lines represent the individual pixels' best linear unbiased predictors (BLUPs). The length of each line varies depending on the availability of data for each pixel across the study period. The thick black line shows the mean fixed effect.

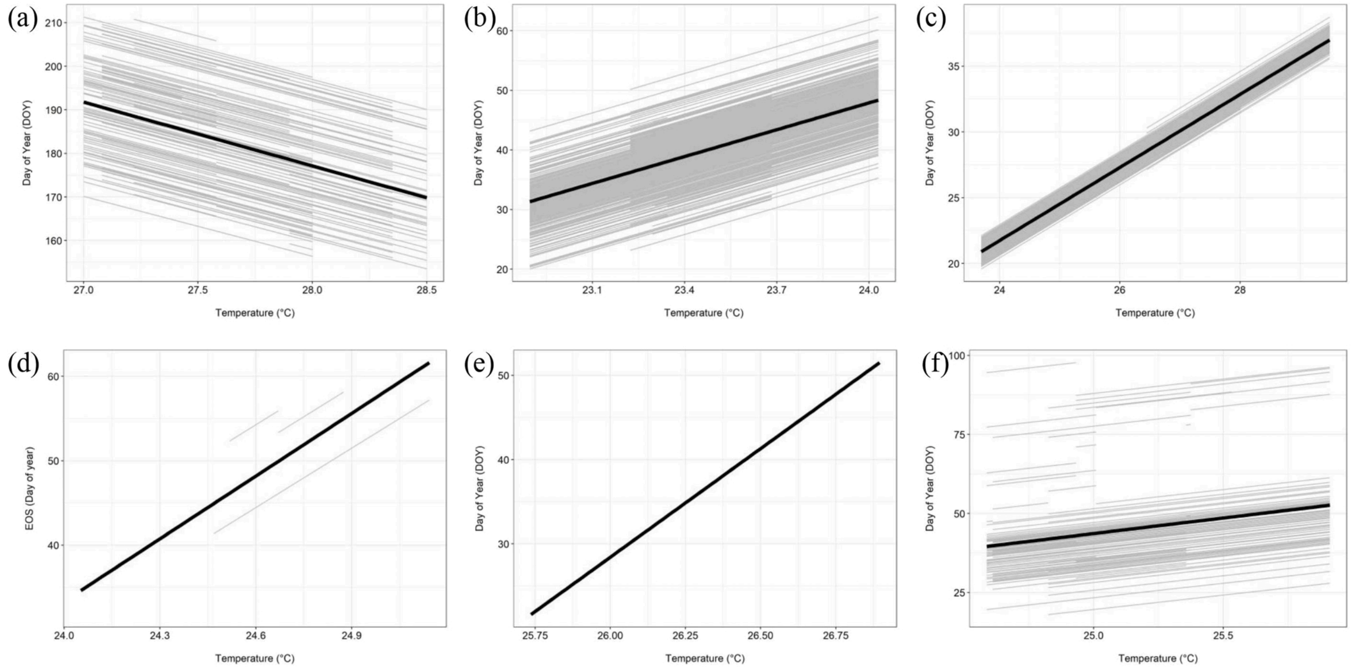

Fig. 8. The linear mixed model of EOS for (a) Palembang; (b) Medan; (c) Tboung Khmum; (d) Ratnapura; (e) Johor and (f) Kedah. The grey lines represent the best linear unbiased predictors (BLUPs) of individual pixels. The length of each line varies depending on the availability of data for each pixel across the study period. The thick black line shows the mean fixed effect.

which was based on the overall mean of SOS and EOS of each study area, corresponds with other studies (Azizan et al., 2021; Carr, 2012; Sanjeeva Rao et al., 1998; Seneviratne et al., 2020) that observed approximately four-week intervals between defoliation and foliation. In addition, we determined that the wintering period is shorter for locations greater than 4 ° latitude north and south, which aligns with findings from (Verheye, 2010). The estimated LOS of the study areas, between 318 and 344 days, is also within the reported range. The values vary depending on the local growing season and are influenced by the multiclonal planting practice adopted in most rubber plantations.

Our finding on a significant increase in the average temperature trend over ten years for four affected study areas (Palembang, Medan, Johor and Ratnapura) is consistent with other recent studies. Suryadi et al. (2018) performed a study on climate change at major cities in

Table 5
Linear mixed model parameters for the SOS and EOS.

Phenological Model	SOS			EOS		
Parameters	Intercept Value	Temperature Coefficient	p-Value	Intercept Value	Temperature Coefficient	p-Value
Palembang	925.21	–25.26	< 0.001	562.59	–13.78	< 0.001
Medan	3.86	3.13	< 0.001	-312.67	15.02	< 0.000
Tboung Khmum	20.76	1.39	< 0.001	-44.80	2.77	< 0.000
Ratnapura	-714.08	31.99	0.112	-528.62	23.47	0.186
Johor	-387.17	17.61	< 0.001	-642.35	25.80	< 0.01
Kedah	-178.49	9.94	< 0.000	-180.10	9.149	< 0.000

Sumatra and found an upward trend in average temperature at Palembang and Medan by 0.0212 °C/year (1980–2016) and 0.00331 °C/year (1982–2016), respectively. This finding confirms the trend detected in this study, although the rate of increase in average temperature is different, where this study recorded an increase of 0.008 °C and 0.003 °C per year for Palembang and Medan, respectively. Similarly, long-term studies on daily (1976 – 2017), monthly (1869 – 2007), and annual (1901–2000) temperature in Ratnapura all showed a significant increasing trend (De Costa, 2008; Esham and Garforth, 2013; Navaratne et al., 2019). This is compelling evidence that warming has occurred in Sri Lanka. Our findings independently confirm those of (Nawagamuwa and Rathnaweera, 2011), who used a different data set obtained from the Department of Meteorology and National Building Research Organization Sri Lanka. They reported a constant increment of 0.0064 °C per year from 2000 to 2010 for Ratnapura, while we found an increase of 0.005 °C per year between 2010 and 2019. Likewise, two studies have reported the same significant increasing trend in temperature in two different study periods for Johor. They both found an annual increase of 0.03 °C from 1970 to 2000 (Kitada et al., 2006) and from 1975 to 2007 (Tan et al., 2015). These two studies used temperature data from the meteorological station at Senai, which is approximately 50 km away from our study area.

In contrast, the two study areas in Tboung Khmum and Kedah did not record a significant monotonic trend based on Mann-Kendal statistical results. These results reflect those of Chim et al. (2021), who also found no significant trends in monthly temperature for Cambodia for the past 20 years (1998 – 2017). Their study applied the same Mann-Kendall statistical test on the temperature data from two meteorological stations in the Siem Reap area. There are no published studies to compare our results with for Kedah.

Of significant interest is the fact that Rubber Leaf Fall commenced in four of the study areas soon after the temperature inflexion points. After the Man-Kendall test results determined a significant trend for four of the study areas, the Pettitt change point test was used to identify any abrupt changes in the temperature time-series data. These were all detected around the same time, between March 2014 and February 2015 (Fig. 4). We used this period to separate the before (P1) and after (P2) periods flanking the change-point. Medan reported Rubber Leaf Fall the year following the detected change-point, while the three other study areas reported the outbreak of the new leaf drop after 2015, with Palembang and Johor in 2017 and Ratnapura in 2019. An abrupt temperature change can cause disturbance in plant growth and development (Hatfield and Prueger, 2015). In fact, climate change has been found to play a role in numerous incidences of emerging tree diseases (Garrett et al., 2021). For example, the outbreak in pine species in North American forests was partly attributed to warmer temperatures (Carroll et al., 2004). Therefore, there is a need to identify the effect of abrupt changes in temperature on rubber growth.

In addition to Rubber Leaf Fall, other phenological metrics were impacted by temperature. Based on the Tukey's HSD test results, for the four affected study areas, we identified significant differences for both SOS and EOS between periods P1 and P2. In contrast, the two unaffected study areas did not have a significant shift in SOS and EOS. The Tukey's HSD test results mirrored the Man-Kendall test results for all the study areas and both phenological metrics. All the study areas that registered a significant difference between the P1 and P2 periods, exhibited a significant change in defoliation and refoliation timing. There is sufficient evidence from other plant systems that links phenological timing to temperature (Cong et al., 2013; Fu et al., 2012; Piao et al., 2019). Thirumalai et al. (2017) demonstrated that agricultural disruption could be linked to the recent extreme temperature event in 2016.

Similarly, Fu et al. (2014) observed statistically significant increasing trends in mean annual temperatures throughout all the phenology stations selected in western-Central Europe from 1982 to 2011. They later concluded that the increasing trend in temperature caused spring phenological advances in the region based on in situ observations and NDVI-based data. Finally, the recent report by The CGIAR Research Program on Forests, Trees and Agroforestry (FTA) has stated that there was an increased incidence of rubber leaf diseases as a result of climate change (Pinizzotto, Kadir et al., 2021b). These findings show that increasing temperatures are having a major impact on the health of rubber plantations.

It is clear that temperature is a key driver of rubber phenology. A wide range of temperature coefficients was observed for both the SOS and EOS LME models. These temperature coefficients reflect the magnitude of temperature-related phenological changes, with areas exhibiting high Sen's Slope values having higher temperature coefficients, indicating higher phenological sensitivity to temperature change. For instance, a degree change in temperature can delay refoliation by 17 days in Johor but only three days in Medan. Conversely, a degree change in temperature can delay defoliation by 26 days and 15 days in Johor and Medan, respectively. A high-temperature coefficient was estimated for the SOS in Ratnapura and Palembang, and the EOS in Johor and Ratnapura. In general, our findings are consistent with Wolf et al. (2017) which showed that the changes to phenology are similar in magnitude to the effects of climate change.

An increase in temperature caused a delay in defoliation and refoliation of the rubber trees in the five northern hemisphere study areas. Our results are consistent with Liyanage et al. (2019), who found that higher temperature delayed the onset of rubber defoliation and refoliation in Southwest China, based on ground data from 100 trees over 32 years. This contrasted with Palembang, our only study area in the southern hemisphere, where an increase in temperature caused an advance in defoliation and refoliation. A study by Hatfield and Prueger (2015) stated that vegetative growth (i.e. node and leaf appearance rate) accelerates as temperatures rise to the optimal level for a plant. Through the most extensive meta-analysis performed on phenological trends among southern hemisphere species by assessing 1208 long-term datasets in 2013, Chambers et al. (2013) reported that plant phenology in this region had shifted earlier than the previous year. They also claimed that the finding obtained in the southern hemisphere might not be relevant to the northern hemisphere because changes or shifts in phenology will not be uniform across the world.

As we can only evaluate the wintering of matured trees, some of our study areas have to be limited in size due to the staggered planting practice in rubber plantations. Only Ratnapura had non-significant SOS and EOS LME models out of all the study areas. The small size of the study area (581 ha) or the high number of clones (10) may explain this.

Missing pixel values due to cloud cover disproportionally impacted the amount of data analysed compared to the larger study areas.

While a clear temperature shift has been associated with Rubber Leaf Fall, without access to historical collections of foliar pathogens, it is impossible to discount the possibility of a change in virulence. Although *Pestalotiopsis* and *Neopestalotiopsis* have been reported as causal agents for Rubber Leaf Fall (Nyaka Ngobisa et al., 2018; Pornsuriya et al., 2020), it is unclear whether they are indeed causal and not natural infections that happen to be there when the leaves fall. This requires further investigation in light of our findings. It is unlikely that a change in the host is responsible for Rubber Leaf Fall because many plantations have multiple genetically distinct clones, and the rubber trees have a productive lifecycle of some 35 years: there has been no wholesale change in the rubber genotypes which could account for the Rubber Leaf Fall. Medan had a small number of cultivated clones compared to other study areas and a low standard deviation, variation and dispersion index for the phenological metrics. In contrast, study areas in research stations such as Palembang and Ratnapura had high numbers of clones and large phenological variations.

We found that Rubber Leaf Fall was associated with an increase in temperature. There was a significant increase in temperature for the four study areas (Palembang, Medan, Johor and Ratnapura), where Rubber Leaf Fall was reported by local authorities, and confirmed here through remote sensing phenology analysis. Furthermore, the Rubber Leaf Fall commenced at or immediately after the inflexion point of the increase in temperature. In contrast, Rubber Leaf Fall was not reported from the other two study areas (Kedah and Tboung Khmum), nor could it be detected through remote sensing, and there was no observed increase in temperature in these areas. While this finding results from the analysis of only six study areas, these are relatively large areas comprising 4597 ha of affected plantations and 3224 ha of unaffected plantations. Among other factors that influenced study area selection, such as availability of satellite data, impact of cloud cover, and rubber stand age, these study areas were selected because local ground reporting was also available. Ideally, this finding needs to be confirmed through investigations of more rubber plantations, but it is clear that changes in average temperature should be included in any consideration of the causes of Rubber Leaf Fall.

It is well established that disease is an adverse interaction of pathogen, host and environment. Any changes in these aspects can have an epidemiological impact. For example, the emergence of a new strain of a pathogen may overcome plant defences targetting previous strains, or planting a susceptible clone in an area of high pathogen incidence may lead to increased disease incidence. Changes in the environment can have a dual influence. When conditions become more favourable for the pathogen, they can facilitate greater dispersal, infectivity or survival, amounting to an increase in overall virulence. Alternately, they can affect host susceptibility by increasing stresses associated with sub-optimal growth conditions. Modifications of the environment can influence the balance across a range of pathogen and host factors that impact disease outcomes. In this case, we have found significant temperature increases in the study areas experiencing Rubber Leaf Fall, but no changes where Rubber Leaf Drop has not been recorded. Thus without further reference to possible changes in virulence of any given group of pre-existing pathogens, or potential underlying changes in host genotypes, the change in the environment appears to be a factor in the development of Rubber Leaf Fall.

5. Conclusion

This study demonstrated that the new Rubber Leaf Fall phenomenon is associated with increased temperature. All of the affected studied areas showed a significant increase in temperature, and a concomitant shift in rubber phenology, confirming a change in the climate. We found that changes in mean temperature led to shifts in the timing of rubber defoliation and refoliation. There were phenological delays in most study areas that experienced an increase in temperature, except for Palembang, which experienced phenological advances. More importantly, we determined that the study areas that experienced an outbreak of the new Rubber Leaf Fall disease recorded a significant increase in temperature and a significant shift in the timing of phenological events. From our findings, it is concluded that increased temperature is a key driving factor which leads to Rubber Leaf Fall disease outbreaks.

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.

Data availability

Data will be made available on request.

Acknowledgement

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108531.

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