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Effect of water deficit of Ultisols, Entisols, Spodosols, and Histosols on oil palm productivity in Central Kalimantan

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ABSTRACT

The same rainfall can cause different degrees of water stress depending on soil type, so the production response shown by plants can be different. This study is essential for growers, especially in predicting oil palm production based on water deficit for each soil type. The study was conducted on oil palm plantations in Central Kalimantan, Indonesia, with four soil types in 1,446.15 ha (40 blocks). The source of data collected from oil palm plantations included bunch number, average bunch weight, rainfall, and soil physical and chemical properties for the last 15 years (2007 - 2021). This experimental study used a two-stage cluster sampling method. The results showed that the best productivity, bunch number, and average bunch weight were found on Ultisols. The four soil types tested showed the same annual production distribution dynamic, but the response rate from each soil type showed differences. Entisols and Spodosols were more prone to drought stress due to water deficit than Ultisols and Histosols because of the differences in soil texture. Water deficit causes a decrease in oil palm productivity by 5 - 22% in the first year (Ultisols 12 - 22%; Entisols 12 - 22%; Spodosols 7 - 19%; Histosols 5 - 15%) and 1 - 8% in the second year (Ultisols 3 - 7%; Entisols 2 - 4%; Spodosols 5 - 8%; Histosols 1 - 5%) compared to previous years production. A decrease in oil palm productivity occurs at 3 - 5 months (bunch failure phase), 1 year (abortion sensitive phase), and 2 - 2.5 years (sex differentiation phase) after a water deficit appears.

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1. INTRODUCTION

The availability of sufficient water is vital in the palm's growth and development process (Carr, 2011; Miranda et al., 2021; Perez, 2017). A water deficit is the main limiting cause of stomatal closure, impaired physiological reactions, reduced photosynthetic rate, and thus impaired and reduced growth and yield of oil palm production (Lopes Filho et al., 2021; Rivera-Mendes et al., 2016). The interaction of water and nutrient availability impacts the growth process, biomass partitioning, nutrient concentration, and morphological and physiological characteristics of oil palms (Lindh et al., 2022). Further, water availability for oil palm is determined by an interaction between climate and soil characteristics that are influenced by rainfall, irrigation, soil type, evapotranspiration, drainage, and percolation factors (Gunawan et al., 2020; Woittiez et al., 2017).

Oil palm productivity in Histosols and Ultisols, respectively, reach 28.81 tons ha^{-1} year^{-1} and 25.17 ha^{-1} year^{-1}. In comparison, production in Spodosols reaches only 5.4 tons ha^{-1} year^{-1} (9 years old), but Spodosols with improvement through breaking the hardpan and mounding can reach > 20.0 tons ha^{-1} year^{-1} (Koedadiri & Adiwiganda, 1998; Nasution et al., 2017; Suwardi, 2021). Oil palms (*Elaeis guineensis* Jacq.) require an average rainfall of 150 mm month^{-1} or 1,750 - 3,000 mm year^{-1} with a dry period of no more than 2 - 3 months (Harahap et al., 2013). Rainfall above 2,500 mm is considered unfavorable because it reduces solar radiation

(Ahmed et al., 2021). Rainfall of more than 3,500 mm year^{-1}, less than 2,000 mm year^{-1}, or less than 100 mm month^{-1} can also reduce oil palm production and CPO levels (Kamil & Omar, 2017; Woittiez et al., 2017). The rainfall distribution is closely related to climate change factors, which affect water availability for the production of fresh fruit bunches (FFB) (Hashim et al., 2014). The same amount of rainfall can cause differences in water stress depending on soil type, so plants' production responses can also differ. This is because each soil type has a different capacity to store water.

Water deficit negatively correlates with increasing oil palm production (Sukarman et al., 2021). Shlyannikov (2016) reported that severe water stress reaching 25% evapotranspiration could affect plant physiology through decreased vegetative growth, plant water status, stomata conductance, transpiration rate, and photosynthesis. Azzeme et al. (2016) stated that water stress has potentially caused crop failure, decreasing FFB production by 40% and CPO by 21 - 65%. A water deficit of more than 400 mm/year can reduce the potential yield of crop productivity by one-third, but it also depends on several factors, such as temperature, wind speed, soil texture, and soil depth (Woittiez et al., 2017). Ardiyanto et al. (2021) examined the effect of an increase in water deficit of 10 mm per month in 10 months before harvest (MBH) in Dystrudept, Paleudults, and Haplohumods on monthly FFB production. They found a reduction in a range of 2 - 12%.

Central Kalimantan has relatively varied soil types with a marginal land area of 7.4 million ha (Suharta, 2010). This study helps understand production dynamics based on both marginal and non-marginal soil distribution, and it is very important in predicting plant productivity based on soil types. To date, no one has studied the effects of water deficit on oil palm productivity for different soil types, so the information available is general. As a consequence, the results are less accurate. Detailed data outlining the effect of water deficit on several soil types are extremely valuable for planters to predict their oil palm production in the near future. Moreover, research related to the comparison of Ultisols, Entisols, Spodosols, and Histosols regarding productivity response, bunch number, and average bunch weight (ABW) of oil palm caused by water deficit has not been reported. Therefore, this study aimed to analyze the relationship between water availability and oil palm productivity in Ultisols, Entisols, Spodosols, and Histosols in oil palm plantations in Central Kalimantan, Indonesia.

2. MATERIALS AND METHODS

2.1 Study Site Characteristics

This study was carried out in an oil palm plantation in Central Kalimantan from January to June 2022. It is an experimental study using a two-stage cluster sampling method. The study site terrain is characterized by flat to slightly wavy topography with elevation ranging from around 5 - 32 meters above sea level (m asl). The site has six soil types: Oxisols, Ultisols, Inceptisols, Histosols, Spodosols, and Entisols.

In addition to these soil types, there are soil map units where each soil type cannot be separated from one another into separate map units: local alluvial complex and organic clay muck. Ultisols at the study site are divided into subgroups based on the USDA classification system, including Typic Hapludults, Typic Kanhapludults, Typic Paleudults, Typic Kandiudults, Aquic Paleudults, and Typic Paleaquults. Histosols consist of subgroups typic haplofibrists and typic haplohemists. Spodosols consist of Typic Haplohumods, and Entisols of Albic Quartzipsamments, Humaqueotic Endoaquents, and Humic Quartzipsamments. Ultisols in this study were selected from the subgroups Aquic palaeudults and Typic paleaquult, Entisols from Albic Quartzipsamment, Spodosols from Typic haplohumod, and Histosols from Typic haplohemist. Table 1 shows climate data of the site study from the nearest weather stations (Meteorological, Climatological, and Geophysical Agency) (Sampit, Central Kalimantan).

2.2 Sampling Methods

This sampling method used is a technique that forms several clusters from the population selection process. The first stage involved selecting the area, climate, soil type, and contour. Then the second stage was done by selecting plant age, variety, and block area. This study investigated four (4) soil types, namely Ultisols, Entisols, Spodosols, and Histosols, with repetitions in ten blocks and a planting density/stand per hectare (SPH) of 131 palms (Table 2). The different oil palm varieties (10 blocks) used for each soil type are Lonsum (4 blocks), IOI (3 blocks), and Felda (3 blocks).

The data collected included rainfall, productivity, bunch number, ABW, and soil physical and chemical properties for the last 15 years (2007 - 2021). The details of the data parameters are shown in Table 3.

2.3 Soil Analysis Methods

Blocks for soil sampling were conducted properly based on the cluster sampling method. Soil samples were collected from 0 - 20 cm on the circle and inter-row of oil palm. Composite soil samples were collected, correctly handled, and submitted for laboratory analysis. Physical properties included in the soil analysis were texture and structure. The chemical soil properties analyzed included organic carbon (Walkley and Black method), nitrogen (Kjeldahl method), P_2O_5 (25% HCl extraction), K_2O (25% HCl extraction), MgO (25% HCl extraction), and pH (pH meter).

2.4 Water Deficit Calculation Methods

The soil water balance equation is needed to determine the water deficit value that will be used to analyze the effect of time (months) on oil palm productivity in the four soil types. The water balance was calculated based on the following formula:

$$B = Res + R - PET \quad [1]$$

Where B: water balance at the end of the month; Res: groundwater reserves at the beginning of the month; R: rainfall; PET: potential evapotranspiration.

Potential evapotranspiration was calculated with the available data on the number of rainy days with values of 122 mm month-1 or 4 mm day^{-1} (rainy days > 10 days) and 152 mm month-1 or 5 mm day^{-1} (rainy days < 10 days)

Table 1. The climate condition in the study locations (2010 – 2021)

No	Parameters	Unit	Year											
			2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	Minimum Air Temperature	(°C)	23.4	22.4	22.4	22.4	22.6	23.0	23.5	23.3	23.0	23.0	23.6	23.4
2	Maximum Air Temperature	(°C)	32.9	32.7	32.6	32.8	33.2	33.0	32.9	32.7	32.8	32.9	32.5	32.4
3	Average Air Temperature	(°C)	26.8	26.4	26.7	26.9	27.1	27.0	27.2	26.9	26.9	27.1	27.1	27.0
4	Relative Humidity	(%)	83.9	83.1	83.2	83.5	82.6	84.8	86.4	85.9	85.3	85.2	86.9	87.0
5	Average Sunshine duration	(hour day^{-1})	4.4	4.5	4.6	4.4	3.7	4.8	5.1	4.8	5.4	5.0	5.0	5.0
6	Total Sunshine duration	hour $month^{-1}$	120	132	134	134	11	127	142	132	145	153	146	150
7	Maximum Wind Speed	(m s^{-1})	3.98	4.62	4.63	4.40	3.75	3.75	4.33	4.21	4.11	3.82	3.99	3.84
8	Average Wind Speed	(m s^{-1})	1.86	2.00	1.89	1.14	1.22	1.24	1.21	1.36	1.16	1.22	1.53	1.29
9	Rainy Days	(day $year^{-1}$)	215	149	143	157	140	127	182	181	164	132	192	179
10	Rainfall	(mm $year^{-1}$)	3,944	2,344	2,531	2,943	2,497	2,041	2,622	3,034	2,838	2,114	3,536	2,772

Table 2. Soil type and area in the studied block

Soil Type	Year of Planting	Stand per Ha (SPH)	Replication (Block)	Area (Ha)
Ultisols	2007	132.7	10	408.32
Entisols	2007	131.7	10	337.96
Spodosols	2007	132.0	10	394.76
Histosols	2007	131.2	10	305.11
Total		**131.9**	**40**	**1,446.15**

Table 3. Parameters and data source

No	Data Source	Data Type	Parameters	Year
1	Company (Site Study)	Secondary Data	Productivity, bunch number, average bunch weight, rainfall, rainy days	2007 - 2021
2	Meteorological, Climatological, and Geophysical Agency	Primary Data	Soil physical and chemical properties	2017 - 2021
		Secondary Data	Air Temperature, Relative Humidity, Sunshine duration, Wind Speed	2010 - 2021

(Afandi et al., 2022; Corley & Tinker, 2015; Suharyanti et al., 2020). However, when there are no rainy days (0 rainy days), the potential evapotranspiration value was calculated as 198 mm $month^{-1}$ or 6.5 – 7.5 mm day^{-1}. The critical deficit factor in oil palm is rarely used, and the value of available water content (AWC) is used to calculate the water balance. The critical deficit value is needed to determine the soil water holding capacity (SWHC), calculated based on the AWC multiplied by 70%. If the water balance is negative, it indicates a water deficit (B < 0 = water deficit).

2.4 Data Analysis Methods

Data were analyzed using ANOVA and Duncan Multiple Range Test (DMRT) to compare oil palm productivity of different soil types. Multiple correlations and multiple regression were used to determine the relationship between water deficit and oil palm productivity in the different soil types.

3. RESULT

3.1 Soil physicochemical properties

Each soil type has different limiting factors that affect its ability to provide water and nutrients. Generally, the limiting factors are determined based on the soil's physical and chemical properties. Entisols, Spodosols, and Histosols are classified as marginal. Analysis of soil chemical properties with soil fertility standards for oil palm plantations is presented in Figure 2. The results of the content of N (0.83%), P (624 ppm), K (0.75 %), and Mg (0.74 Meq 100 g^{-1}) in Histosols show conformity at a very high level. In this study, Histosols have relatively good chemical properties because the sub-type, Typic Haplohemist, has a characteristic upper soil layer (0 - 50 cm), formed from organic substances that have decomposed to a point where the initial organic matter source is no longer recognizable (sapric). Further down the profile, the subsoil (50 - 100 cm) is composed of semi-rotted organic material, and some of the original substance is still recognizable. This makes the nutrient content of N, P, K, and Mg in Histosols optimal compared to Ultisols. Ultisols contain low levels of N (0.06 %), very high P (325 ppm), very low K (0.16 %), and very low Mg (0.24 Meq 100 g^{-1}).

Entisols and Spodosols show lower nutrient content (N, P, K, and Mg) than Ultisols and Histosols. Entisols and Spodosols are classified as sandy soils that are poor in nutrients and water. Entisols had the lowest nutrient content; N - very low (0.02 %), P - low (81 ppm), K - very low (0.09 %), and Mg - very low (0.18 Meq 100 g^{-1}). This is because Entisols have deep soil profiles (> 100 cm) with sandy humus topsoil. The lack of organic matter and dominant sand fraction classify Entisols as nutrient-poor soils. Even though P, K, and Mg content in Spodosols are at the same level, N content in Spodosols (low) was higher than that in Entisols (very low). Spodosols contain low N (0.06 %), low P (98 ppm), very low K (0.06 %), and very low Mg (0.19 Meq 100 g^{-1}). This is because Spodosols' subgroup, Typic Haplohumods, has a shallow soil profile (50 –

100 cm), limited by a cementation layer of Fe, Al-oxide, and humus known as a spodic horizon. In terms of plant vegetation in the field, Spodosols showed better vegetation than Entisols.

The pH levels of Ultisols (4.72), Entisols (4.55), Spodosols (4.89), and Histosols (4.23) in Figure 1 show moderate levels required for oil palm growth. Although Histosols have a better ability to store water (Table 4) and provide nutrients (Figure 1), the pH of Histosols is lower than other soil types. A low pH can be a limiting factor for the soil in fulfilling optimum nutrient and water requirements for oil palm. This contributes to why oil palm production in Histosols is lower than that of Ultisols.

The value of water availability in soil is affected mainly by its texture. Histosols included in the organic category (peat) have the highest available water content (400 mm). A high available water value indicates a high level of water availability for oil palm. The productivity of Ultisols and Histosols for oil palm plantations is quite diverse, depending on their limiting factors. However, the use of land with Ultisols generally has fewer and lighter restrictions than Histosols. Although water availability values of Histosols are higher than in Ultisols, Histosols have irreversible drying properties, causing the soil to have a poor ability to bind water, especially during the dry season. Histosols (peat) that have experienced extreme drought will show difficulty absorbing water, and water additions cannot be stored. Ultisols with sandy loam texture have 125 mm available water, Entisols with loamy sand texture have 91.7 mm available water, and Spodosols with sandy texture has the lowest available water at 58.3 mm.

3.2 Oil palm productivity in several soil types

Comparative analysis of oil palm productivity on several soil types was carried out when the palms entered the Mature Palm 1 (MP1) period (4 years old). At 1 - 3 years old, palms enter an immature plant period (IMP) where no FFB has been harvested. Analysis results showed that the best oil palm productivity during MP1 to MP12 (15 years old) was on Ultisols with 23.5 tons ha^{-1} $year^{-1}$. Histosols productivity is 7% lower (3.4 tons ha^{-1} $year^{-1}$) than Ultisols. The productivity of Entisols and Spodosols is lower than Ultisols and Histosols, and the difference is 33% (7.7 tons ha^{-1} $year^{-1}$) and 31% (7.2 tons ha^{-1} $year^{-1}$) compared to Ultisols.

Soil type significantly affects productivity, bunches number, and ABW on oil palm. The highest bunch production is on Ultisols (2,104 bunches ha^{-1} $year^{-1}$) followed by Histosols (1,750 bunches ha^{-1} $year^{-1}$), with a high variance reaching 15% (653 bunches ha^{-1} $year^{-1}$). The lowest bunches number is on Entisols and Spodosols with a respective variance of 30% (625 bunches ha^{-1} $year^{-1}$) and 22% (471 bunches ha^{-1} $year^{-1}$) compared to Ultisols. There is no significant difference between the ABW of Ultisols and Histosols, although Histosols are 0.4% lower (0.05 kg $bunch^{-1}$). On the other hand, the ABW variance of Entisols (14%; 1.7 kg $bunch^{-1}$) and Spodols (18%; 1.2 kg $bunch^{-1}$) are lower than Ultisols.

3.3 Effect of water deficit on decreasing oil palm productivity

3.3.1 Dynamics of oil palm productivity and monthly rainfall

Effect of rainfall on the distribution of oil palm production (MP1 - MP12) on Ultisols, Entisols, Spodosols, and Histosols show the same production dynamic distribution (Figure 3), but response rate, increasing percentage, and decreasing productivity in each soil type show differences. The production rate response shows a difference between a forward and backward decrease in monthly production due to the impact of monthly rainfall and water deficit.

Water deficit ($r = -0.31^{**}$; $p = 0.032$), rainy days ($r = 0.48^{**}$; $p = 0.000$), and rainfall ($r = 0.43^{**}$; $p = 0.002$) are correlated to the increase in oil palm productivity. This is because water deficit is directly related to the amount of available water needed by oil palm to grow and produce. Rainfall and rainy days are related to the frequency and amount of water that enters the soil. An essential role in water availability is further played by the ability of soil to store water and provide it back to plants.

3.3.2 Correlations of rainfall to water deficit on several soil types

A valid method for calculating water balance can provide information on water availability and accurate production predictions. The previous study did not consider the value of available water content (AWC) and critical deficit of each soil type in calculating water balance in oil palm plantations (Afandi et al., 2022; Ardiyanto et al., 2021; Darlan et al., 2016; Evizal et al., 2021; Kaeng et al., 2017; Monzon et al., 2022). Most of the AWC values used are the same, which refers to Ultisols, even though the area has different soil types. Therefore, the AWC value must be calculated based on the soil texture for each soil type. As described in Table 4, Ultisols, Histosols, Entisols, and Spodosols have different textures resulting in different AWC values

Figure 4 explains that Spodosols, Entisols, and Ultisols can endure water deficit for a shorter period than Histosols, where Spodosols hold the least water compared to other soil types. This is because each has a different ability to store water in the soil, as determined by its texture. Histosols have an organic texture (peat), so it has a higher ability to store water than the other three types of soil. Due to the soil texture of Entisols (sand) and Spodosols (loamy sand), the dominant sand fraction causes lower water binding ability.

3.3.3 Effect of water deficit on oil palm productivity on several soil types

Analysis of the water deficit impact on oil palm productivity should occur during Plateau Yield Phase (8 – 15 years old). Plateau Yield Phase (PYP) is the peak production phase, and its production is not affected by the age of the oil palm. So, the analysis of increasing productivity in this study was not carried out in Ascend Yield Phase (AYP) or Declining Yield Phase (DYP). During AYP, there is a significant increase in production due to the effect of plant age, while during DYP, there is a decrease in production due to decreasing plant productive age.

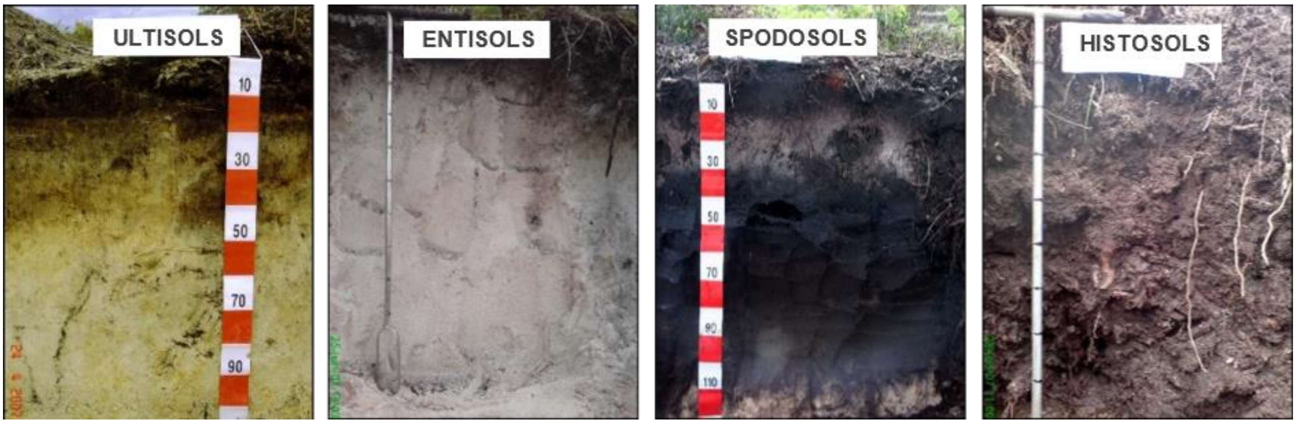

Figure 1. Ultisols, Entisols, Spodosols, and Histosols at the study site (Paramananthan, 2007)

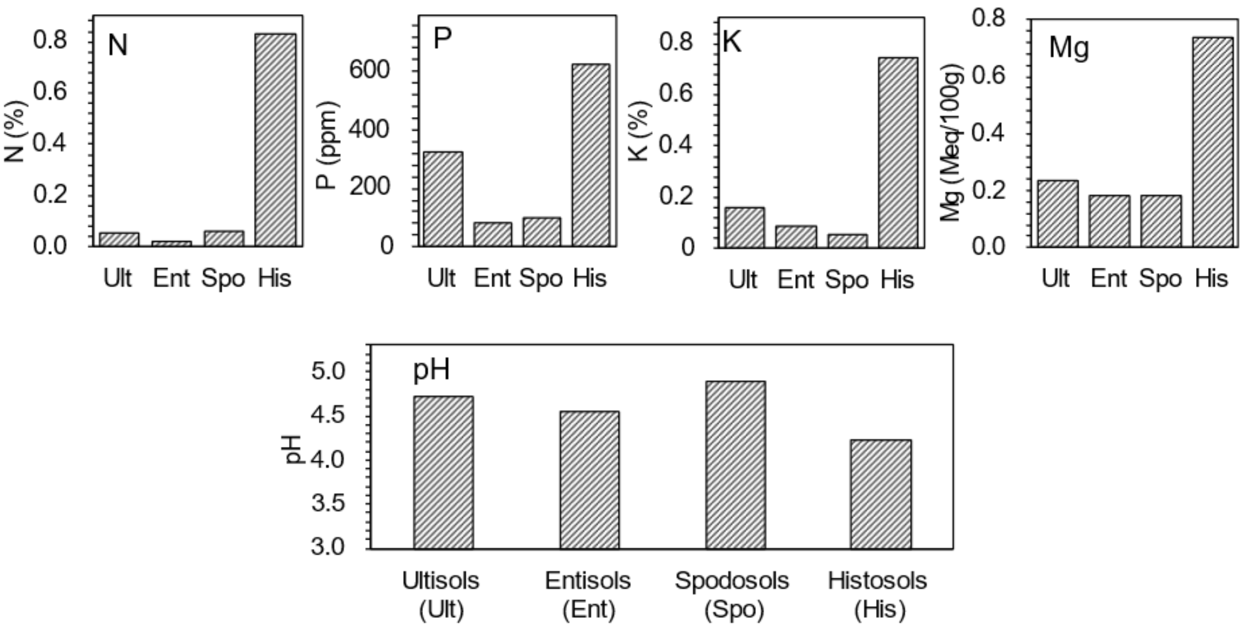

Figure 2. N, P, K, Mg, and pH levels in Ultisols, Entisols, Spodosols, and Histosols soil

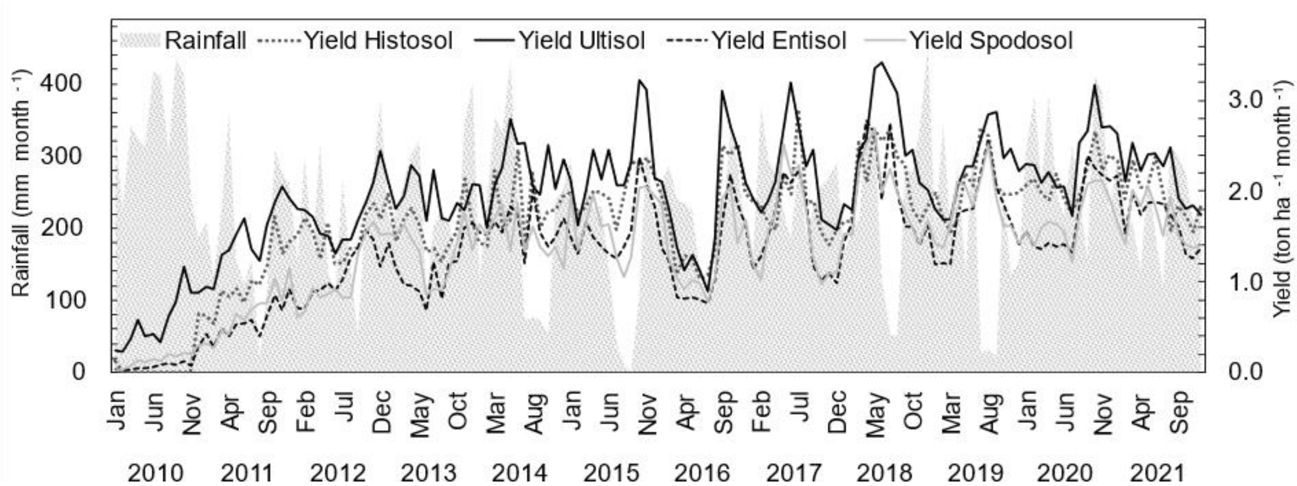

Figure 3. Correlations of rainfall to oil palm productivity dynamic on Ultisols, Entisols, Spodosols, and Histosols

Table 4. Available Water in Ultisols, Entisols, Spodosols, and Histosols

Soil Type	Soil Texture	Available Water Content (mm)	Critical Deficit (mm)
Ultisols	Sandy Loam	125.0	87.5
Entisols	Loamy Sand	91.7	64.2
Spodosols	Sand	58.3	40.8
Histosols	Peat	400.0	280.0

Water deficit causes a decrease in oil palm productivity by 5 - 22% (Ultisols 12 - 22%; Entisols 12 - 22%; Spodosols 7 - 19%; Histosols 5 - 15%) in the first year and 1 - 8% in the second year (Ultisols 3 - 7%; Entisols 2 - 4%; Spodosols 5 - 8%; Histosols 1 - 5%) compared to the previous years' production (Table 6). The higher the water deficit value, the higher the potential for a decrease in productivity. A productivity decrease was seen in 2016 due to a water deficit that occurred 1 - 2 years earlier, in 2014 and 2015. In contrast, the decrease in productivity in 2019 was due to a water deficit in 2018 and 2019 of 0 - 335 mm year^{-1}. This decrease was lower than in 2016, as the 2014 and 2015 deficit was 55 - 459 mm year^{-1}.

Ultisols endured the highest decrease in production due to water deficit, both in weight (ton^{-1} ha^{-1} year^{-1}) and percentage from the previous years' production (Table 6). The lowest impact of decreased production was found in Histosols. This is because the water deficit in Ultisols (412 mm year^{-1}) is higher than in Histosols (220 mm year^{-1}), but both show the same production distribution dynamic due to water deficit. Production in Ultisols and Histosols in 2016 showed the most significant decrease due to the double impact of the water deficit for two consecutive years: 2014 plus 2015. In 2017, production increased by 20% for Ultisols and 12% for Histosols compared to 2016. But compared to 2015, there was still a 7% decrease in Ultisols and 5% in Histosols. In 2017, it seemed as though production had increased, whereas, in 2016, production decreased due to the double impact of two years of water deficit. This explains why in Table 6, there is an increase in production, and in Figure 5, a decrease in productivity.

As oil palms were 15 years old, the highest productivity was achieved in 2018 on both Ultisols (30.7 tons ha^{-1} year^{-1}) and Histosols (25.8 tons ha^{-1} year^{-1}). This could be because there was no water deficit in the previous two years (2016 and 2017). A double impact also occurred on Ultisols in 2020 due to the water deficit in 2018 and 2019, but the effect was not as significant as in 2016. Based on Table 6, there was a 5% increase in Ultisols productivity in 2020 (28.5 tons ha^{-1} year^{-1}) compared to 2019 (27.1 tons ha^{-1} year^{-1}), but when compared to 2018 (30.7 tons ha^{-1} year^{-1}), production decreased by 7% in 2020. The water deficit in 2019 also caused a decrease in oil palm production in 2021 (effect of 2nd year) on Ultisols and Histosols.

Spodosols and Entisols show a more frequent decrease in production than Ultisols and Histosols during the eight years of observation (2014 – 2021), as presented in Table 6. Although Entisols and Spodosols are both classified as sandy soils, Entisols have a more significant decrease in productivity than Spodosols. The dynamic of decreased productivity due to water deficit in Entisols and Spodosols is still the same as the description for Ultisols and Histosols above. However, Entisols and Spodosols showed decreased productivity for three consecutive years due to the influence of water deficit in the previous 1 - 2 years (2018 and 2019), as shown in Figure 6..

Table 5. Oil palm production on Ultisols, Entisols, Spodosols, and Histosols

No	Soil Type	Average			Variance		
		Productivity (ton ha^{-1} yr^{-1})	Bunch Number (bunch ha^{-1} yr^{-1})	ABW (kg per bunch)	Productivity (%)	Bunch Number (%)	ABW (%)
1	Ultisols	23.53 ^{a}	2104 ^{f}	12.3 ^{m}	-	-	-
2	Entisols	15.86 c	1479 h	10.54 n	33%	30%	14%
3	Spodosols	16.30 c	1633 g	10.09 n	31%	22%	18%
4	Histosols	20.09 b	1785 g	12.23 m	15%	15%	0%
	Total	19.04	1762	11.17			

Remark: means sharing the same superscript are not significantly different from each other (DMRT, P<0.05)

Table 6. Effect of water deficit on decreasing oil palm production on Ultisols, Entisols, Spodosols, and Histosols in PYP (age 8 – 15 years)

No	Note	Soil Type	Oil Palm Productivity (ton ha^{-1} year^{-1})							
			2014 TM5	2015 TM6	2016 TM7	2017 TM8	2018 TM9	2019 TM10	2020 TM11	2021 TM12
1	Water Deficit (mm tahun^{-1})	Ultisol	248	412	0	0	135	289	0	0
		Entisol	271	436	0	0	158	312	0	0
		Spodosol	295	459	14	0	182	335	0	0
		Histosol	55	220	0	0	0	96	0	0
2	Yield (ton ha^{-1} tahun^{-1})	Ultisol	26.7 ↑	27.7 ↑	21.6 ↓	25.9 ↑	30.7 ↑	27.1 ↓	28.5 ↑	26.4 ↓
		Entisol	19.1 ↑	19.1 ↓	15.0 ↓	18.4 ↑	23.6 ↑	20.7 ↓	20.6 ↓	20.3 ↓
		Spodosol	18.3 ↑	19.8 ↑	16.0 ↓	18.7 ↑	23.2 ↑	21.7 ↓	20.5 ↓	19.9 ↓
		Histosol	21.5 ↑	23.5 ↑	20.0 ↓	22.3 ↑	25.8 ↑	24.5 ↓	25.4 ↑	24.3 ↓

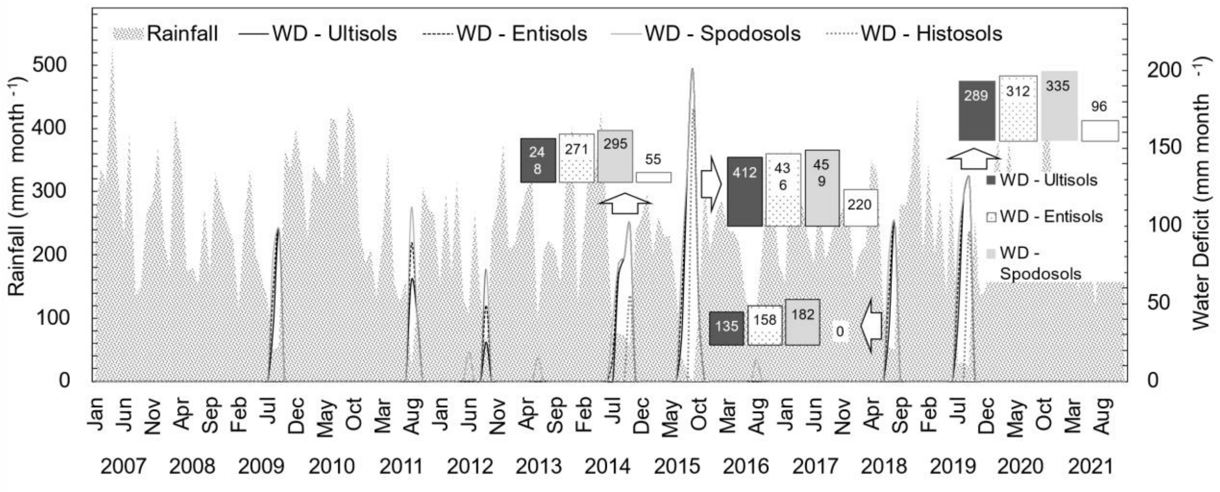

Figure 4. Distribution of water deficit on oil palm plantations on Ultisols, Entisols, Spodosols, and Histosols at the same location

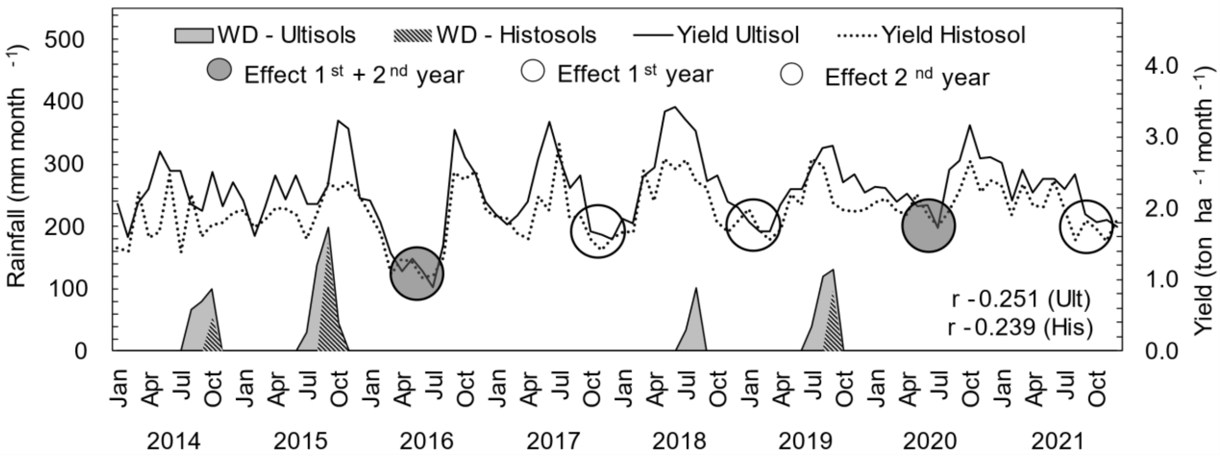

Figure 5. Impact of water deficit on oil palm productivity on Ultisols and Histosols

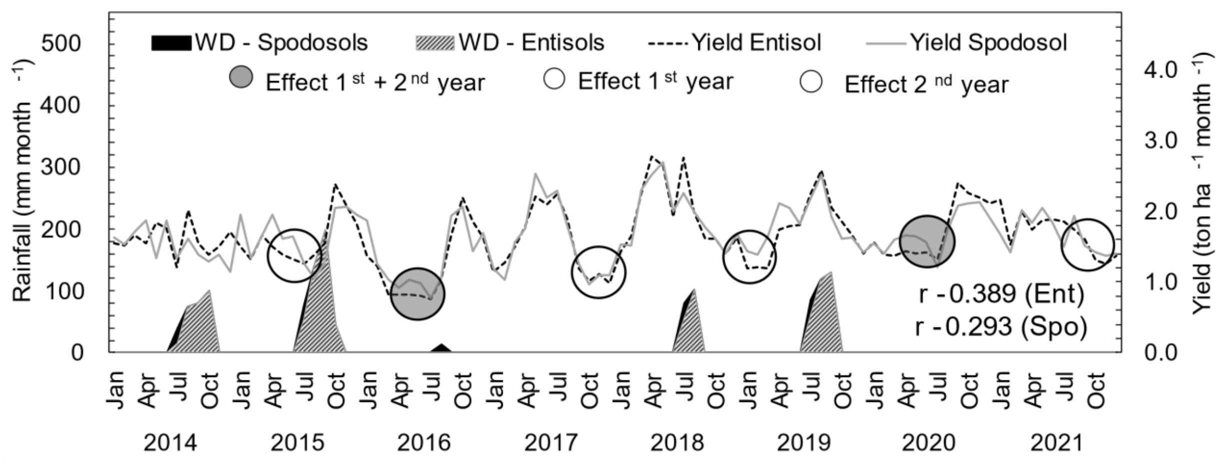

Figure 6. Impact of water deficit on oil palm productivity on Entisols and Spodosols

4. DISCUSSION

Generally, FFB productive variance is influenced by bunch number and ABW (Shi et al., 2017). Plant age, climate, soil type, and technical culture of oil palm also greatly influence bunch number and ABW. Ultisols have a better level of land suitability for oil palm growth than Entisols, Spodosols, and Histosols. Ultisols have higher productivity, followed by Histosols, Spodosols, and Entisols. Histosols have the highest nutrient content, followed by Ultisols, and Entisols and Spodosols are the lowest. The acidity level of the four soil types was in the moderate range. Soil acidity level significantly affects nutrient availability in soil because of its reaction with soil particles and nutrients (Neina, 2019). Jackson and Meetei (2018) explain that macro and micro-nutrients are more widely available in soil with optimum pH. Macronutrients (N, K, Ca, Mg, and S) are more available at pH 6.5 – 8.0, and micronutrients (B, Cu, Fe, Mn, Ni, and Zn) at pH

5.0 – 7.0. Low soil pH affects the population and activity of soil organisms that play a role in converting N, S, and P into available forms for plants (Memoli et al., 2020).

It has been reported that the main limiting factor in Ultisols is lack of nutrient P, aeration and porosity characteristics, low stability index, and Fe and Al oxidation, so crop productivity can still be optimized with proper soil management practices (Aji et al., 2022; Cristancho et al., 2011; Holilullah et al., 2015; Igwe et al., 2013). On the other hand, in Histosols, the limiting factors that can affect crop productivity include high acidity, low fertility, low density, susceptibility to excessive drought, lack of micronutrients, and nutrient imbalances (Rinaldi et al., 2019; Wigena, Subardja, et al., 2013).

Ultisols with sandy loam texture better hold and provide water for oil palm growth and production than other mineral soils (Entisols and Spodosols). Spodosols and Entisols have low soil aggregation, larger soil pores than clay, high infiltration capacity, and lower water and nutrient storage capacity, so drought stress and nutrient deficiency are higher (Fries et al., 2020; Gunawan et al., 2021). The low proportion of clay in Spodosols and Entisols reduces field capacity and production potential because the potential for nutrient leaching in sandy soils is high, and water availability is low, causing soil and plants to be susceptible to drought, especially in the dry season (Wigena, Marwanto, et al., 2013). Furthermore, sandy soils have more macro pores and a smaller surface area than clay soil, making it difficult to hold water (Pujawan et al., 2016).

Soil water availability factor also plays an essential role in increasing oil palm production. Water carries nutrients from the soil to plants (Ojeda & Mattana, 2015), so even if there are high amounts of nutrients available in soil, if there is no water or low water availability, the process of transporting nutrients from the soil to leaves is not optimal. The interaction between water availability and dissolved nutrients is influenced by water's osmotic and hydraulic processes through the cohesion mechanism (Miranda et al., 2021). Water availability in soil affects the movement dynamic of solutes/nutrients absorbed into roots (El-Nesr et al., 2014) because differences in the spatial distribution of water determine nutrient transport. Also, nutrient uptake sites in the root system allow water and solutes to move along symplastic pathways between cells (Pinto & Ferreira, 2015). The plant's ability to extract water and nutrients in soil affects the balance of water and nutrients transported into plant tissues (Madhu & Hatfield, 2013).

The monthly production response of oil palm to rainfall on the four soil types has the same stable dynamic, except for Spodosols. High porosity and low water-holding capacity cause Spodosols to be very susceptible to the potential effects of water deficits and water stress. Darlan et al. (2016) state that the drought stress factor due to water deficit is correlated with low rainfall levels and affects the performance of oil palm on its growth, development, and productivity. The decrease in production due to water deficit in Histosols was smaller than in Ultisols, Spodosols, and Entisols. The high organic matter content causes Histosols to rarely experience a water deficit. In addition, the effect of the time lag of water deficit on production (tonnage, FFB number, and ABW) varies between soil types. For example, decreased production due to 2014 and 2015 deficits occurred in 2016, and water deficits in 2016 and 2018 reduced production in 2020 and 2021. The oil palm production decrease in 2020 only occurred in Entisols and Spodosols, while it happened to all soil types in 2021. This is closely related to differences in physical and chemical properties of each soil type which in turn affects the water status of oil palm production through its influence on sex determination, flower abortion, and bunch failure.

More specifically, the effect of water deficit on decreased productivity occurs in several important phases of oil palm growth. These phases include the initiation of flowers to sex determination, sensitivity to abortion, and bunches failure (Kamalrudin & Abdullah, 2014; Tani et al., 2020). Harahap et al. (2013) added that the effects of stress on vegetative growth consist of leaf area, growth of new buds, and root shoot ratio. Effects on generative growth include abnormal inflorescence, embryo abortion, and abnormal seed and fruit development. Woittiez et al. (2017) reported that a water deficit of more than 400 mm year^{-1} resulted in a 33% reduction in potential yield, depending on climate and soil characteristics. A single increase in water deficit of 100 mm year^{-1} causes a decrease in oil palm production by 6 - 10% (Suharyanti et al., 2020). Salmiyati et al. (2014) argue that increasing the water deficit of 50 mm year^{-1} in combination with an increase in temperature of 1°C can reduce production by 2.15 tons ha^{-1} year^{-1}. Hermantoro and Rudyanto (2018) added that every 100 mm year^{-1} increase in rainfall, 1°C temperature, and 50 mm year^{-1} water deficit can reduce oil palm productivity by 2 tons ha^{-1} year^{-1}.

At flower initiation to sex determination, water deficit causes a decrease in productivity in Ultisols because it reduces flowers' potential to form both male and female flowers. The impact occurred about 2 - 2.5 years after the water deficit occurred, that is, 27 - 30 MBH on Ultisols, 26 - 29 MBH on Spodosols, 27 - 29 MBH on Entisols, and 26 - 27 MBH on Histosols. Furthermore, bunch abortion causes a decrease in the bunch number harvested due to bunch losses. The impact of a water deficit on decreasing productivity caused by abortion occurs about a year after a water deficit, so 14 - 15 MBH in Ultisols and 13 - 15 MBH in Entisols, but not significant for Spodosols and Histosols. Nonetheless, rainfall significantly affected the sensitive phase of abortion in Histosols at 13 MBH. These results provide more detailed and accurate information about water deficit effects on a series of mechanisms that determine oil palm productivity through the sex determination phase, flower abortion, and bunch failure sorted for Ultisols, Entisols, Spodosols, and Histosols. Accurate time lag information is essential for plantation management in the context of mitigating climate change effects, as the impact of climate change is predicted to be even more significant in the coming decades.

Agusta et al. (2020) state that water stress during the dry season causes infertile oil palm flowers, which are affected by rainfall three years before harvest. This contradicts research by Corley and Tinker (2015), who state that abortion generally occurs at 5 - 10 MBH but mainly at 9 - 10 MBH. Stress factors due to climate change, environmental conditions, technical culture, and genetic factors are possible causes of differences in fruit development, maturity rate, and oil palm productivity (Saripudin & Putra, 2015; Yousefi et al., 2020). Bunch failure is a condition where pollinated flowers cannot develop optimally into fruit. It can reduce production because ABW produced is lower than usual. The effect of water deficit on the bunch failure phase can be observed from ABW data because there is a decrease in ABW. Bunch failure due to water deficit in Ultisols occurs at 3 MBH, Entisols at 3 - 4 MBH, and Spodosols at 3 - 5 MBH, while Histosols do not show a significant effect on bunch failure. Based on this, the impact of decreased production due to bunch failure occurred in 3 - 5 MBH. Suharyanti et al. (2020) added that soil water stress could also affect the anthesis phase of oil palm, causing bunch failure.

Decreased productivity due to a decrease in bunch number and ABW can be caused by variations in climate, environmental conditions, technical culture, and genetic factors (Ipir et al., 2017; Musyadik & Fathnur, 2020). Water stress and thermal time cause differences in leaf growth and flower initiation stage to ripe bunches (Hossain et al., 2020; Murugesan et al., 2017; Suresh et al., 2021). Temperature is related to the bunch development rate, whereas rainfall and humidity are correlated with the bunch maturity rate (Teixeira das Chagas et al., 2019). High rainfall is also not good and can even reduce oil palm productivity. It can increase the growth and attack of the pathogenic fungus *Marasmius palmivorus*, reduce air temperature, and reduce the duration of sunlight, thereby disrupting the photosynthesis process (Perez, 2017; Salmiyati et al., 2014; Shi et al., 2017).

5. CONCLUSION

The four soil types tested showed similar annual production distribution dynamics, but the response rate of increasing productivity from each soil type showed differences. The best productivity, bunch number, and ABW were found on Ultisols. Entisols and Spodosols are more prone to drought stress due to water deficit than Ultisols and Histosols because of the differences in soil texture. Water deficit causes a decrease in oil palm productivity by 5 - 22% in the first year (Ultisols 12 - 22%; Entisols 12 - 22%; Spodosols 7 - 19%; Histosols 5 - 15%) and 1 - 8% in the second year (Ultisols 3 - 7%; Entisols 2 - 4%; Spodosols 5 - 8%; Histosols 1 - 5%) compared to previous years' production. Water deficit and rainfall also have a significant effect on decreasing productivity compared to rainy days. A decrease in oil palm productivity occurs at 3 - 5 months (bunch failure phase), 1 year (abortion sensitive phase), and 2 - 2.5 years (sex differentiation phase) after a water deficit.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests that may appear and influence the work reported in this paper.

References

Afandi, A. M., Zulkifli, H., Nur, Z. H. A. Z. A., Norliyana, Z. Z., Hisham, H., Saharul, A. M., & Vu, T. T. A. (2022). Oil Palm Water Requirement and the Need for irrigation in Dry malaysian Areas. *Journal of Oil Palm Research*, 1-15. https://doi.org/10.21894/jopr.2022.0052

Agusta, H., Pratanu, B. G., Saragih, J. F., Handoyo, G. C., & Sulistiyono, E. (2020). The dynamics of precipitation and its relation to flowering status and oil palm productivity. *IOP Conference Series: Earth and Environmental Science*, *418*(1), 012043. https://doi.org/10.1088/1755-1315/418/1/012043

Ahmed, A., Ishak, M. Y., Uddin, M. K., Abd Samad, M. Y., Mukhtar, S., & Danhassan, S. S. (2021). Effects of Some Weather Parameters on Oil Palm Production in the Peninsular Malaysia. https://doi.org/10.20944/preprints202106.0456.v1

Aji, W. A., Saloko, S. A., Kurniawan, I., & Nurcahya, M. A. (2022). The Effect of Rainfall and Rain Days On Palm Oil Production. *Tropical Plantation Journal*, *1*(1), 16-20. https://doi.org/10.22013/tpj.v1I1.3

Ardiyanto, A., Murtilaksono, K., Wahjunie, E. D., & Sutandi, A. (2021). Pengaruh Komponen Neraca Air Terhadap Produktivitas Kelapa Sawit pada Berbagai Jenis Tanah:: Studi Kasus Kalimantan Tengah dan Barat. *Jurnal Penelitian Kelapa Sawit*, *29*(1), 11-20. https://doi.org/10.22302/iopri.jur.jpks.v29i1.125

Azzeme, A. M., Abdullah, S. N. A., Aziz, M. A., & Wahab, P. E. M. (2016). Oil palm leaves and roots differ in physiological response, antioxidant enzyme activities and expression of stress-responsive genes upon exposure to drought stress. *Acta Physiologiae Plantarum*, *38*(2), 52. https://doi.org/10.1007/s11738-016-2073-2

Carr, M. K. V. (2011). The Water Relations and Irrigation Requirements of Oil Palm (Elaeis Guineensis): A Review. *Experimental Agriculture*, *47*(4), 629-652. https://doi.org/10.1017/S0014479711000494

Corley, R., & Tinker, P. (2015). The Oil Palm. The Oil Palm. *Chichester, UK: John Wiley & Sons, Ltd. doi*, *10*, 9781118953297. https://doi.org/10.1002/9781118953297

Cristancho, J. A., Hanafi, M. M., Syed Omar, S. R., & Rafii, M. Y. (2011). Alleviation of soil acidity improves the performance of oil palm progenies planted on an acid Ultisol. *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science*, *61*(6), 487-498. https://doi.org/10.1080/09064710.2010.506448

Darlan, N. H., Pradiko, I., & Siregar, H. H. (2016). Dampak el nino 2015 terhadap performa tanaman kelapa sawit di bagian selatan sumatera (effect of el nino 2015 on oil palm performance in southeastern part of sumatera). *Jurnal tanah dan iklim*, *40*(2), 113-120. https://doi.org/10.2017/jti.v40i2.3146

El-Nesr, M. N., Alazba, A. A., & Šimůnek, J. (2014). HYDRUS simulations of the effects of dual-drip subsurface irrigation and a physical barrier on water movement and solute transport in soils. *Irrigation Science*, *32*(2), 111-125. https://doi.org/10.1007/s00271-013-0417-x

Evizal, R., Sari, R. Y., Saputra, H., Setiawan, K., & Prasmatiwi, F. E. (2021). Pengaruh Irigasi pada Pertumbuhan dan Produksi Kelapa Sawit. *Jurnal Agrotropika*, *20*(1), 58-67. https://doi.org/10.23960/ja.v20i1.4848

Fries, A., Silva, K., Pucha-Cofrep, F., Oñate-Valdivieso, F., & Ochoa-Cueva, P. (2020). Water Balance and Soil Moisture Deficit of Different Vegetation Units under Semiarid Conditions in the Andes of Southern Ecuador. *Climate*, *8*(2), 30. https://doi.org/10.3390/cli8020030

Gunawan, S., Budiastuti, M. T. S., Sutrisno, J., & Wirianata, H. (2020). Effects of organic materials and rainfall intensity on the productivity of oil palm grown under sandy soil condition. *International Journal on Advanced Science, Engineering and Information Technology*, *10*(1), 356-361. https://doi.org/10.18517/ijaseit.10.1.11001

Gunawan, S., Sri Budiastuti, M. T., Sutrisno, J., & Wirianata, H. (2021). The Performance of Oil Palm Productivity and Management of Organic Materials at Various Rain Intensity in Sandy Soil. *IOP Conference Series: Earth and Environmental Science*, *709*(1), 012088. https://doi.org/10.1088/1755-1315/709/1/012088

Harahap, I. Y., Rahutomo, S., Pangaribuan, Y., Hidayat, T. C., Harsanto, W. A., & Fauzi, W. R. (2013). *Air & Kelapa Sawit* (1 ed.). Pusat Penelitian Kelapa Sawit (PPKS). Indonesia

Hashim, Z., Muhamad, H., Subramaniam, V., & May, C. Y. (2014). Water footprint: Part 2—FFB production for oil palm planted in Malaysia. *Journal of Oil Palm Research*, *26*(4), 282-291. http://jopr.mpob.gov.my/water-footprint-part-2-ffb-production-for-oil-palm-planted-in-malaysia/

Hermantoro, H., & Rudyanto, R. (2018). Modeling and Simulation of Oil Palm Plantation Productivity Based on Land Quality and Climate Using Artificial Neural Network. *International Journal of Oil Palm*, *1*(2), 65-70. http://www.ijop.id/index.php/ijop/article/view/9

Holilullah, H., Afandi, A., & Novpriansyah, H. (2015). Karakterisitk sifat fisik tanah pada lahan produksi rendah dan tinggi di pt great giant pineapple. *Jurnal Agrotek Tropika*, *3*(2). https://doi.org/10.23960/jat.v3i2.2014

Hossain, M. Z., Bahar, M. M., Sarkar, B., Donne, S. W., Ok, Y. S., Palansooriya, K. N., Kirkham, M. B., Chowdhury, S., & Bolan, N. (2020). Biochar and its importance on nutrient dynamics in soil and plant. *Biochar*, *2*(4), 379-420. https://doi.org/10.1007/s42773-020-00065-z

Igwe, C. A., Zarei, M., & Stahr, K. (2013). Soil hydraulic and physico-chemical properties of Ultisols and Inceptisols in south-eastern Nigeria. *Archives of Agronomy and Soil Science*, *59*(4), 491-504. https://doi.org/10.1080/03650340.2011.649475

Ipir, H. V., Astuti, Y. T. M., & Santosa, T. N. B. (2017). Pengaruh Topografi Terhadap Sex Ratio dan Fruit Set pada Kelapa Sawit. *Jurnal Agromast*, *2*(2). http://journal.instiperjogja.ac.id/index.php/JAI/article/view/401/376

Jackson, K., & Meetei, T. T. (2018). Influence of soil pH on nutrient availability: A Review. *Journal of Emerging Technologies and Innovative Research*, *5*(12), 707-713. https://www.jetir.org/view?paper=JETIRDZ06090

Kaeng, S. E., Rogi, J. E., & Pongoh, J. (2017). Neraca Air Lahan untuk Pengembangan Tanaman Kelapa Sawit (Elaeis guinensis Jacq), di Kecamatan Sangkub, Kabupaten Bolaang Mongondow Utara. *AGRI-SOSIOEKONOMI*, *13*(3A), 33-38. https://doi.org/10.35791/agrsosek.13.3A.2017.18012

Kamalrudin, M., & Abdullah, R. (2014). Malaysian palm oil–moving ahead to sustainable production growth. *Oil Palm Industry Economic Journal*, *14*(1), 24-33. http://opiej.mpob.gov.my/malaysian-palm-oil-moving-ahead-to-sustainable-production-growth/

Kamil, N. N., & Omar, S. F. (2017). The impact of El Niño and La Niña on Malaysian palm oil industry. *Oil Palm Bulletin*, *74*, 1-6. http://palmoilis.mpob.gov.my/OPB/index.php/2020/03/29/the-impact-of-el-nino-and-la-nina-on-malaysian-palm-oil-industry/

Koedadiri, A., & Adiwiganda, M. (1998). Integrated reclamation of tertiary soil fertility in oil palm plantation. *Warta Pusat Penelitian Kelapa Sawit (Indonesia)*. https://agris.fao.org/agris-search/search.do?recordID=ID2000001277

Lindh, M., Hoeber, S., Weih, M., & Manzoni, S. (2022). Interactions of nutrient and water availability control growth and diversity effects in a Salix two-species mixture. *Ecohydrology*, *15*(5), e2401. https://doi.org/10.1002/eco.2401

Lopes Filho, W. R. L., Rodrigues, F. H. S., Ferreira, I. V. L., Correa, L. O., Cunha, R. L., & Pinheiro, H. A. (2021). Physiological responses of young oil palm (Elaeis guineensis Jacq.) plants to repetitive water deficit events. *Industrial Crops and Products*, *172*, 114052. https://doi.org/10.1016/j.indcrop.2021.114052

Madhu, M., & Hatfield, J. L. (2013). Dynamics of Plant Root Growth under Increased Atmospheric Carbon Dioxide. *Agronomy Journal*, *105*(3), 657-669. https://doi.org/10.2134/agronj2013.0018

Memoli, V., Panico, S. C., Santorufo, L., Barile, R., Di Natale, G., Di Nunzio, A., Toscanesi, M., Trifuoggi, M., De Marco, A., & Maisto, G. (2020). Do Wildfires Cause Changes in Soil Quality in the Short Term? *International Journal of Environmental Research and Public Health*, *17*(15), 5343. https://doi.org/10.3390/ijerph17155343

Miranda, M., Silva, S., Silveira, N., Pereira, L., Machado, E., & Ribeiro, R. (2021). Root Osmotic Adjustment and Stomatal Control of Leaf Gas Exchange are Dependent on Citrus Rootstocks Under Water Deficit. *Journal of Plant Growth Regulation*, *40*. https://doi.org/10.1007/s00344-020-10069-5

Monzon, J. P., Jabloun, M., Cock, J., Caliman, J.-P., Couëdel, A., Donough, C. R., Vui, P. H. V., Lim, Y. L., Mathews, J., Oberthür, T., Prabowo, N. E., Edreira, J. I. R., Sidhu, M., Slingerland, M. A., Sugianto, H., & Grassini, P. (2022). Influence of weather and endogenous cycles on spatiotemporal yield variation in oil palm. *Agricultural* *and Forest Meteorology*, *314*, 108789. https://doi.org/10.1016/j.agrformet.2021.108789

Murugesan, P., Aswathy, G. M., Kumar, K. S., Masilamani, P., Kumar, V., & Ravi, V. (2017). Oil palm (Elaeis guineensis) genetic resources for abiotic stress tolerance: A review. *Indian Journal of Agricultural Sciences*, *87*(5), 571-579. https://epubs.icar.org.in/index.php/IJAgS/article/view/70087

Musyadik, & Fathnur. (2020). Analisis Hubungan Unsur Cuaca Terhadap Fluktuasi Produksi Sawit Di Kab . Konawe Utara. *Jurnal Ecosolum*, *9*(2), 1-10. https://doi.org/10.20956/ecosolum.v9i2.10641

Nasution, R. K., Rahayu, E., & Astuti, Y. T. M. (2017). Kajian Produktivitas Tanaman Kelapa Sawit (Elaeis Guineensis Jacq) pada Jenis Tanah yang Berbeda di PT. Subur Arum Makmur I, Desa Danau Lancang, Kec. Tapung Hulu, Kab. Kampar, Riau. *Jurnal Agromast*, *2*(1).

Neina, D. (2019). The Role of Soil pH in Plant Nutrition and Soil Remediation. *Applied and Environmental Soil Science*, *2019*, 5794869. https://doi.org/10.1155/2019/5794869

Ojeda, G., & Mattana, S. (2015). vila A., AlcaZiz J., Volkmann M., Bachmann J., 2015. *Are soil-water functions affected by biochar application*, 249-250. https://doi.org/10.1016/j.geoderma.2015.02.014

Paramananthan, S. (2007). *Soils of Ladang Sarana Titian Permata Kecamatan Seruyan Hilir Kabupaten Seruyan Provinsi Kalimantan Tengah Indonesia*. PT. Sarana Titiap Permata (unpublished).

Perez, R. I. (2017). *Analyzing and modelling the genetic variability of aerial architecture and light interception of oil palm (Elaeis guineensis Jacq)* [Thesis, Agricultural sciences. Montpellier SupAgro].

Pinto, E., & Ferreira, I. M. P. L. V. O. (2015). Cation transporters/channels in plants: Tools for nutrient biofortification. *Journal of Plant Physiology*, *179*, 64-82. https://doi.org/10.1016/j.jplph.2015.02.010

Pujawan, M., Afandi, A., Novpriansyah, H., & Manik, K. E. (2016). Kemantapan agregat tanah pada lahan produksi rendah dan tinggi di PT Great Giant Pineapple. *Jurnal Agrotek Tropika*, *4*(1). https://doi.org/10.23960/jat.v4i1.1915

Rinaldi, P. S., 'Akromah, Z. N., Ramadhan, H., Husna, S., Syamsudin, D. L., Panggabean, P. B., Murdianti, R. A., Fatahillah, M. H., Perala, I., Rizqia, E. K., Yahya, S. A., Novitasari, A., & Wibowo, C. (2019). Physical and Chemical Analysis of Land in Forest Peat Swamp in Resort Pondok soar, Tanjung Puting National Park, Central Kalimantan. *IOP Conference Series: Earth and Environmental Science*, *394*(1), 012037. https://doi.org/10.1088/1755-1315/394/1/012037

Rivera-Mendes, Y. D., Cuenca, J. C., & Romero, H. M. (2016). Physiological responses of oil palm (Elaeis guineensis Jacq.) seedlings under different water soil conditions. *Agronomía Colombiana*, *34*(2), 163-171. https://doi.org/10.15446/agron.colomb.v34n2.55568

Salmiyati, heryansyah, A., Idayu, I., & Supriyanto, E. (2014). Oil Palm Plantations Management Effects on Productivity Fresh Fruit Bunch (FFB). *APCBEE Procedia*, *8*, 282-286. https://doi.org/10.1016/j.apcbee.2014.03.041

Saripudin, E., & Putra, E. T. S. (2015). Midrib and flower phenology emergence of two genotypes of oil palm in Sumatera and Kalimantan. Prosiding Seminar Nasional Masyarakat Biodiversitas Indonesia, https://doi.org/10.13057/psnmbi/m010340

Shi, P., Wang, Y., Lei, X., Cao, H., & Li, D. (2017). Correlation and regression analysis of fresh fruit bunch yield components in oil palm (Elaeis guineensis). *Guangxi Zhiwu/Guihaia*, *37*(9), 1130-1136. http://journal.gxzw.gxib.cn/en/

Shlyannikov, V. (2016). Nonlinear stress intensity factors in fracture mechanics and their applications. *Procedia Structural Integrity*, *2*, 744-752. https://doi.org/10.1016/j.prostr.2016.06.096

Suharta, N. (2010). Karakteristik dan permasalahan tanah marginal dari batuan sedimen masam di Kalimantan. *Jurnal Litbang Pertanian*, *29*(4), 139-146. https://core.ac.uk/download/pdf/300046217.pdf

Suharyanti, N. A., Mizuno, K., & Sodri, A. (2020). The effect of water deficit on inflorescence period at palm oil productivity on peatland. E3S Web of Conferences, https://doi.org/10.1051/e3sconf/202021105005

Sukarman, S., Wirianata, H., Budiharjo, K., Primananda, S., & Purwantisari, S. (2021). Estimasi Produksi Tandan Kelapa Sawit Berdasarkan Analisis Ketersediaan Air dengan Teknik Oil Palm Dissection. *Jurnal BETA (Biosistem dan Teknik Pertanian)*, *9*(2), 291-299. https://doi.org/10.24843/JBETA.2021.v09.i02.p16

Suresh, K., Behera, S. K., Manorama, K., & Mathur, R. K. (2021). Phenological stages and degree days of oil palm crosses grown under irrigation in tropical conditions. *Annals of applied biology*, *178*(1), 121-128. https://doi.org/10.1111/aab.12641

Suwardi. (2021). *Manajemen Tanah Spodosols Melalui Sistem Pecah Hardpan dan Mounding untuk Meningkatkan Produksi Tanaman Kelapa Sawit* [Thesis, Institut Pertanian STIPER]. Yogyakarta.

Tani, N., Abdul Hamid, Z. A., Joseph, N., Sulaiman, O., Hashim, R., Arai, T., Satake, A., Kondo, T., & Kosugi, A. (2020). Small temperature variations are a key regulator of reproductive growth and assimilate storage in oil palm (Elaeis guineensis). *Scientific Reports*, *10*(1), 650. https://doi.org/10.1038/s41598-019-57170-8

Teixeira das Chagas, K. P., Barbosa Carvalho, B. L., Gurgel Guerra, C. A., Rodrigues Silva, R. A., & de Almeida Vieira, F. (2019). Fenologia do dendezeiro e correlações com variáveis climáticas. *Ciência Florestal (01039954)*, *29*(4). https://doi.org/10.5902/1980509822640

Wigena, I. G. P., Marwanto, S., & Jubaedah, J. (2013). Variation of Peat Bulk Density and Carbon Density under Several Land Use Types. *Jurnal tanah dan iklim*, *37*(2).

https://ejurnal.litbang.pertanian.go.id/index.php/jti/article/view/11253

Wigena, I. G. P., Subardja, D., & Andriati, A. (2013). Evaluasi Kesesuaian Lahan Mineral dan Gambut untuk Peremajaan Tanaman Kelapa Sawit (Studi Kasus pada Beberapa Kebun Plasma di Provinsi Riau). *Jurnal Sumberdaya Lahan*, *7*(2). https://ejurnal.litbang.pertanian.go.id/index.php/jsl/article/view/6435

Woittiez, L. S., van Wijk, M. T., Slingerland, M., van Noordwijk, M., & Giller, K. E. (2017). Yield gaps in oil palm: A quantitative review of contributing factors. *European Journal of Agronomy*, *83*, 57-77. https://doi.org/10.1016/j.eja.2016.11.002

Yousefi, M., Mohd Rafie, A. S., Abd Aziz, S., Azrad, S., & Abd Razak, A. b. (2020). Introduction of current pollination techniques and factors affecting pollination effectiveness by Elaeidobius kamerunicus in oil palm plantations on regional and global scale: A review. *South African Journal of Botany*, *132*, 171-179. https://doi.org/10.1016/j.sajb.2020.04.017