The Effect of Climate Anomalies on Oil Palm Productivity: A Quantitative Analysis

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Abstract. Oil palm productivity is strongly influenced by climate anomalies, particularly rainfall and temperature fluctuations linked to El Niño events. This study quantitatively assessed their impacts using climate data (2014–2023) and productivity data (2016–2023) from 124.49 ha of oil palm plantations (10–17 years old) in South Kalimantan, Indonesia. Time-lagged regression models (0, 1, and 2 years) revealed that a 1°C increase in temperature one year prior reduced the yield by 3.741 bunches per tree and 7.08 tons per hectare. Rainfall in the same period increased average bunch weight by 0.156 kg per 100 mm, though it did not affect yield or bunch number. Two years before harvest, rainfall exerted a stronger positive influence: every 100 mm increase raised bunch number by 0.133, average bunch weight by 0.079 kg, and yield by 0.422 ton per ha, while a 1°C temperature rise reduced 1.29 bunches per tree, 0.26 kg in bunch weight, and 3.24 ton per ha. In contrast, current-year rainfall had a negative effect, lowering yield by 0.307 tons per hectare for every 100 mm. These findings highlight that oil palm productivity is most sensitive to climate anomalies one to two years prior to harvest, emphasising the importance of long-term climate management strategies for sustainable production.

1 Introduction

Indonesia's rapid growth in CPO production has changed its position as the world's largest CPO producer, which is widely used in the food, cosmetics, and biofuel industries, and contributes significantly to the economies of many producing countries. However, palm oil production is susceptible to climatic variables, especially rainfall and temperature. Fluctuations in climate patterns, including the increasing frequency of El Niño events, have been linked to changes in the productivity of oil palm plantations. These anomalies can significantly impact crop growth, yields, and sustainability, making it essential to understand their effectsn palm oil production.

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Palm oil productivity has exhibited significant variability in recent years, largely influenced by climate anomalies, such as those caused by El Niño. Changes in rainfall patterns, including droughts, directly impact palm oil yields, reducing overall productivity. A study by Sato & Ikoma [1] found that increased temperatures can decrease the number of bunches per tree and decrease fruit quality. The effect of irregular rainfall patterns on oil palm productivity has also been documented, with extreme weather conditions leading to declining growth rates [2]. The frequency of these anomalies is expected to increase, making it crucial for researchers, policymakers, and stakeholders in the palm oil industry to collaborate in developing strategies to mitigate their impact on palm oil production [3].

Previous studies have primarily focused on the immediate effects of rainfall and temperature variability on oil palm growth and yield. However, these approaches often overlook the delayed physiological responses of the oil palm, which has a long reproductive cycle. Unlike prior studies, this research introduces a time-lag analysis, assessing not only current-year climate anomalies but also their impacts one and two years before harvest. This approach offers a more comprehensive understanding of how past climate variability influences current productivity outcomes. By explicitly accounting for lagged effects, the study offers a novel contribution to palm oil–climate research, highlighting the importance of incorporating historical climate signals into yield prediction and management strategies.

2 Data Analysis

The research was conducted at the PT. Citra Putra Kebun Asri, Jorong District, Tanah Laut Regency, South Kalimantan. Climate data were obtained from monthly records from 2014 to 2023. Productivity data (tons per ha, average bunch weight, number of bunches per tree) were collected from 2016 to 2023 on 124.49 ha of oil palm planted land with a planting age of 10–17 years. The plantation site was selected based on uniform age classes (10–17 years) and consistent management practices to minimise variability unrelated to climate conditions. Data collection was restricted to a fixed plantation area of 124.49 ha to ensure comparability across years. Standardised measurement protocols were applied for productivity indicators (bunches per tree, average bunch weight, and yield per hectare), and the same sources of climate data (BMKG monthly rainfall and temperature records) were used throughout the study period to maintain consistency and reliability over time. The analysis was conducted using quantitative descriptive methods, correlation analysis, and multiple regression, employing a time lag model of 0, 1, and 2 years to examine the impact of climate anomalies on oil palm productivity. Multiple linear regression is a linear regression model that involves more than one independent variable or predictor expressed in mathematical equations as follows.

$$Y = a + b1X1 + b2X2 + \cdots + bnXn$$

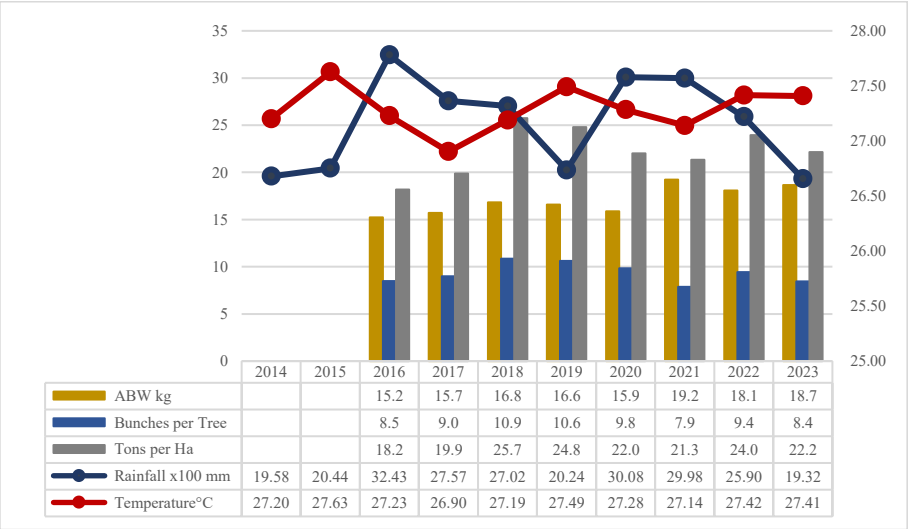
Description:

Y	= Dependent Variable
X1,X2,X3	= Independent variables
a	= Konstanta
b1,b2,b3	= Regression Coefficients
e	= Confounding Variable

3 Results

Rainfall and air temperature data from 2014 to 2023 reflect 10 years of climate anomaly data. Oil palm productivity data for 2016 to 2023 provides an overview of production trends

influenced by seasonal factors and plant physiological conditions. Oil palm productivity and climate anomalies are presented in Figure 1 below:



	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
ABW kg			15.2	15.7	16.8	16.6	15.9	19.2	18.1	18.7
Bunches per Tree			8.5	9.0	10.9	10.6	9.8	7.9	9.4	8.4
Tons per Ha			18.2	19.9	25.7	24.8	22.0	21.3	24.0	22.2
Rainfall x100 mm	19.58	20.44	32.43	27.57	27.02	20.24	30.08	29.98	25.90	19.32
Temperature°C	27.20	27.63	27.23	26.90	27.19	27.49	27.28	27.14	27.42	27.41

Fig. 1. Graph of rainfall, air temperature, and oil palm productivity.

The analysis of the data in Table 1 reveals trends in average bunch weight (ABW), bunches per tree, and productivity per hectare (tons per hectare), as well as climatic conditions over several years, focusing on the 2-, 1-, and 0-year lag periods. During the 2-year gap period, a decrease in the number of bunches and productivity per hectare was observed between 2016 and 2023, which correlated with fluctuations in rainfall and temperature in previous years. Within the 1-year time lag, the data indicated that the ABW was slightly higher than in the previous year, which could potentially be attributed to better rainfall conditions. In a 0-year gap, a direct comparison between temperature and precipitation revealed dissimilar productivity, suggesting that other potential factors may influence productivity beyond climatic conditions. Analysis of this data suggests a possible indirect influence of environmental factors on productivity, which may not be immediately reflected in the same year.

Multiple regression analysis of the effect of rainfall and air temperature in the current year (CY) is presented in Table 1.

Table 1. The effect of rainfall and air temperature for the current year (cy) on oil palm productivity.

Independent Variables	**P-Value**		
	Bunches per Tree	**ABW (kg)**	**Tons per Ha**
Rainfall (mm)	0.049*	0.001*	0.000*
Air Temperature (oC)	0.269	0.000*	0.027*
Dependence Variable	Regression Equations		R2
Bunches per Tree	Y = 35.5 - 0.000637 CH(CY) - 0.898 Tavg(CY)		9.24%
Average Bunch Weight	Y = -114.6 - 0.001252 CH(CY) + 4.949 Tavg(CY)		41.57%
Productivity Tons per Ha	Y = -77.0 - 0.003070 CH(CY) + 3.94 Tavg(CY)		32.13%

Description : CH(CY) = Rainfall for the current year; Tavg(CY) = Average Air Temperature for the Current Year.

The regression analysis in Table 1 examines the effect of the current year's rainfall (CH(CY)) and air temperature (Tavg(CY)) on palm oil productivity. The p-value indicates that rainfall (CH(CY)) has a significant impact on the three dependent variables: bunches per

tree, ABW (kg), and tons per ha productivity, with p-values of 0.049*, 0.001*, and 0.000*, respectively. Air temperature (Tavg(CY)) had a significant effect on ABW (kg) and Tons per ha, with p values of 0.000* and 0.027*, but not significant for bunches per tree (p value = 0.269). The regression equation indicates that a 100 mm increase in rainfall per year results in a decrease of 0.0637 bunches per tree, 0.1252 ABW (kg), and 0.3070 tons per hectare in productivity. An increase in air temperature of 1 °C increased the ABW (kg) by 4.949, but had no significant effect on the bunches per tree, collectively reducing productivity by 3.94 tons per ha. In conclusion, rainfall and air temperature have a significant impact on palm oil productivity, with rainfall exhibiting the most pronounced influence across all variables.

Table 2. The effect of rainfall and lag-1 year (T-1) air temperature on oil palm productivity.

Independent Variables	P-Value		
	Bunches per Tree	**ABW (kg)**	**Tons per Ha**
Rainfall (mm)	0.087	0.002*	0.228
Air Temperature (oC)	0.000*	0.144	0.000*
Dependence Variable	Regression Equations		R2
Bunches per Tree	Y = 112.6 - 0.000430 CH(T-1) - 3.741 Tavg(T-1)		51.54%
Average Bunch Weight	Y = -25.8 + 0.001558 CH(T-1) + 1.417 Tavg(T-1)		18.25%
Productivity Tons per Ha	Y = 213.2 + 0.000871 CH(T-1) - 7.08 Tavg(T-1)		34.63%

Description: CH(T-1) = Rainfall 1 Year Before Harvest; Tavg(T-1) = Average Air Temperature 1 Year Before Harvest.

The regression analysis in Table 2 shows the relationship between rainfall (CH(T-1)) and air temperature (Tavg(T-1)) with palm oil productivity. Based on p-values, air temperature (Tavg(T-1)) significantly affects the dependent variables of bunches per tree and productivity (tons per ha), with p-values of 0.000* and 0.000*, respectively, indicating a strong statistical relationship. On the other hand, rainfall (CH(T-1)) only had a significant effect on ABW (kg) with a p value of 0.002*, but had no significant impact on bunches per tree (p-value = 0.087) or tons per ha (p value = 0.228). The regression equation shows that for every 100 mm increase in rainfall per year, the number of bunches per tree decreases by 0.0430, while for every 1 °C increase in air temperature, the number of bunches per tree decreases by 3.741. ABW (kg) increased by 0.1558 for each unit of 100 mm increase in precipitation, but decreased by 1.417 for each increase in air temperature. Finally, production per hectare (tons per hectare) decreased by 7.08 for each unit increase in air temperature, but increased by 0.0871 for every 100 mm increase in precipitation. In conclusion, air temperature one year before harvest has a more significant impact on oil palm productivity than rainfall, particularly on the number of bunches per tree and tons per hectare.

Table 3. The effect of rainfall and air temperature lag-2 year (T-2) on oil palm productivity.

Independent Variables	P-Value		
	Bunches per Tree	**ABW (kg)**	**Tons per Ha**
Rainfall (mm)	0.000*	0.072	0.000*
Air Temperature (oC)	0.02*	0.801	0.003*
Dependence Variable	Regression Equations		R2
Bunches per Tree	Y = 41.1 + 0.001325 CH(T-2) - 1.290 Tavg(T-2)		44.04%
Average Bunch Weight	Y = 22.1 + 0.000794 CH(T-2) - 0.26 Tavg(T-2)		6.18%
Productivity Tons per Ha	Y = 99.6 + 0.004219 CH(T-2) - 3.24 Tavg(T-2)		67.25%

Description: CH(T-2) = Rainfall 2 Years Before Harvest; Tavg(T-2) = Air temperature 2 years before harvest.

The regression analysis in Table 3 examined the impact of rainfall (CH(T-2)) and air temperature (Tavg(T-2)) from two years before harvest on oil palm productivity. The p-value

indicates that rainfall significantly affects the number of bunches per tree and the productivity in tons per hectare, with p-values of 0.000* and 0.000*, respectively. At the same time, it has no significant effect on ABW (kg) (p-value = 0.072). Air temperature significantly affected bunches per tree and tons per ha, with p values of 0.02* and 0.003*, but no significant effect on ABW (kg) (p value = 0.801). The regression equation indicates that a 100 mm increase in rainfall results in 0.1325 additional bunches per tree, 0.0794 additional ABW (kg), and 0.4219 additional tons per hectare. On the other hand, the increase in air temperature lowered the bunches per tree by 1.290, ABW (kg) by 0.26 kg, and decreased productivity by 3.24 tons per hectare. In conclusion, rainfall and air temperature from the previous two years significantly affected oil palm productivity, with rainfall having a positive influence on all variables, while an increase in air temperature had a strong negative influence on the number of bunches, resulting in a decrease in productivity two years after the incident.

To provide a clearer overview, the comparative effects of rainfall and temperature anomalies on oil palm productivity at different lag periods are presented in Figure 2. This graphical summary complements the regression tables and highlights the magnitude of positive and negative influences across Lags 0, 1, and 2.

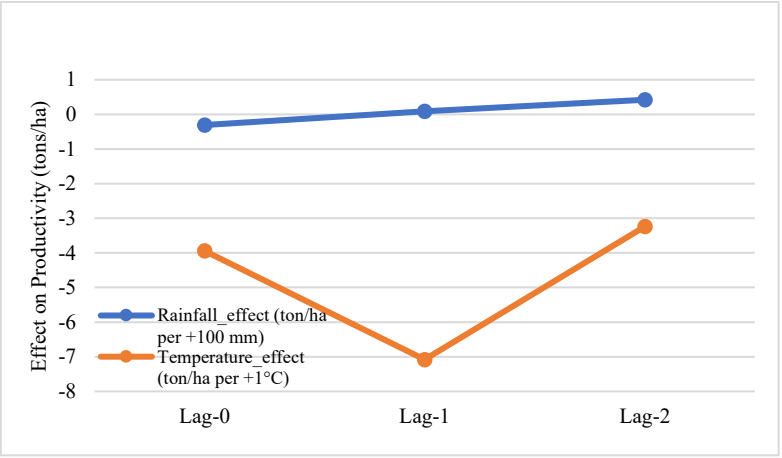


Fig. 2. Effects of rainfall and temperature on oil palm productivity (lag 0–2 years).

As shown in Figure 2, rainfall exhibited a negative effect on productivity in the current year (Lag-0), a slight positive effect one year before harvest (Lag-1), and a stronger positive effect two years before harvest (Lag-2). In contrast, temperature consistently showed negative effects on productivity, with the largest decline observed at Lag-1. These graphical patterns align with the regression outputs presented in Tables 1 through 3.

4 Discussion

The study revealed that during the two-year gap period, declines in the number of bunches and productivity per hectare were recorded in 2016, 2017, 2021, and 2023, with the pattern of fluctuations in rainfall and temperature in previous years playing a significant role. Climate anomalies have a significant impact on the decline in oil palm productivity, especially in terms of the number of bunches and tons per hectare. High rainfall fluctuations and unstable temperatures, characteristic of the El Niño phenomenon, occurred repeatedly in Indonesia in 2014, 2015, 2018, 2019, and 2023, causing disturbances that impacted the resilience of oil palm plants [6, 7, 8]. The results of the research conducted by Sidhu et al.[9] highlight that the initial drought severely affected younger palms, but recovery rates varied, leading to

significant yield declines (23% for younger palms and 30% for older palms) over time. This indicates that climate change not only impacts yields in a single year but also hampers long-term recovery, especially after El Niño events, highlighting the persistent influence of climatic stress on perennial crops.

At a one-year lag, ABW (average bunch weight) increased slightly, likely due to improved rainfall conditions after the drought. However, at a zero-year lag, direct comparisons between temperature and rainfall produced inconsistent results, suggesting that both past climatic factors and other unmeasured variables influence productivity. Pradiko et al. [10], emphasized that current oil palm yields are strongly influenced by climate conditions in previous years, reinforcing the importance of considering cumulative stress and recovery processes when interpreting annual yield fluctuations.

Regression analysis (Table 1) showed that current-year rainfall (CH(CY)) significantly influenced productivity, with higher rainfall reducing bunch numbers, ABW, and yield per hectare. This effect likely results from excessive water that creates anaerobic soil conditions, leaches nutrients, and interferes with root function. Abubakar et al [8] noted that higher rainfall can decrease oil palm productivity, mainly due to fluctuations in soil moisture that adversely affect crop growth. Research indicates that changes in monsoon patterns, characterised by irregular rainfall, can disrupt the optimal moisture levels necessary for oil palm cultivation. These fluctuations in soil moisture have a significant impact on the yield and quality of oil palm fruit. Kong et al. [11] further highlighted that extreme rainfall events cause runoff and nutrient washout, lowering rainfall use efficiency (RUE) and limiting nutrient uptake, which in turn reduces photosynthesis and yield. These findings demonstrate that rainfall in the current year, although essential, can be detrimental when it is excessive or irregular.

Air temperature (Tavg(CY)) did not significantly affect bunch numbers but was positively associated with ABW (resulting in a 4.949 kg increase), while reducing yield by 3.94 tons per hectare. This suggests that higher temperatures may promote faster fruit filling and improve individual bunch size, but simultaneously reduce overall productivity due to thermal stress that limits carbon assimilation and increases respiration losses. High temperatures negatively impact crop yields by disrupting key physiological processes, including net carbon assimilation, membrane stability, and water balance. Although higher air temperatures can improve certain aspects of crop quality, the adverse effects of heat stress during critical developmental stages can lead to significant crop yield losses [12]. Other opinions, such as those of Li et al. [13], highlight that heat stress disrupts physiological and metabolic processes, which can negatively impact fruit yields. Therefore, it makes sense that higher air temperatures can improve certain aspects of fruit quality but simultaneously lower yields due to the detrimental effects of thermal stress on plant physiological functioning. This study shows that rainfall in the current year (Lag-0 year) has a dominant influence on palm oil productivity. At the same time, air temperature plays a more complex role, increasing one variable but decreasing another.

The regression analysis in Table 2 shows that the previous year's air temperature (Tavg(T-1)) significantly influences oil palm productivity, especially in Bunches per Tree and Tons per ha, with a p value of 0.000* in both variables. Each 1°C increase in temperature in the previous year reduced the bunches per tree by 3.741 and tons per ha by 7.08. This suggests that higher air temperatures in the previous year can significantly reduce crop yields. This effect of high temperatures aligns with other research findings that suggest higher temperatures can disrupt the growth and fruit formation cycle in oil palm. Ismail et al. [14] highlight that oil palm trees produce the most fruit in warm, humid regions, suggesting that high temperatures can indeed disrupt the growth and fruit formation cycle.

In contrast, rainfall one year before harvest (CH(T-1)) only had a significant effect on ABW, where each additional 100 mm increased average bunch weight by 0.1558 kg. This

suggests that sufficient water supply during the pre-fruit development phase enhances assimilate partitioning, improving bunch filling and size. However, rainfall did not significantly affect bunch numbers or yield per hectare, which are more strongly determined by age and seasonal cycles [15]. Consequently, productivity per hectare is largely driven by the interaction between ABW and bunch numbers, with age trends explaining most of the variance. Moreover, the study indicates that air temperature one year earlier has an even greater impact than rainfall, as higher temperatures can disrupt growth and fruit formation cycles.

The regression analysis in Table 3 shows that the previous two years of rainfall (CH(T-2)) had a significant influence on oil palm productivity, particularly in terms of bunches per tree and Tons per hectare, with p-values of 0.000* and 0.000*, respectively. An increase in rainfall of 100 mm in the previous two-year period increased the Bunches per Tree by 0.1325, ABW by 0.0794 kg, and Tons per ha by 0.4219. These results suggest that rainfall two years prior could increase the number of bunches, serving as a determining factor in oil palm productivity. Agustiana et al. [16] state that the availability of water, especially during flowering, is an important limiting factor for oil palm production. Water deficits can lead to reduced female flower production and overall plant stress, which impacts growth and development. This highlights the significance of rainfall not only as a direct water source but also as a crucial determinant of reproductive potential in oil palm.

The air temperature of the previous two years (Tavg(T-2)) also significantly affected productivity, with a p value of 0.02* for Bunches per Tree and 0.003* for Tons per ha. The increase in temperature led to a decrease in Bunches per Tree by 1,290, ABW by 0.26 kg, and Tons per ha productivity by 3.24. Two years earlier, the adverse effects of air temperature indicated that higher temperatures could reduce productivity in the long run, along with the increased thermal stress that occurs in plants. Etman et al. [18] state that high temperatures can alter the ecology of pests and diseases, allowing them to thrive and potentially spread throughout the plantation. The disruption of the pollination process due to the decline in pollinating insect populations further exacerbates the negative impact on oil palm production. The study states that the previous two years of air temperature had a significant impact on the number of bunches produced, which in turn greatly affected the productivity of palm oil.

These time-lagged effects reflect the unique physiology of oil palm. The reproductive cycle spans two to three years, with distinct stages of inflorescence initiation, sex differentiation, and fruit development occurring long before harvest. Drought and erratic rainfall reduce photosynthesis, carbohydrate reserves, and female flower initiation, thereby lowering future bunch potential. Prolonged heat stress increases respiration, disrupts carbon assimilation, and reduces pollen viability, leading to poor fruit set and reduced yields. Together, these mechanisms explain why anomalies one or two years earlier strongly determine current yields, as productivity integrates the cumulative effects of past environmental stress on reproductive development.

5 Conclusion

The study reveals that declines in palm oil productivity over several years correlate with fluctuations in rainfall and temperature caused by the El Niño phenomenon, which has become more frequent in recent years, hindering the recovery of palm oil productivity. A 1°C increase in temperature in the previous year reduced the number of bunches per tree by 3.741 and Tons per ha by 7.08, disrupting the growth and fruit formation cycle. Rainfall from the previous year had a significant effect on ABW, with an increase in rainfall of 100 mm and an increase in ABW of 0.1558 kg, although the impact on the number of bunches per tree and Tons per ha was not significant. After the El Niño event, an increase in rainfall of 100 mm two years before harvest increased the number of bunches per tree by 0.1325, ABW by

0.0794 kg, and Tons per ha by 0.4219. In contrast, a temperature increase two years before harvest reduced the number of bunches per tree by 1,290, ABW by 0.26 kg, and Tons per ha by 3.24, suggesting that high temperatures had a detrimental effect on oil palm productivity in the following two years. Rainfall and stable temperatures two years before harvest support optimal oil palm productivity. In practical terms, adaptive plantation management is essential, including supplemental irrigation, mulching, soil moisture conservation, and drought preparedness programs, supported by the integration of long-term climate forecasts into plantation planning to ensure resilient and sustainable oil palm production.

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