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Impact of El Niño on Oil Palm Yield in Malaysia

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Abstract: Oil palm crop yield is sensitive to heat and drought. Therefore, El Niño events affect oil palm production, resulting in price fluctuations of crude palm oil due to global supply shortage. This study developed a new Fresh Fruit Bunch Index (FFBI) model based on the monthly oil palm fresh fruit bunch (FFB) yield data, which correlates directly with the Oceanic Niño Index (ONI) to model the impact of past El Niño events in Malaysia in terms of production and economic losses. FFBI is derived from Malaysian monthly FFB yields from January 1986 to July 2021 in the same way ONI is derived from monthly sea surface temperatures (SST). With FFBI model, the Malaysian oil palm yields are better correlated with ONI and have higher predictive ability. The descriptive and inferential statistical assessments show that the newly proposed FFBI time series model (adjusted R-squared = 0.9312 and residual median = 0.0051) has a better monthly oil palm yield predictive ability than the FFB model (adjusted R-squared = 0.8274 and residual median = 0.0077). The FFBI model also revealed an oil palm under yield concern of the Malaysian oil palm industry in the next thirty-month forecasted period from July 2021 to December 2023.

Keywords: oil palm; extreme temperature; El Niño; yield modelling and prediction

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Citation: Khor, J.F.; Ling, L.; Yusop, Z.; Tan, W.L.; Ling, J.L.; Soo, E.Z.X. Impact of El Niño on Oil Palm Yield in Malaysia. *Agronomy* **2021**, *11*, 2189. https://doi.org/10.3390/agronomy11112189

Academic Editors: Miklós Neményi and Anikó Nyéki

Received: 6 October 2021
Accepted: 26 October 2021
Published: 29 October 2021

1. Introduction

The edible oil and fat sectors consist of 17 varieties of oils and fats that can be categorized into vegetable oils and animal fats. As seen in Figure 1, global edible oil and fat output increased by around 176% in the span of 26 years, from 84.6 million tons (Mt) in 1992/93 to 233.3 Mt in 2018/19. That equates to a mean annual increment of 5.7 Mt [1].

Palm oil made a significant 40% rise in demand, which was an increase of about 2.3 Mt per year in the whole edible oil and fat sectors within the aforementioned period [1]. The said increase was a consequence of the growing demand for palm oil consumption within the food sector, specifically household consumable oil, the cosmetics sector and biodiesel fuel. Typically, vegetable oils are regarded to be an effective replacement for fossil fuels that can lead to a renewable energy source [2].

Palm oil is by far the most manufactured oil relative to many other edible oils and fats, accounting for nearly 31.3% of total edible oils and fats manufactured [1]. As presented in Table 1, oil palm is the most efficient in terms of edible oil yield per hectare with yields of about 4.27 tons per hectare per year (t/ha/yr) (combined palm and palm kernel oil) and at least six times more productive than any other oilseed [3,4]. This claim is supported by the national oil yield of 4.02 t/ha/yr in Malaysia (Appendix A: 3.66 t/ha/yr for palm oil and 0.36 t/ha/yr for palm kernel oil) [5–7]. Its input-output ratio is greater than that of other edible oils and fats. As a result, a smaller plantation area is required for oil palms to produce the same quantity of edible oil than other crops. Oil palm cultivation is also extremely alluring given the limited land resources available globally. In addition, the production cost for palm oil is about 700 USD per ton (USD/t), much cheaper compared to other vegetable oils. The next lowest cost is 850 USD/t for rapeseed oil [8–10].

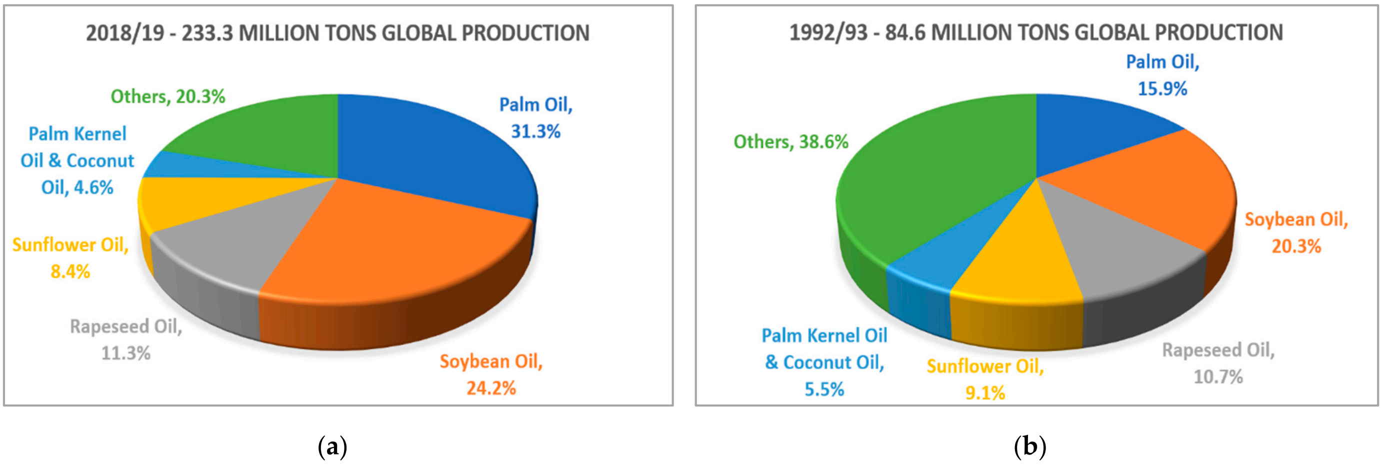

Figure 1. Market shares of 17 edible oils and fats produced internationally in: (**a**) 2018/19 and; (**b**) 1992/93. Created with data from [1].

Table 1. Average productivity of various major oil crops. Created with data from [3,4].

Crop	Oil Yield (t/ha)
Palm Oil	3.82
Palm kernel	0.45
Palm + Palm kernel oil	**4.27**
Rapeseed	0.69
Sunflower	0.52
Groundnut	0.45
Coconut	0.34
Cottonseed	0.19
Soybean	0.38
Corn	0.15

Oil palm crop is a crucial income resource in Malaysia, as the revenue from palm oil exports amounted to 5.16% of the country's Gross Domestic Product (GDP) in 2020 [11–13]. Situated between the Indian and Pacific Oceans, Malaysia, being the second largest exporter (after Indonesia) of palm oil in the world [14] is susceptible to El Niño and La Niña occurrences. El Niño (warm phase) and La Niña (cool phase) are phases of a larger phenomenon called the El Niño-Southern Oscillation (ENSO). During non-El Niño conditions (ENSO neutral), trade winds blow westwards across the tropical Pacific Ocean, pushing warm surface water towards the western Pacific (Asia and Australia). During an El Niño event, trade winds which normally blow westwards weaken or reverse direction, now blowing eastwards across the tropical Pacific Ocean, bringing warm water towards the coasts of South America. As warm water accumulates at the coasts of South America, convection above the warm surface water causes warm air to rise and precipitation happens. As a result, drastically increased rainfall would be seen in Ecuador and northern Peru. On the other side of the tropical Pacific Ocean, El Niño brings droughts to Malaysia, Indonesia and Australia [15–17].

Scientists use the Oceanic Niño Index (ONI) to measure deviations from normal sea surface temperatures [17]. This study uses ONI to classify El Niño events from January 1986 to June 2021 as shown in Table 2. The ONI is the running three-month mean SST anomaly for the Niño 3.4 region (5° N–5° S, 120° W–170° W). El Niño events are characterized by five consecutive overlapping three-month periods at or above +0.5 °C anomaly [18,19]. In general, El Niño causes lower rainfall, higher temperatures and abnormally dry conditions in Malaysia [20–22]. This study analysed the impact of past El Niño events on the oil palm production in Malaysia.

Table 2. Categories of El Niño events occurred during the period of 1986 to 2021. Created with data from [19].

Very Strong	Strong	Moderate	Weak
1997/98	1987/88	1986/87	2004/05
2015/16	1991/92	1994/95	2006/07
		2002/03	2014/15
		2009/10	2018/19

Yield of fresh fruit bundles (FFB) and crude palm oil (CPO) are affected by El Niño as oil palm crop is sensitive to prolonged drought periods like other oil crops [22–24]. During the occurrence of El Niño, a high level of water stress is generated for the palm trees due to reduced rainfall and increased temperature [2].

Many researchers have looked into the relationship between rainfall, temperature and oil palm production in Malaysia [2,20,22,25–29]. However, the direct correlation between ENSO index and oil palm production has yet to be analysed. Furthermore, past studies lack the quantification study of actual financial losses due to the impact of El Niño on the Malaysian oil palm industry. Therefore, this study investigated the direct relationship between ONI and the monthly oil palm FFB yield. The objective of this study is to model the impact of El Niño on the palm oil production in Malaysia by proposing a newly derived Fresh Fruit Bunch Index (FFBI). The impacts are then quantified financially in terms of opportunity losses and real Malaysian GDP value. This study also aims to forecast the Malaysian oil palm yields in the near future using the newly proposed FFBI time series model.

2. Materials and Methods

2.1. Study Area

Located in Southeast Asia, Malaysia consists of two geological regions separated by the South China Sea. Peninsula Malaysia (or West Malaysia) shares a land border with Thailand to the north and Singapore to its south. Located on the northern part of the Borneo Island, East Malaysia borders Indonesia and surrounds the Sultanate of Brunei [30]. The total land area is 328,550 km^2 [31]. In 2020, the total area planted with oil palm in Malaysia is 58,653 km^2 (nearly 18% of the total land area) [7]. Figure 2 shows the location map of oil palm plantation areas in Malaysia.

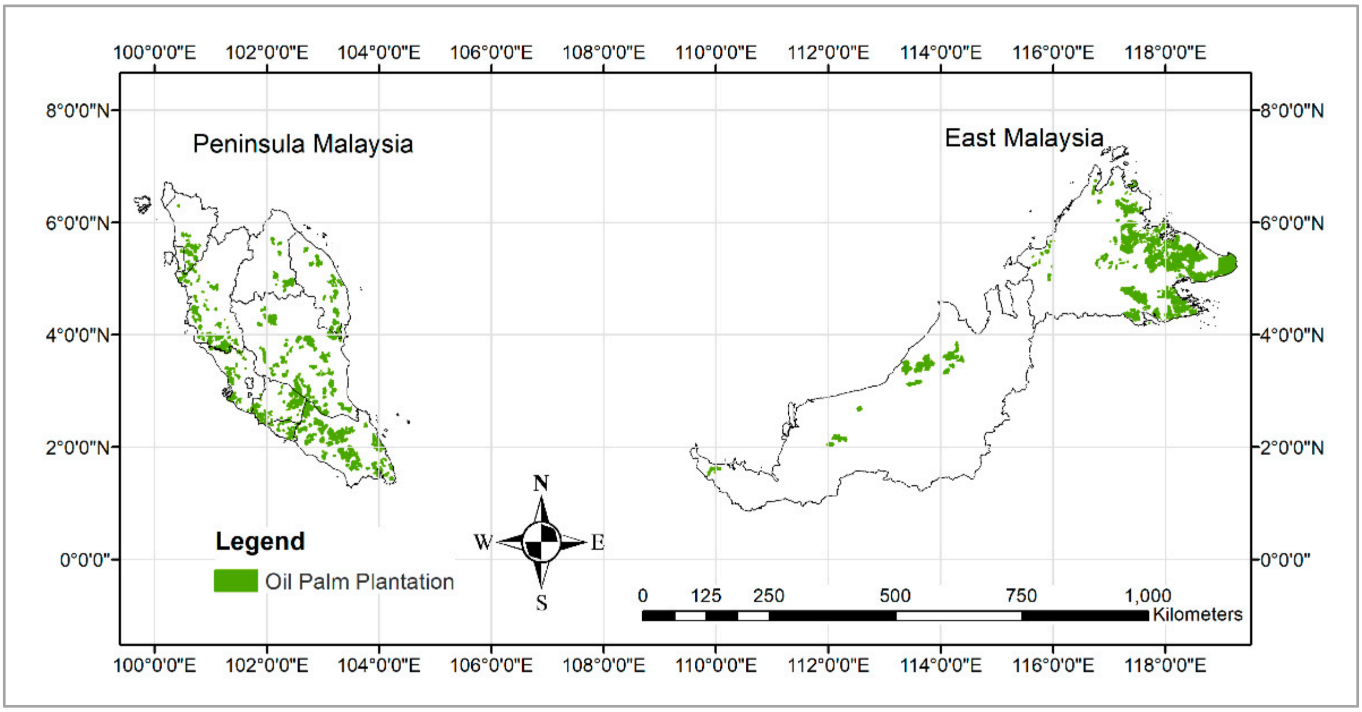

Figure 2. Location map of oil palm plantation areas in Malaysia. Created with data from [32].

2.2. The New Fresh Fruit Bunch Index (FFBI) Model

Fresh Fruit Bunch Index (FFBI) is created with the monthly Malaysian oil palm FFB yield data [5–7] (Appendix B) through a similar calculation method of ONI (Appendix D) which is based on the monthly sea surface temperatures (SST) tracked by the National Oceanic and Atmospheric Administration (NOAA) [18]. In this study, monthly oil palm FFB yields from January 1986 to July 2021 (total 427 data points) in Malaysia were used [5–7]. The national average FFB yield for each month was calculated on the month-to-month basis from 1986 to 2020 in Table 3.

Table 3. Average FFB yield for each month from 1986 to 2020 in Malaysia. Created with data from [5–7].

Month	Average FFB Yield (t/ha)
January	1.3194
February	1.1903
March	1.3234
April	1.4049
May	1.4829
June	1.5109
July	1.6329
August	1.7420
September	1.8543
October	1.8146
November	1.6746
December	1.4743

FFB yields from January 2021 to July 2021 were not included in calculating these averages as data points in the full year of 2021 are still not available.

$FFB_{anomaly}$, the difference between FFB yield and average FFB yield (Table 3) at each corresponding month was calculated using Equation (1):

$$FFB_{anomaly} = FFB - FFB_{average} \quad (1)$$

The new FFBI (Appendix C) was then calculated by taking the 3-month running mean of $FFB_{anomaly}$, as shown in Equation (2):

$$FFBI_i = (FFB_{anomaly, i-1} + FFB_{anomaly, i} + FFB_{anomaly, i+1})/3, \quad (2)$$

where $FFB_{anomaly, i-1}$ and $FFB_{anomaly, i+1}$ were the FFB anomalies one month before and after the month that was being calculated. Hence, from 427 points of FFB yields, a total of 425 points of FFBI was derived, from February 1986 to June 2021.

2.3. Correlation Test between Malaysian Oil Palm Yields and Oceanic Niño Index (ONI)

The relationships between FFB and FFBI with ONI were tested using correlation tests. Normality tests were conducted beforehand to determine whether parametric or non-parametric correlation tests should be used. If a given dataset has less than 2000 samples, the Shapiro-Wilk test is suggested rather than the Kolmogorov-Smirnov test. This paper used a dataset which has less than 2000 samples, and therefore, the Shapiro-Wilk test was used. If the p-value is greater than 0.05, then the dataset is considered to be normally distributed [33]. Based on the normality tests (Table 4), FFB and ONI data distribution were determined to be non-normally distributed, and FFBI data distribution was normally distributed. As such, non-parametric Spearman's rho correlation test was used to investigate the relationship between the oil palm yields and ONI in a lag period from 0 to 18 months. A Spearman's rho correlation is also referred as Spearman correlation or Spearman rank correlation. The strength of association between the variables tested is expressed in a single value between −1 and +1, which is a bivariate correlation analysis. A positive correlation coefficient indicates a positive relationship between the two variables (as values of one variable increase, values of the other variable also increase), while a negative correlation coefficient expresses a negative relationship (as values of one variable increase, values of the other variable decrease). A correlation coefficient with a value of zero indicates that no relationship exists between the variables. The Spearman correlation does not assume that the variables are normally distributed, hence being used in this study as not all the variables were normally distributed [34,35]. All of the tests were conducted using IBM SPSS Statistics version 26.0 [36].

Table 4. Shapiro-Wilk normality test results for FFB, FFBI and ONI.

Variable	p-Value	Normality
FFB	0.0103 (<0.05)	Non-normal
FFBI	0.1922 (>0.05)	Normal
ONI	0.0000 (<0.05)	Non-normal

2.4. Time Series Forecasting

FFB and FFBI time series forecasting models with ONI as its predictor were created using the Expert Modeler in IBM SPSS Statistics version 26.0 [36]. The FFBI time series model was also validated repeatedly using a 30-year moving time frame. Six FFBI time series models were created and validated using different block periods (1986–2015, 1987–2016, 1988–2017, 1989–2018, 1990–2019 and 1991–2020). Each model forecasted FFBI one year ahead of the respective block period to be compared and validated with the observed FFBI. Residual analyses for each model were also performed in which the 99% confidence intervals of the residuals' median, standard deviation and variance were computed using BCa bootstrapping method in this study. Using monthly Malaysian FFB data points from February 1986 to June 2021 (N = 425), the final FFB and FFBI time series forecasting models were created to forecast for another 30 months from July 2021 until December 2023.

R-squared measures the proportion of the variable in the dependent variable explained by all of the independent variables in the model, while adjusted R-squared measures the proportion of variation explained by only those independent variables that really help in explaining the dependent variable. As such, the adjusted R-squared will decrease if independent variables that do not help in predicting the dependent variable are added to the model [37]. The adjusted R-squared ($R^2{}_{adj}$) was derived from the R-squared produced by the models using Equation (3):

$$R^2{}_{adj} = 1 - \left[\frac{\left(1 - R^2\right)(n-1)}{n-k-1} \right], \quad (3)$$

where R^2 is the R-squared of the models, N is the number of data points and K is the number of independent regressors [38].

To compare the FFB and FFBI time series models, residual analyses were conducted using IBM SPSS Statistics version 26.0. Residual between the predicted and observed data point was calculated [39,40]. Descriptive statistics of the residuals from both models were calculated for model comparison, including residuals' skewness, range, median, standard deviation and variance. Shapiro-Wilk normality tests were also conducted for the residuals to determine whether the median or mean residuals should be referred for model prediction accuracy comparison. As the residuals from both models were determined to be non-normally distributed, the FFB and FFBI model's median residuals were used for comparison assessment. The non-parametric inferential statistics of the bias corrected and accelerated (BCa) bootstrapping method was conducted with 2000 random samples (with replacement) to compute the 99% confidence intervals (CI) of the residuals' median, standard deviation and variance.

2.5. Mann-Kendall Trend Test and Sen's Slope

The Mann-Kendall trend test was used to evaluate the trends of FFBI during the occurrence of each El Niño events. Mann-Kendall test statistics (S) can be calculated using Equation (4):

$$S = \sum\nolimits_{i=1}^{n-1} \cdot \sum\nolimits_{j=i+1}^{n} \operatorname{sign}(x_i - x_k), \quad (4)$$

where x_i and x_k are sequential data in the series and

$$\operatorname{sign}(x_i - x_k) = \begin{cases} +1 \text{ when } (x_i - x_k) > 0 \\ 0 \text{ when } (x_i - x_k) = 0 \\ -1 \text{ when } (x_i - x_k) < 0 \end{cases} \quad (5)$$

The variance of S (Var(S)) is estimated as:

$$\operatorname{Var}(S) = \frac{s(n-1)(2n+5) - \sum_{p-1}^{q} \left(t_p - 1\right)\left(2t_p + 5\right)}{18}, \quad (6)$$

where t_p defines the ties of the *p*th value, and q represents the number of the tied value. The standardized test static for the Mann-Kendall test (Z) can be calculated, as shown in Equation (7):

$$Z = \begin{cases} \frac{S-1}{\sqrt{\operatorname{Var}(S)}} \text{when } S > 0 \\ 0 \text{ when } S = 0 \\ \frac{S+1}{\sqrt{\operatorname{Var}(S)}} \text{when } S < 0 \end{cases} \quad (7)$$

The sign of Z indicates the direction of the trend. The negative value of Z indicates a decreasing trend and vice versa. At the 5% significance level, the null hypothesis of no trend is rejected if the absolute value of Z is higher than 1.64 [41]. This study used the excel template developed by Finnish Meteorological Institute [42] to conduct the Mann-Kendall trend tests and Sen's slope estimation for FFBI during El Niño events.

The Sen's slope method was used for the estimation of the monthly change in FFBI from February 1986 to June 2021. The Sen's slope is calculated as the median of all the slopes estimated between all the successive data points of FFBI time series as [41]:

$$\text{Sen's Slope} = \text{median}\left[\frac{\Delta\text{FFBI}}{\Delta\text{t}}\right], \quad (8)$$

where ΔFFBI is the change of FFBI in the change of time, Δt between two subsequent FFBI data.

2.6. Opportunity Loss Modelling of El Niño Events

During or after the occurrence of an El Niño event in the study period, the first clump of continuous monthly negative FFBI was considered to be the oil palm yield losses triggered by El Niño. The oil palm FFB yield losses (FFBL) due to the observed El Niño event were computed by summing up the absolute magnitude of the negative FFB. As such, the opportunity loss caused by the El Niño event was calculated using Equation (9):

$$\text{OL} = \text{FFB}_\text{L} \times \text{Area} \times \text{OER} \times \text{Price}, \quad (9)$$

where OL is the opportunity loss caused by El Niño in the unit of USD, area is the oil palm matured area (Appendix K), OER is the oil extraction rate (Appendix K) to convert oil palm from fresh fruit bunch to crude palm oil (CPO) and price is the CPO price (Appendix J) [5–7].

The opportunity losses for all El Niño events within the study period were projected to December 2021 for fair comparison using a hypothetical discount rate of 6%. This computation was done using FV function in Microsoft Excel software as shown in Figure 3,

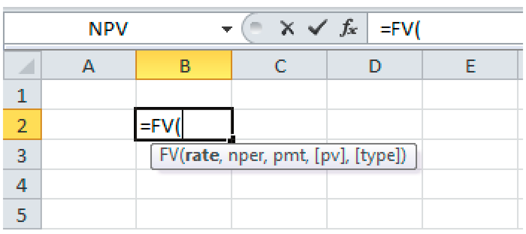

Figure 3. FV function in Microsoft Excel.

where FV is the future value, rate is the discount rate per period, NPER is the total number of payment periods, PMT is the payment made for each period, PV is the present value and type is the representation of the timing of payment (1 for payment at the beginning of the period and 0 for payment at the end of the period).

3. Results

3.1. Predictive Ability of Fresh Fruit Bunch Index (FFBI) Model

3.1.1. Correlation with Oceanic Niño Index (ONI)

The newly proposed FFBI model (Appendix C) has an improved ability to model the impact of El Niño events on the oil palm production in Malaysia compared to FFB model. Based on the non-parametric Spearman's rho correlation test (Table 5), FFBI has statistically significant correlations with ONI at lag periods from 2 to 16 months, with the highest correlation of −0.399 at 0.01 alpha level. On the other hand, the correlations of FFB and ONI are only significant at lag periods from 6 to 13 months, with the highest correlation of −0.217 at 0.01 alpha level.

Table 5. Spearman's rho correlation between FFB and FFBI with ONI at lag periods from 0 to 18 months.

Lag Period (Months)	FFB & ONI		FFBI & ONI	
	Spearman's rho Coefficient	*p*-Value	Spearman's rho Coefficient	*p*-Value
0	−0.027	0.578	−0.064	0.188
1	−0.029	0.557	−0.087	0.074
2	−0.030	0.540	−0.106	0.029 *
3	−0.034	0.479	−0.125	0.010 **
4	−0.049	0.317	−0.154	0.001 **
5	−0.079	0.104	−0.197	0.000 **
6	−0.120	0.013 *	−0.254	0.000 **
7	−0.165	0.001 **	−0.313	0.000 **
8	−0.200	0.000 **	−0.364	0.000 **
9	−0.217	0.000 **	−0.394	0.000 **
10	−0.211	0.000 **	−0.399	0.000 **
11	−0.188	0.000 **	−0.381	0.000 **
12	−0.159	0.001 **	−0.348	0.000 **
13	−0.128	0.008 **	−0.303	0.000 **
14	−0.095	0.050	−0.248	0.000 **
15	−0.060	0.214	−0.183	0.000 **
16	−0.030	0.542	−0.112	0.021 *
17	−0.007	0.878	−0.039	0.424
18	0.009	0.849	0.023	0.642

* Correlation is significant at $\alpha = 0.05$. ** Correlation is significant at $\alpha = 0.01$. Lag period refers to the number of months FFB and FFBI are delayed corresponding to the ONI at that month.

3.1.2. Time Series Forecasting

Based on the statistical assessment of the FFB and FFBI time series model (Table 6), the FFBI model (Appendix F) has an adjusted R-squared of 0.9312, which is significantly higher than the FFB model (Appendix E) with adjusted R-squared of 0.8274 only. Compared to the FFB model with residual sum of squares (RSS) of 4.6876, the FFBI model has much lower RSS at 0.5459 only. The FFBI model also has a lower median residual (0.0051) than the FFB model (0.0077). Other than that, residual of the FFBI model has lower skewness, range, standard deviation and variance compared to the FFB model.

Table 6. FFB and FFBI time series forecasting models' summary with residual analyses using descriptive and inferential statistics at $\alpha = 0.01$.

Dependent Variable	FFB (tons/Hectare)	New FFBI (tons/Hectare)
Predictor	ONI	ONI
Modelled Period	Feb 1986–Jun 2021 (N = 425)	Feb 1986–Jun 2021 (N = 425)
Forecasted Period	Jul 2021–Dec 2023 (N = 30)	Jul 2021–Dec 2023 (N = 30)
Model	ARIMA (2,0,2) (1,1,1)	ARIMA (3,1,3) (0,0,1)
Adjusted R-Squared	0.8274	0.9312
Residual Sum of Squares (RSS)	4.6876	0.5459
Residual Skewness	−0.6903	−0.4162
Residual Range	0.7644	0.2790
Residual Median	0.0077	0.0051
Residual Median (BCa 99% CI)	[−0.0076, 0.0258]	[−0.0001, 0.0096]
Residual Standard Deviation	0.1067	0.0359
Residual Standard Deviation (BCa 99% CI)	[0.0941, 0.1192]	[0.0320, 0.0396]
Residual Variance	0.0114	0.0013
Residual Variance (BCa 99% CI)	[0.0088, 0.0142]	[0.0010, 0.0016]

3.2. *Production, Financial and Economical Loss in the Malaysian Oil Palm Industry due to El Niño*

With the application of FFBI, oil palm FFB trends from January 1986 to June 2021 were studied. Based on the Mann Kendall's (MK) trend test (Table 7), almost every El Niño event in the aforementioned period is accompanied by a significant decreasing trend of FFBI (at least 0.05 alpha level), except for 2002/03′s moderate El Niño and 2014/15′s weak El Niño. Those downward FFBI trends could be observed from 0 to 6 months after an El Niño event (Table 8).

Table 7. Mann Kendall's trend test and Sen's Slope Test during each El Niño event from January 1986 to June 2021.

Category	El Niño Events	MK Trend of FFBI	Sen's Slope
Very Strong	1997/98	Decreasing ***	−0.0348
	2015/16	Decreasing ***	−0.0438
Strong	1987/88	Decreasing **	−0.0986
	1991/92	Decreasing *	−0.0970
Moderate	1986/87	Decreasing **	−0.0479
	1994/95	Decreasing *	−0.0527
	2002/03	No Trend	
	2009/10	Decreasing ***	−0.0379
Weak	2004/05	Decreasing ***	−0.0267
	2006/07	Decreasing *	−0.0360
	2014/15	No Trend	
	2018/19	Decreasing ***	−0.0439

* Trend is significant at $\alpha = 0.05$. ** Trend is significant at $\alpha = 0.01$. *** Trend is significant at $\alpha = 0.001$.

Table 8. Oil palm yield loss and opportunity loss due to each El Niño event from January 1986 to June 2021.

Category	El Niño Events	Lag	Negative FFBI Period	Oil Palm Yield Loss	Opportunity Loss	Projected to December 2021
		(Months)	(Months)	(t/ha)	(USD)	(USD)
Very Strong	1997/98	0	16	3.0739	799,512,628.04	3,118,809,718.44
	2015/16	2	25	3.5197	2,223,629,847.24	3,026,040,134.75
Strong	1987/88	4	8	1.2702	86,205,737.87	621,682,504.89
	1991/92	3	9	0.9798	74,237,749.64	422,833,751.88
Moderate	1986/87	1	8	1.2279	59,553,760.49	451,416,000.07
	1994/95	3	4	0.1373	17,843,504.29	83,902,729.92
	2002/03	3	6	0.2844	68,135,456.56	206,588,187.64
	2009/10	4	9	0.7400	484,337,375.58	925,974,111.78
Weak	2004/05	6	7	0.3016	74,053,854.49	189,770,606.98
	2006/07	3	5	0.2035	89,253,638.73	208,552,751.05
	2014/15	0	5	0.3808	197,547,898.49	296,149,942.22
	2018/19	4	12	2.1576	1,308,607,860.03	1,481,072,202.50

USD = 4.2189178 as of 24 August 2021 [12]. Opportunity losses were projected using 6% discount rate. Opportunity loss for 2018/19 weak El Niño is excluded in the following analyses because the event has unexplained high production loss.

When the FFBI plummets below zero, oil palm production would suffer losses due to El Niño. Those losses could last between 4 to 25 months (Table 8) depending on the severity of the El Niño events, before recovering to normal productions. Both very strong El Niño events caused oil palm yield losses of about 3.0739 ton per hectare (t/ha) in 1997/98 and 3.5197 t/ha in 2015/16. Those losses equate to an average oil palm yield loss of 3.2968 t/ha in Malaysia, causing approximately 3.07 billion USD of opportunity losses when projected to December 2021 using a 6% discount rate (Table 9).

Table 9. Averaged oil palm yield loss and opportunity loss due El Niño according to category.

Category	Lag	Negative FFBI Period	Oil Palm Yield Loss	Opportunity Loss	Projected to December 2021
	(Months)	(Months)	(t/ha)	(USD)	(USD)
Very Strong	1.0	20.5	3.2968	1,511,571,237.64	3,072,424,926.59
Strong	3.5	8.5	1.1250	80,221,743.75	522,258,128.39
Moderate	2.8	6.8	0.5974	157,467,524.23	416,970,257.35
Weak	3.0	5.7	0.2953	120,285,130.57	231,491,100.09

USD = 4.2189178 as of 24 August 2021 [12]. Opportunity losses were projected using 6% discount rate.

The oil palm production and opportunity losses decrease as the severity of El Niño events decrease (Figure 4). The oil palm yields were estimated to reduce by 1.1250 t/ha during a strong El Niño event, 0.5974 t/ha during a moderate El Niño event and about 0.2953 t/ha during a weak El Niño event on average. In financial terms, a strong El Niño event could cause opportunity losses of approximately 522 million USD, 416 million USD for a moderate El Niño event and 231 million USD for a weak El Niño event in Malaysia (Table 9).

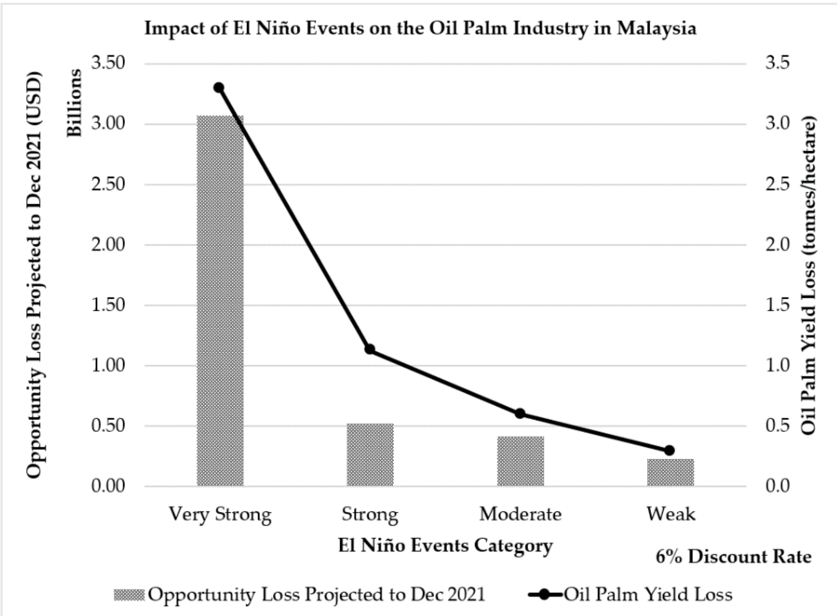

Figure 4. Oil palm yield loss and opportunity loss due to El Niño according to category.

This study then accumulates the opportunity losses at a hypothetical 6% discount rate to show the collective impact of every El Niño event from January 1986 to June 2021 (except for 2018/19 weak El Niño) on the oil palm industry in Malaysia (Figure 5). The total combined loss is estimated to be 9.55 billion USD by the end of 2021, which is approximately 2.84% of Malaysia's GDP in 2020 [11]. Using SPSS, the cumulative opportunity losses model was modelled with a cubic model with an adjusted R-squared of 0.985, standard error of estimate of 0.331 billion USD and significant at p-value less than 0.0001 (Figure 5).

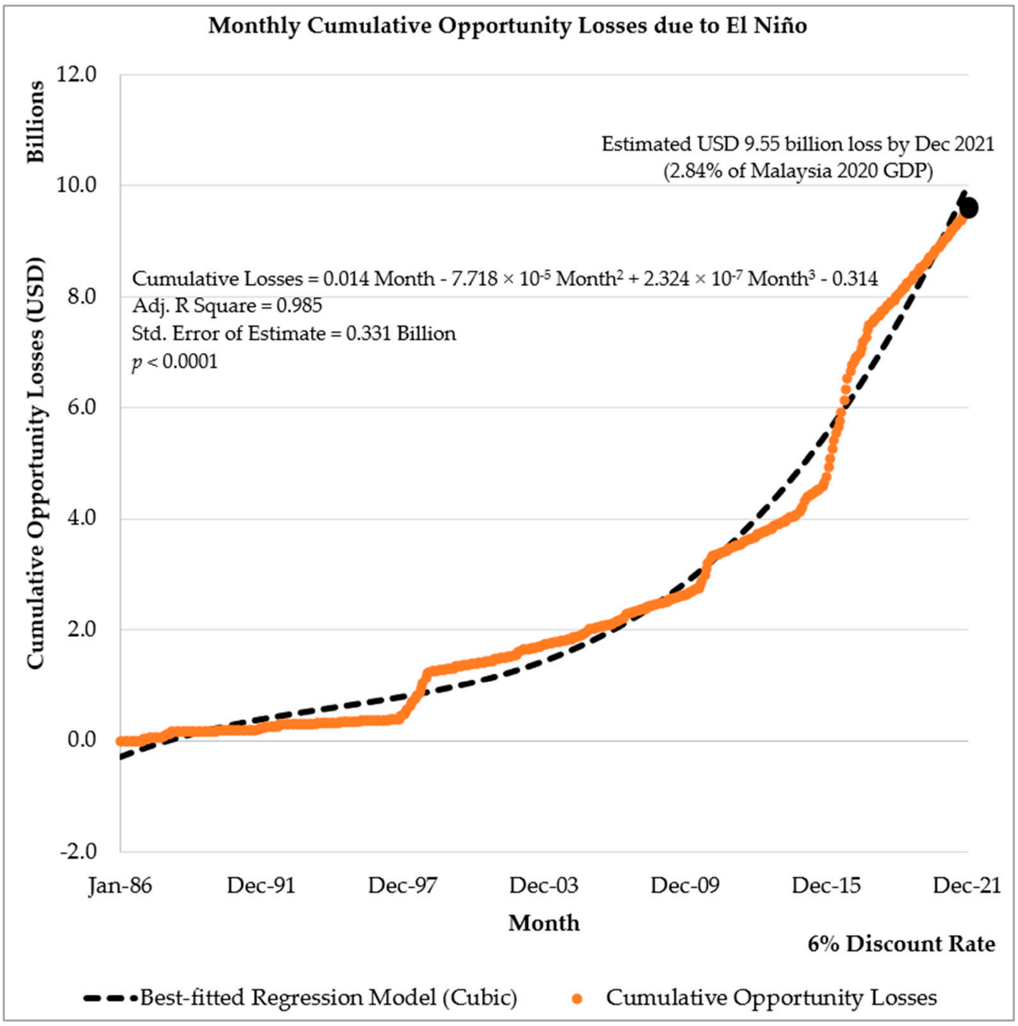

Figure 5. Monthly cumulative opportunity losses in the Malaysian oil palm industry due to El Niño projected to December 2021.

4. Discussion

4.1. Predictive Ability of the New Fresh Fruit Bunch Index (FFBI)

Based on Spearman's rho correlation tests (Table 5), both FFB and the proposed FFBI have negative correlations with ONI. This shows that when ONI increased during past El Niño events, water stress was induced in palm trees, causing oil palm production reduction in Malaysia [2,20–22,25]. The new FFBI has significantly higher correlation with ONI compared to FFB. By converting monthly FFB data into FFBI, the impact of El Niño on the monthly oil palm production in Malaysia could be modelled with higher precision.

The comparison between the FFB and FFBI time series model (Table 6) shows that FFBI model has better predictive ability than FFB model. Based on the residual analyses, both models have median residuals with 99% confidence intervals which span across zero, indicating their capabilities to produce a monthly oil palm production prediction with low error [40]. However, the FFBI time series model has a higher adjusted R-squared, lower RSS, median residual, residual skewness, residual range, residual standard deviation and residual variance than the FFB model. By having higher correlation with ONI and significantly better monthly oil palm yield forecasting ability, FFBI model is a better predictive modelling tool for the Malaysian oil palm industry stakeholders to better understand the impact of El Niño events. With the application of FFBI model, decision making processes could be enhanced so that appropriate measures could be taken to prepare for the adverse effects of El Niño on oil palm production in the future.

The validation tests using six different FFBI models in different time frames showed that the proposed FFBI model is consistent. The adjusted R-squared of all the validated models are consistent and stable, in the range of 0.916 to 0.9354 (Appendix G). The residuals of all the models have median residuals with 99% confidence intervals which span across zero, further supporting the forecasting ability and stability of the proposed FFBI model. Furthermore, the predicted FFBI produced by the validation models tend to follow the trend of real observed FFBI (derived from historical FFB [5–7], see Appendix H). The FFBI model also outperformed the FFB model as the forecasted FFBI (Appendix F) from 2021 to 2023 is closer to the observed FFBI from January 2021 to June 2021 (Appendix I).

4.2. Trends of Oil Palm Yields during El Niño Events

In the Spearman's rho correlation tests (Table 5), FFBI shows a significant correlation with ONI with lag periods from 2 to 16 months. This is on par with other studies that reported lag periods from 3 to 24 months to witness oil palm production reduction in Malaysia due to El Niño events and drought [2,20,22,25–29]. Since there is no fixed way to explain the nature, the El Niño events could affect the oil palm yields after a period of time and are not constrained to a single fixed period. The FFBI model of this study suggests that the oil palm production could be affected after 2 to 16 months of the occurrence of El Niño events in Malaysia.

Using the FFBI model, trends of oil palm yield in Malaysia during each El Niño event from January 1986 to June 2021 were studied on an event-by-event basis. In general, oil palm yields started to decrease after 0 to 6 months of an El Niño event, according to the Mann Kendall's trend tests (Table 7). The industry would suffer production losses when the oil palm yields continue to plummet, and this could last for 4 to 25 months depending on the severity of El Niño events (Table 8) before the oil palm yields would recover.

4.3. Impact of El Niño Events on the Malaysian Oil Palm Industry

As shown in Figure 4, very strong El Niño events have a significantly bigger impact on the Malaysian oil palm production compared to other categories of El Niño. Averaged oil palm reduction during very strong El Niño events is about 2.9 times more than the production loss in strong El Niño, 5.5 times more than the moderate El Niño and 11.2 times more than weak El Niño (Table 9). When a very strong El Niño happens, oil palm yields in Malaysia are expected to suffer production losses for about 21 months continuously. For other types of El Niño events, oil palm yields are expected to be negative in terms of FFBI for approximately 6 to 9 months. The total combined opportunity losses from the past 11 El Niño events in Malaysia since 1986 are estimated to be 9.55 billion USD when projected to December 2021. This equates to 2.84% of the Malaysia GDP in 2020 [11] (Figure 5). Undeniably, extreme temperature caused by El Niño is a major factor affecting the oil palm production in Malaysia.

However, the occurrence of El Niño event cannot be controlled. The adverse weather condition caused by El Niño cannot be remedied by concerted intervention [33]. To enhance performance of the oil palm industry in Malaysia, other underlying factors affecting oil palm production should be further investigated. These factors include labour shortage and ageing palm trees [1,43]. Based on the annual Malaysian oil palm FFB yields from 1986 to 2020 [5–7] (Appendix K), the FFB yields did not recover to the national average after the 2015/16 very strong El Niño. The Malaysian oil palm FFB yields continued to stay below the mean lower confidence limit (BCa bootstrapped 99% CI) continuously from 2017 to 2020, facing a downward trend, even though there was only a weak occurrence of El Niño in 2018/19 [18,19]. In addition, based on the FFBI validation models, the observed FFBI (derived from historical FFB) from 2016 to 2021 is found to be mostly below the predicted FFBI (Appendix I), showing the possibility that there might be other significant underlying factors affecting oil palm production in Malaysia.

Surely, El Niño would not be the reason to cause the current production downtrend in the Malaysian oil palm industry. One of the reasons might be labour shortage. Oil palm plantations struggle to hire foreign workers for the harvesting of oil palm, while locals shun the idea of working in plantations. The shortage of manpower became worse under the prolonged foreign labour hiring freeze due to the COVID-19 situation and caused more losses to the industry [44]. Another underlying factor is the ageing of palm trees due to the slow replanting process in Malaysia [45]. In 2020, about 35% of the oil palm plantations owned by a private plantation firm (IOI Corporation Berhad) in Malaysia were of prime age, while 37% already passed their prime production phase [46]. Replanting schemes are not attractive to plantation owners due to the lower profit margin of the oil palm sector in the recent years. Backlog of old oil palm trees slow down the improvement of crop yield in Malaysia [47]. According to the United States Department of Agriculture (USDA) [43], aged oil palm trees are to be replaced with new high yield varieties to increase the crop yield. However, many plantation owners are reluctant to replace aged trees in times of high palm oil prices in order to continue gaining profits. Researchers [8] also supported the idea that a proper replanting program is required to improve the oil palm yield in Malaysia. Based on the historical records, oil palm yields dropped during the 1997/98 very strong El Niño and successfully recovered about a year after. However, the oil palm yields maintained at low production since the 2015/16 very strong El Niño. It is possible that the aged palm trees suffered damage from the heat stress of recent very strong El Niño and failed to recover.

4.4. Global Applicability of FFBI

For the previous ten years, more than USD 50 billion has been invested in the Malaysian and Indonesian oil palm sectors [48]. In 2019, almost 88% of the world's palm oil production comes from the top three palm oil producing countries, Indonesia, Malaysia and Thailand [14]. They are located in the same region (Southeast Asia) with the same climatic pattern [49–51]. Hence, the supply of palm oil in the global market will be heavily affected in the event of extreme weather such as El Niño event. Thus, the newly proposed FFBI can be utilized to model the threat of El Niño in the oil palm industry, so that these countries can brace themselves for the adverse effects of intense climate conditions on the oil palm yields in the industry.

5. Conclusions

This study proposes a new oil palm yield index, namely Fresh Fruit Bunch Index (FFBI) that is derived from the monthly oil palm FFB yields. It has shown improvement in the trend and oil palm yield modelling in Malaysia with respect to El Niño events. The FFBI shows a significantly higher correlation with ONI compared to FFB yields based on Spearman's rho correlation tests at 0.01 alpha level. The FFBI time series model has also shown a significantly higher predictive accuracy when compared to the FFB model. The new FFBI model has an adjusted R-squared of 0.9312, which is significantly higher than the FFB model with adjusted R-squared of 0.8274 only. The FFBI model also has smaller errors based on residual analyses.

The proposed FFBI provides an improved method to model the impact of El Niño events in the Malaysian oil palm industry, as financial losses caused by El Niño events cannot be neglected. A very strong El Niño event is estimated to cause 3.07 billion USD of opportunity losses when projected to December 2021 using a 6% discount rate. The total combined opportunity losses of 13 past El Niño events, starting from 1986 (excluding 2018/19 weak El Niño) is approximately 9.55 billion USD, which is about 2.84% of Malaysia's 2020 GDP.

The FFBI model reveals that the recent under yield situation of the Malaysian oil palm yield may continue in future. This study further shows that El Niño is not the sole factor affecting the Malaysian oil palm production. Hence, other underlying factors affecting Malaysian oil palm yields such as ageing oil palm trees should be further investigated for the implementation of preventive steps to preserve the sustainable competitive edge of the Malaysian oil palm industry in the international arena. Future work should incorporate

Indonesian and Thailand monthly FFB dataset to study the possible global production impact as these countries (Indonesia, Malaysia and Thailand) in the same region produce around 88% of the global palm oil supply.

Author Contributions: Conceptualization, L.L. and Z.Y.; methodology, L.L. and J.F.K.; software, L.L. and J.F.K.; validation, L.L., W.L.T. and Z.Y.; formal analysis, L.L. and J.F.K.; investigation, L.L. E.Z.X.S. and J.F.K.; resources, J.F.K., L.L. and Z.Y.; data curation, L.L. and J.F.K.; writing—original draft preparation, J.F.K.; writing—review and editing, L.L., J.F.K., J.L.L. and Z.Y.; visualization, L.L. and J.F.K.; supervision, L.L., W.L.T. and Z.Y.; project administration, L.L. and Z.Y.; funding acquisition, L.L. and Z.Y. All authors have read and agreed to the published version of the manuscript.

Funding: The research was supported by Ministry of Higher Education (MoHE) through Fundamental Re-search Grant Scheme (FRGS/1/2021/WAB07/UTAR/02/1), Universiti Tunku Abdul Rahman (IPSR/RMC/UTARRF/2019-C2/L07) and partly supported by the Brunsfield Engineering Sdn. Bhd., Malaysia (Brunsfield 8013/0002 & 8126/0001).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Oil palm data can be found in Palm Oil Registration & Licensing Authority (PORLA) reports "PORLA palm oil statistics" from 1986 to 1999 and Malaysian Palm Oil Board (MPOB) reports "Malaysian oil palm statistics" from 2000 to 2020 in MPOB libraries located in Kelana Jaya and Bangi, Malaysia. Recent oil palm data is available at <https://bepi.mpob.gov.my/index.php/en/> (accessed 17 August 2021). ONI data is available at <https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php> (accessed 25 October 2021).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Annual productivity of crude palm oil (CPO) and crude palm kernel oil (CPKO) from 1975 to 2020 in Malaysia [5–7].

Year	CPO Yield (t/ha)	CPKO Yield (t/ha)	Year	CPO Yield (t/ha)	CPKO Yield (t/ha)
1975	3.66	0.17	2000	3.46	0.41
1976	3.48	0.16	2001	3.66	0.44
1977	3.54	0.18	2002	3.59	0.40
1978	2.95	0.17	2003	3.75	0.43
1979	3.65	0.21	2004	3.73	0.42
1980	3.78	0.22	2005	3.80	0.45
1981	3.76	0.22	2006	3.93	0.47
1982	3.83	0.28	2007	3.83	0.44
1983	3.43	0.29	2008	4.08	0.47
1984	4.25	0.32	2009	3.93	0.45
1985	4.33	0.35	2010	3.69	0.42
1986	4.41	0.36	2011	4.01	0.43
1987	3.39	0.34	2012	3.84	0.43
1988	3.47	0.34	2013	3.85	0.43
1989	3.88	0.38	2014	3.84	0.42
1990	3.64	0.41	2015	3.78	0.40
1991	3.48	0.37	2016	3.21	0.34
1992	3.43	0.37	2017	3.53	0.39
1993	3.78	0.42	2018	3.42	0.39
1994	3.43	0.41	2019	3.47	0.39
1995	3.50	0.41	2020	3.33	0.38
1996	3.55	0.41	Average:	3.66	0.36
1997	3.63	0.40			
1998	3.02	0.36			
1999	3.58	0.40			

Appendix B

Table A2. Monthly oil palm fresh fruit bunch (FFB) yield in tons per hectare from January 1986 to July 2021 in Malaysia [5–7].

	January	February	March	April	May	June	July	August	September	October	November	December
1986	1.68	1.37	1.38	1.34	1.29	1.29	1.65	1.64	1.95	1.94	1.67	1.33
1987	1.09	1.04	1.08	1.20	1.20	1.49	1.64	1.87	2.05	1.78	1.47	1.17
1988	0.95	0.97	1.19	1.34	1.38	1.67	1.69	1.85	1.78	1.68	1.57	1.41
1989	1.19	1.09	1.20	1.26	1.43	1.61	1.81	2.05	2.14	2.02	2.02	1.68
1990	1.37	1.26	1.35	1.34	1.72	1.55	1.72	1.88	1.93	1.74	1.51	1.22
1991	0.99	0.97	1.25	1.41	1.59	1.43	1.73	1.88	1.98	1.88	1.49	1.23
1992	1.12	1.07	1.20	1.35	1.41	1.42	1.67	1.75	1.92	1.77	1.71	1.41
1993	1.21	1.17	1.20	1.66	1.63	1.73	1.86	1.99	2.31	2.06	1.83	1.53
1994	1.38	1.16	1.23	1.29	1.30	1.41	1.53	1.71	1.92	1.98	1.77	1.69
1995	1.55	1.29	1.39	1.38	1.35	1.50	1.64	1.73	1.87	1.83	1.82	1.58
1996	1.33	1.06	1.43	1.40	1.64	1.64	1.63	1.86	1.90	1.94	1.64	1.43
1997	1.23	1.12	1.42	1.58	1.63	1.68	1.77	1.82	1.95	1.88	1.67	1.30
1998	1.03	1.18	1.15	1.20	1.27	1.38	1.49	1.61	1.65	1.48	1.41	1.10
1999	0.98	1.05	1.29	1.65	1.85	1.76	1.75	1.76	1.88	1.89	1.76	1.61
2000	1.38	1.26	1.26	1.32	1.33	1.35	1.39	1.62	1.88	2.02	1.96	1.56
2001	1.80	1.51	1.46	1.51	1.57	1.48	1.43	1.57	1.78	1.81	1.70	1.52
2002	1.47	1.21	1.34	1.32	1.40	1.43	1.51	1.68	1.87	1.79	1.57	1.38
2003	1.29	1.12	1.40	1.56	1.67	1.73	1.83	1.82	1.83	1.66	1.46	1.62
2004	1.25	1.18	1.25	1.33	1.44	1.53	1.69	1.71	1.97	1.77	1.68	1.74
2005	1.50	1.31	1.52	1.56	1.61	1.50	1.62	1.70	1.82	1.75	1.61	1.40
2006	1.23	1.34	1.51	1.61	1.70	1.64	1.67	1.87	1.97	1.70	1.90	1.43
2007	1.45	1.25	1.30	1.35	1.43	1.39	1.62	1.83	1.89	1.85	1.95	1.68
2008	1.68	1.42	1.51	1.52	1.62	1.65	1.78	1.79	1.76	1.90	1.87	1.68
2009	1.52	1.30	1.42	1.39	1.48	1.52	1.60	1.63	1.74	2.14	1.77	1.69
2010	1.44	1.22	1.44	1.38	1.44	1.49	1.64	1.71	1.66	1.72	1.55	1.34
2011	1.15	1.20	1.51	1.60	1.78	1.79	1.79	1.69	1.96	1.95	1.68	1.59
2012	1.35	1.18	1.21	1.25	1.34	1.43	1.68	1.67	2.00	1.96	1.97	1.85
2013	1.63	1.32	1.30	1.33	1.35	1.37	1.65	1.74	1.90	1.93	1.83	1.67
2014	1.49	1.21	1.39	1.45	1.53	1.43	1.55	1.94	1.80	1.79	1.68	1.37
2015	1.15	1.07	1.33	1.55	1.64	1.61	1.68	1.89	1.81	1.84	1.57	1.34
2016	1.04	0.97	1.10	1.17	1.27	1.45	1.47	1.54	1.57	1.51	1.46	1.36
2017	1.20	1.13	1.32	1.38	1.45	1.37	1.61	1.61	1.62	1.78	1.75	1.67
2018	1.48	1.22	1.38	1.36	1.32	1.17	1.28	1.39	1.62	1.70	1.63	1.61
2019	1.52	1.34	1.42	1.42	1.40	1.34	1.49	1.55	1.57	1.57	1.35	1.22
2020	1.06	1.10	1.19	1.41	1.44	1.65	1.59	1.62	1.65	1.50	1.33	1.19
2021	1.03	0.97	1.20	1.28	1.32	1.35	1.30					

Appendix C

Table A3. Derived monthly Fresh Fruit Bunch Index (FFBI) in tons per hectare from February 1986 to June 2021 in Malaysia.

	January	February	March	April	May	June	July	August	September	October	November	December
1986	NULL	0.20	0.06	−0.07	−0.16	−0.13	−0.10	0.00	0.04	0.07	−0.01	−0.13
1987	−0.17	−0.21	−0.20	−0.24	−0.17	−0.10	0.04	0.11	0.10	−0.01	−0.18	−0.29
1988	−0.30	−0.24	−0.14	−0.10	0.00	0.04	0.11	0.03	−0.03	−0.10	−0.10	−0.10
1989	−0.10	−0.12	−0.12	−0.11	−0.03	0.07	0.19	0.26	0.27	0.28	0.25	0.20
1990	0.11	0.05	0.01	0.07	0.07	0.12	0.09	0.10	0.05	−0.05	−0.16	−0.25
1991	−0.27	−0.21	−0.10	0.01	0.01	0.04	0.05	0.12	0.11	0.00	−0.12	−0.21
1992	−0.19	−0.15	−0.10	−0.08	−0.07	−0.04	−0.02	0.04	0.01	0.02	−0.02	−0.05
1993	−0.06	−0.08	0.04	0.09	0.21	0.20	0.23	0.31	0.32	0.29	0.15	0.09
1994	0.03	−0.02	−0.08	−0.13	−0.13	−0.13	−0.08	−0.02	0.07	0.11	0.16	0.18
1995	0.18	0.13	0.05	−0.03	−0.06	−0.05	−0.01	0.00	0.01	0.06	0.09	0.09
1996	0.00	0.00	−0.01	0.09	0.09	0.09	0.08	0.05	0.10	0.05	0.02	−0.06
1997	−0.07	−0.02	0.07	0.14	0.16	0.15	0.13	0.10	0.08	0.05	−0.04	−0.16
1998	−0.16	−0.16	−0.13	−0.20	−0.18	−0.16	−0.14	−0.16	−0.22	−0.27	−0.32	−0.33
1999	−0.28	−0.17	0.02	0.19	0.29	0.24	0.13	0.05	0.04	0.06	0.10	0.09
2000	0.09	0.02	−0.03	−0.10	−0.13	−0.19	−0.18	−0.11	0.04	0.17	0.19	0.28
2001	0.30	0.31	0.19	0.11	0.05	−0.05	−0.14	−0.15	−0.08	−0.02	0.02	0.07
2002	0.07	0.06	−0.02	−0.05	−0.08	−0.10	−0.09	−0.06	−0.02	−0.04	−0.07	−0.08
2003	−0.06	−0.01	0.05	0.14	0.19	0.20	0.16	0.08	−0.03	−0.13	−0.07	−0.05
2004	0.02	−0.05	−0.05	−0.06	−0.03	0.01	0.01	0.05	0.01	0.03	0.08	0.15

Table A3. *Cont.*

	January	February	March	April	May	June	July	August	September	October	November	December
2005	0.19	0.17	0.16	0.16	0.09	0.03	−0.02	−0.03	−0.05	−0.05	−0.07	−0.08
2006	0.00	0.08	0.18	0.20	0.18	0.13	0.10	0.09	0.04	0.08	0.02	0.10
2007	0.05	0.06	−0.01	−0.04	−0.08	−0.06	−0.02	0.04	0.05	0.12	0.17	0.28
2008	0.27	0.26	0.18	0.15	0.13	0.14	0.11	0.03	0.01	0.06	0.16	0.20
2009	0.17	0.14	0.06	0.03	0.00	−0.01	−0.05	−0.09	0.03	0.10	0.21	0.14
2010	0.12	0.09	0.04	0.02	−0.03	−0.02	−0.02	−0.07	−0.11	−0.14	−0.12	−0.14
2011	−0.10	0.01	0.13	0.23	0.26	0.24	0.13	0.07	0.06	0.08	0.09	0.05
2012	0.05	−0.03	−0.09	−0.14	−0.13	−0.06	−0.04	0.04	0.07	0.20	0.27	0.33
2013	0.27	0.14	0.01	−0.08	−0.12	−0.09	−0.04	0.02	0.05	0.11	0.16	0.17
2014	0.13	0.09	0.04	0.05	0.00	−0.04	0.01	0.02	0.04	−0.02	−0.04	−0.09
2015	−0.13	−0.09	0.01	0.10	0.13	0.10	0.10	0.05	0.04	−0.04	−0.07	−0.17
2016	−0.21	−0.24	−0.23	−0.22	−0.17	−0.15	−0.14	−0.22	−0.26	−0.27	−0.21	−0.15
2017	−0.10	−0.06	−0.03	−0.02	−0.07	−0.07	−0.10	−0.13	−0.13	−0.06	0.08	0.14
2018	0.13	0.08	0.01	−0.05	−0.18	−0.29	−0.35	−0.31	−0.23	−0.13	−0.01	0.10
2019	0.16	0.15	0.09	0.01	−0.08	−0.13	−0.17	−0.21	−0.24	−0.28	−0.27	−0.28
2020	−0.20	−0.16	−0.07	−0.06	0.03	0.02	−0.01	−0.12	−0.21	−0.29	−0.31	−0.31
2021	−0.26	−0.21	−0.16	−0.14	−0.15	−0.22	NULL					

Appendix D

Table A4. Oceanic Niño Index (ONI) from January 1983 to June 2021 [18].

	January	February	March	April	May	June	July	August	September	October	November	December
1983	2.2	1.9	1.5	1.3	1.1	0.7	0.3	−0.1	−0.5	−0.8	−1.0	−0.9
1984	−0.6	−0.4	−0.3	−0.4	−0.5	−0.4	−0.3	−0.2	−0.2	−0.6	−0.9	−1.1
1985	−1.0	−0.8	−0.8	−0.8	−0.8	−0.6	−0.5	−0.5	−0.4	−0.3	−0.3	−0.4
1986	−0.5	−0.5	−0.3	−0.2	−0.1	0.0	0.2	0.4	0.7	0.9	1.1	1.2
1987	1.2	1.2	1.1	0.9	1.0	1.2	1.5	1.7	1.6	1.5	1.3	1.1
1988	0.8	0.5	0.1	−0.3	−0.9	−1.3	−1.3	−1.1	−1.2	−1.5	−1.8	−1.8
1989	−1.7	−1.4	−1.1	−0.8	−0.6	−0.4	−0.3	−0.3	−0.2	−0.2	−0.2	−0.1
1990	0.1	0.2	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.3	0.4	0.4
1991	0.4	0.3	0.2	0.3	0.5	0.6	0.7	0.6	0.6	0.8	1.2	1.5
1992	1.7	1.6	1.5	1.3	1.1	0.7	0.4	0.1	−0.1	−0.2	−0.3	−0.1
1993	0.1	0.3	0.5	0.7	0.7	0.6	0.3	0.3	0.2	0.1	0.0	0.1
1994	0.1	0.1	0.2	0.3	0.4	0.4	0.4	0.4	0.6	0.7	1.0	1.1
1995	1.0	0.7	0.5	0.3	0.1	0.0	−0.2	−0.5	−0.8	−1.0	−1.0	−1.0
1996	−0.9	−0.8	−0.6	−0.4	−0.3	−0.3	−0.3	−0.3	−0.4	−0.4	−0.4	−0.5
1997	−0.5	−0.4	−0.1	0.3	0.8	1.2	1.6	1.9	2.1	2.3	2.4	2.4
1998	2.2	1.9	1.4	1.0	0.5	−0.1	−0.8	−1.1	−1.3	−1.4	−1.5	−1.6
1999	−1.5	−1.3	−1.1	−1.0	−1.0	−1.0	−1.1	−1.1	−1.2	−1.3	−1.5	−1.7
2000	−1.7	−1.4	−1.1	−0.8	−0.7	−0.6	−0.6	−0.5	−0.5	−0.6	−0.7	−0.7
2001	−0.7	−0.5	−0.4	−0.3	−0.3	−0.1	−0.1	−0.1	−0.2	−0.3	−0.3	−0.3
2002	−0.1	0.0	0.1	0.2	0.4	0.7	0.8	0.9	1.0	1.2	1.3	1.1
2003	0.9	0.6	0.4	0.0	−0.3	−0.2	0.1	0.2	0.3	0.3	0.4	0.4
2004	0.4	0.3	0.2	0.2	0.2	0.3	0.5	0.6	0.7	0.7	0.7	0.7
2005	0.6	0.6	0.4	0.4	0.3	0.1	−0.1	−0.1	−0.1	−0.3	−0.6	−0.8
2006	−0.9	−0.8	−0.6	−0.4	−0.1	0.0	0.1	0.3	0.5	0.8	0.9	0.9
2007	0.7	0.2	−0.1	−0.3	−0.4	−0.5	−0.6	−0.8	−1.1	−1.3	−1.5	−1.6
2008	−1.6	−1.5	−1.3	−1.0	−0.8	−0.6	−0.4	−0.2	−0.2	−0.4	−0.6	−0.7
2009	−0.8	−0.8	−0.6	−0.3	0.0	0.3	0.5	0.6	0.7	1.0	1.4	1.6
2010	1.5	1.2	0.8	0.4	−0.2	−0.7	−1.0	−1.3	−1.6	−1.6	−1.6	−1.6
2011	−1.4	−1.2	−0.9	−0.7	−0.6	−0.4	−0.5	−0.6	−0.8	−1.0	−1.1	−1.0
2012	−0.9	−0.7	−0.6	−0.5	−0.3	0.0	0.2	0.4	0.4	0.3	0.1	−0.2
2013	−0.4	−0.4	−0.3	−0.3	−0.4	−0.4	−0.4	−0.3	−0.3	−0.2	−0.2	−0.3
2014	−0.4	−0.5	−0.3	0.0	0.2	0.2	0.0	0.1	0.2	0.5	0.6	0.7
2015	0.5	0.5	0.5	0.7	0.9	1.2	1.5	1.9	2.2	2.4	2.6	2.6
2016	2.5	2.1	1.6	0.9	0.4	−0.1	−0.4	−0.5	−0.6	−0.7	−0.7	−0.6
2017	−0.3	−0.2	0.1	0.2	0.3	0.3	0.1	−0.1	−0.4	−0.7	−0.8	−1.0
2018	−0.9	−0.9	−0.7	−0.5	−0.2	0.0	0.1	0.2	0.5	0.8	0.9	0.8
2019	0.7	0.7	0.7	0.7	0.5	0.5	0.3	0.1	0.2	0.3	0.5	0.5
2020	0.5	0.5	0.4	0.2	−0.1	−0.3	−0.4	−0.6	−0.9	−1.2	−1.3	−1.2
2021	−1.0	−0.9	−0.8	−0.7	−0.5	−0.4						

Appendix E

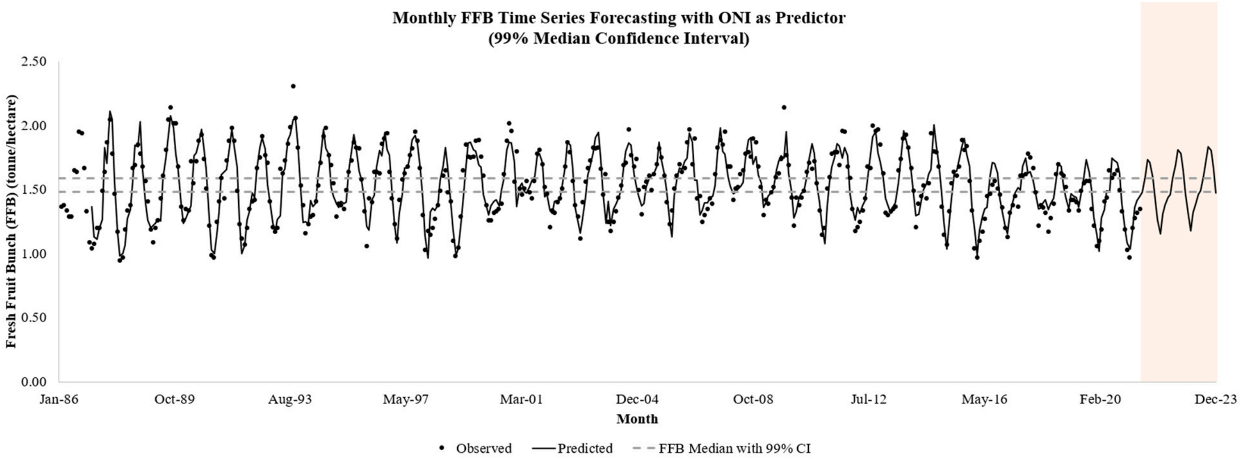

Figure A1. FFB time series, ARIMA (2,0,2) (1,1,1) model with ONI as predictor (adjusted R-squared = 0.8274). Modelled period: February 1986 to June 2021 (N = 425). 30 months forecasted period: July 2021 to December 2023 (N = 30, highlighted area of Figure A1). Note: Dash lines represent BCa 99% confidence interval range of monthly oil palm yield in Malaysia. FFB model predicts monthly oil palm yield to fluctuate around the BCa 99% confidence interval range in next 30 months.

Appendix F

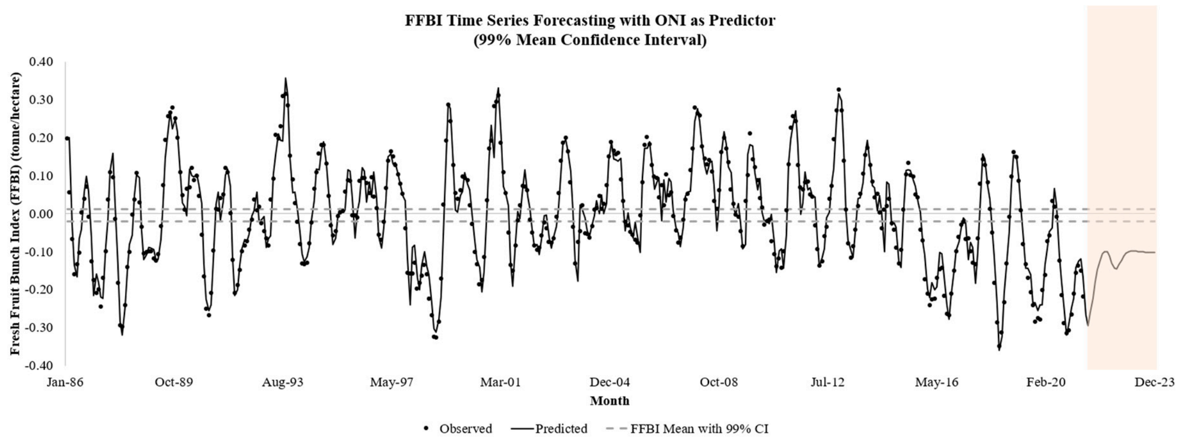

Figure A2. The new FFBI time series, ARIMA (3,1,3) (0,0,1) model with ONI as predictor (adjusted R-squared = 0.9312). Modelled period: February 1986 to June 2021 (N = 425). 30 months forecasted period: July 2021 to December 2023 (N = 30, highlighted area of Figure A2). Note: Dash lines represent BCa 99% confidence interval range of monthly oil palm yield in Malaysia. Unlike FFB model (Figure A1), FFBI model revealed a future monthly under yield concern of Malaysian oil palm industry.

Appendix G

Table A5. FFBI time series forecasting validation models' summary with residual analyses using descriptive and inferential statistics at $\alpha = 0.01$.

Modelled Period	1986–2015	1987–2016	1988–2017	1989–2018	1990–2019	1991–2020
Model	ARIMA (1,1,5) (0,0,1)	ARIMA (0,0,4) (0,0,0)	ARIMA (3,1,3) (0,0,1)	ARIMA (0,0,4) (0,0,0)	ARIMA (0,0,4) (0,0,1)	ARIMA (3,1,3) (0,0,1)
R−Squared	0.9285	0.9164	0.9281	0.9198	0.9238	0.9354
Adjusted R−Squared	0.9283	0.9162	0.9279	0.9196	0.9236	0.9352
Residual Skewness	−0.5314	−0.1992	−0.7146	−0.3753	−0.5032	−0.7131
Residual Range	0.2310	0.3372	0.2288	0.2741	0.2405	0.2265

Table A5. *Cont.*

Modelled Period	1986–2015	1987–2016	1988–2017	1989–2018	1990–2019	1991–2020
Residual Median	0.0001	−0.0002	0.0001	0.0020	0.0015	0.0036
(BCa 99% CI)	[−0.0044, 0.0063]	[−0.0058, 0.0083]	[−0.0052, 0.0063]	[−0.0039, 0.0064]	[−0.0048, 0.0081]	[−0.0028, 0.0079]
Residual Standard Deviation	0.0342	0.0375	0.0345	0.0374	0.0367	0.0343
(BCa 99% CI)	[0.0304, 0.0382]	[0.0331, 0.043]	[0.0303, 0.0387]	[0.0333, 0.0415]	[0.0326, 0.0408]	[0.0305, 0.0382]
Residual Variance	0.0012	0.0014	0.0012	0.0014	0.0013	0.0012
(BCa 99% CI)	[0.0009, 0.0015]	[0.0011, 0.0018]	[0.0009, 0.0015]	[0.0011, 0.0017]	[0.0011, 0.0017]	[0.0009, 0.0015]

Appendix H

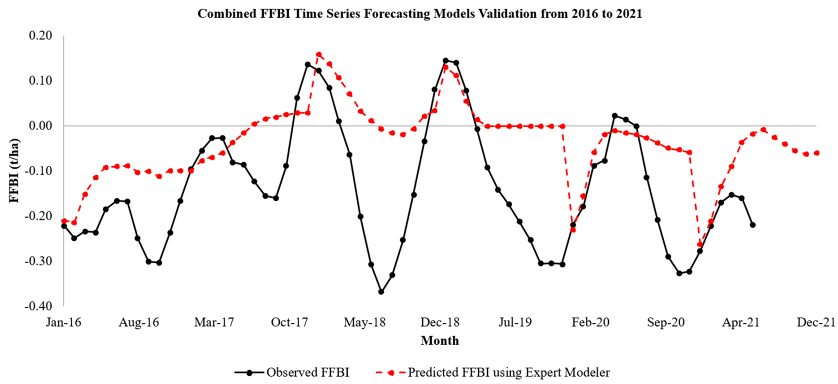

Figure A3. FFBI time series forecasting validation models (total of 6 models combined). Modelled period: moving 30 years starting from 1986 (N = 360) with 12 months forecasted period. Note: Predicted FFBI (Red dash line) from January 2016 to December 2016 are values predicted from 1986–2015 model and so on with a moving 30 years validation.

Appendix I

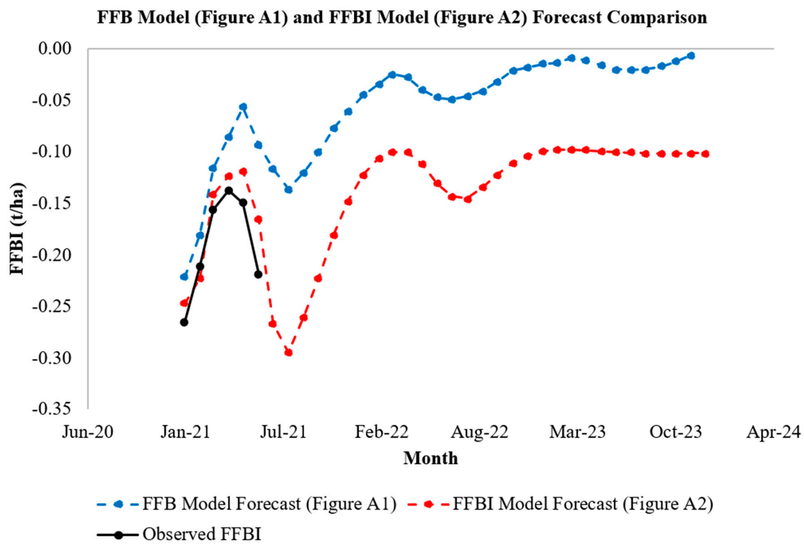

Figure A4. Predicted values from 2021 to 2023 (N = 36) using FFB model (Figure A1) and proposed FFBI model (Figure A2) were compared to observed FFBI from January 2021 to June 2021 (N = 6).

Appendix J

Table A6. Monthly crude palm oil (CPO) price in Malaysian Ringgit (MYR) per ton from January 1986 to June 2021 [52].

	January	February	March	April	May	June	July	August	September	October	November	December
1986	637	476	653	553	589	573	504	448	504	723	718	712
1987	900	750	748	690	725	751	678	721	800	760	883	1093
1988	1068	895	906	916	1017	1220	1011	981	979	1073	985	967
1989	955	942	903	922	904	810	668	699	779	787	633	659
1990	696	683	695	705	700	710	701	708	707	752	863	896
1991	848	850	770	775	755	768	867	791	807	883	884	914
1992	888	891	905	848	848	859	826	841	868	917	938	953
1993	960	968	933	875	851	820	847	852	780	787	857	992
1994	970	943	974	1089	1107	1086	1185	1278	1404	1478	1647	1580
1995	1449	1551	1489	1311	1296	1345	1419	1321	1355	1417	1392	1354
1996	1185	1178	1214	1250	1188	1077	1099	1238	1142	1181	1207	1255
1997	1296	1264	1258	1281	1230	1157	1163	1305	1573	1709	1784	2075
1998	2392	2117	2145	2295	2292	2323	2428	2499	2234	2333	2302	2156
1999	1854	1563	1523	1586	1355	1232	988	1310	1239	1235	1245	1176
2000	1133	1040	1196	1149	1035	1030	1033	1003	901	852	822	804
2001	780	751	880	766	764	865	1236	1069	940	990	1097	1146
2002	1155	1150	1152	1204	1426	1355	1502	1470	1361	1510	1588	1644
2003	1619	1594	1433	1355	1416	1408	1280	1339	1460	1762	1737	1774
2004	1778	1947	1937	1888	1610	1550	1419	1515	1413	1438	1425	1387
2005	1274	1403	1461	1429	1412	1408	1377	1370	1460	1445	1391	1415
2006	1443	1507	1437	1481	1444	1491	1641	1578	1559	1661	1940	1995
2007	1900	1960	2070	2214	2581	2427	2608	2420	2644	2880	2930	3050
2008	3232	4005	3395	3395	3498	3598	3050	2620	2090	1515	1632	1695
2009	1779	1895	2000	2595	2560	2230	2189	2370	2105	2208	2472	2663
2010	2445	2595	2556	2558	2436	2373	2517	2570	2730	3061	3412	3788
2011	3809	3472	3326	3270	3393	3072	3096	3009	2905	2938	3018	3175
2012	3078	3270	3433	3471	3101	3020	2980	3019	2546	2496	2370	2438
2013	2557	2397	2378	2286	2397	2344	2236	2404	2320	2593	2654	2659
2014	2559	2800	2634	2623	2423	2426	2257	1929	2217	2306	2172	2266
2015	2146	2305	2165	2102	2216	2229	2120	1991	2375	2363	2344	2485
2016	2443	2548	2725	2593	2620	2353	2316	2526	2636	2763	3073	3109
2017	3029	2770	2646	2508	2499	2459	2675	2706	2695	2815	2603	2503
2018	2492	2559	2425	2362	2429	2326	2194	2248	2174	2150	2040	2121
2019	2299	2121	2106	2095	2069	1951	2070	2234	2135	2485	2744	3052
2020	2604	2319	2402	2088	2292	2297	2677	2738	2714	3011	3305	3600
2021	3490	3742	3612	3868	3919	3599						

Appendix K

Table A7. Annual oil palm matured area, oil extraction rate (OER) and fresh fruit bunch (FFB) yield from 1986 to 2020 in Malaysia [5–7].

Year	Matured Area (ha)	OER (%)	FFB Yield (t/ha)
1986	1,360,579	19.62	22.15
1987	1,373,147	19.87	17.10
1988	1,530,906	19.87	17.52
1989	1,672,096	19.78	19.57
1990	1,746,054	19.64	18.53
1991	1,826,267	19.47	17.85
1992	1,890,268	19.21	17.83
1993	2,020,516	18.67	20.26
1994	2,144,080	18.63	18.42
1995	2,243,065	18.51	18.93
1996	2,353,147	18.71	18.95
1997	2,513,183	19.03	19.10
1998	2,638,020	18.91	15.98
1999	2,856,701	18.60	19.26
2000	2,941,791	18.86	18.33
2001	3,005,267	19.22	19.14

Table A7. *Cont.*

Year	Matured Area (ha)	OER (%)	FFB Yield (t/ha)
2002	3,188,307	19.91	17.97
2003	3,303,133	19.75	18.99
2004	3,450,960	20.03	18.60
2005	3,631,440	20.15	18.88
2006	3,703,254	20.04	19.60
2007	3,764,389	20.13	19.03
2008	3,915,924	20.21	20.18
2009	4,075,702	20.49	19.20
2010	4,202,213	20.45	18.03
2011	4,281,837	20.35	19.69
2012	4,352,872	20.35	18.89
2013	4,526,089	20.25	19.02
2014	4,689,321	20.62	18.63
2015	4,859,397	20.46	18.48
2016	5,001,438	20.18	15.91
2017	5,110,713	19.72	17.89
2018	5,189,344	19.95	17.16
2019	5,216,822	20.21	17.19
2020	5,231,743	19.92	16.73

Annual FFB yields highlighted in red are the ones below the mean 99% confidence interval [18.02, 19.08]. All FFB yields below the mean confidence limit are associated with El Niño years, except for 2017 and after. Although there was a weak El Niño in 2018/19, the annual FFB yields never fall below the mean confidence limit due to weak El Niño based on the historical 35 years records.

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