Effects of rainfall and groundwater level on soil subsidence, water content, and yield of oil palm

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Abstract. Peatlands have long been cultivated for various agricultural crops in Indonesia. However, nowadays land fires are often associated with drained peatlands. We present a four-year study looking at the effects of groundwater level (GWL) on peat reduction, moisture content, and yield. Observations were made on oil palm plantations in tropical peatlands of Riau Province. GWL was observed in 417 plots of 139 blocks and recorded once a week. Peat moisture was monitored automatically and recorded every hour. Subsidence poles were made in 36 blocks and recorded once a month. The results showed that peat subsidence, water content, and yield were affected by GWL fluctuations. There is a relationship between GWL and changes in peat subsidence (R² = 0.26). A strong relationship was seen between the GWL and the water content of the peat soil at the 10 cm layer (R² = 0.65). A strong relationship was also found between GWL and oil palm yield 20 months later (R² = 0.65). In conclusion, by maintaining GWL at a depth of 40-60 cm, peat moisture at the surface can be maintained, peat subsidence can be minimized and oil palm production remains high at an average of 22 tonnes year⁻¹, thereby also reducing susceptibility to fire.

1. Introduction
Indonesia has been the largest palm oil producer in the world since 2006. The area of oil palm has increased from 0.3 million ha in 1980 to 11.3 million ha in 2018 [1,2]. Palm oil commodities are a mainstay for Indonesia's national income and foreign exchange, which can be seen from the value of plantation commodity exports. In 2015 total oil palm product exports reached US$ 16.943 billion [2]. A portion of palm oil production in Indonesia comes from peatlands and therefore this is attracting global concern regarding potential environmental risk. However, a recent study shows that well-managed peatland increases the peat bulk density and water capillarity, also maintains a high peat soil moisture, thus reducing peat vulnerability to fire [3-5].

Peatlands in Indonesia cover around 10% of the land area, around 14.9 million ha, spread over Sumatra around 6,436,649 ha (43.18%), followed by Kalimantan around 4,778,004 ha (32.06%) and Papua 3,690,921 ha (24.76%) [6-7]. This number is very small compared to the size of global peatlands estimated at around 400 million ha [8]. About 45% of the 14.9 million hectares of Indonesian peatlands have been drained and converted into other uses including the wood and pulp industry, food agriculture (eg rice), agriculture, and degraded critical land [9-14]. Oil palm plantations cover approximately 1.54 million ha [6-7].

Globally, peatlands have been recognized as the largest carbon sink in terrestrial ecosystems, but their management has been problematic [15]. Lack of understanding in managing peat for agricultural cultivation may cause environmental damage such as a decrease in groundwater level changes in the physical properties of peat to become denser, lower total porosity, diffusion of oxygen, air capacity, the volume
of available water, and infiltration rate of water [16], an irreversible decrease in the soil leading to CO₂ emissions [17-19] and also affected the distribution of moisture throughout the peat soil profile [20]. Degraded peat is also susceptible to high fire risk which causes danger of smoke and fog which in turn results in economic losses [21], health, and additional CO₂ emissions [22-24].

In the past, drained peatlands for oil palm cultivation are often mentioned in many discussions as the main factors that trigger the loss of water that makes cultivated peat more vulnerable to fire hazards during the dry season [25,26,17]. However, the current development of technology and science provides a better understanding of how peatland for oil palm plantations should be managed [3,4,5,27]. The vast development of science and technology, enabling new strategy to prevent peat cultivation to fall into such situation through the implementation of a water governance system [3]. This is a complex system that includes not only topographic information, water level dynamics, climate, but also land subsidence parameters. Managing the dynamics of interacting factors in peatland management is a tremendous challenge for oil palm farmers as they have to maintain higher yields and the ecological function of the peat itself at the same time [5].

The aim of this study is to evaluate key factors determining subsidence, water content, and yield and to provide an overview of peat management for oil palm cultivation by discussing the key factors for peat management in an effort to reduce the risk of peat drought that can trigger fires and prevent a decline in peatland which has the potential to flood cultivation areas.

2. Methods

2.1. Location of observations, climatic conditions, and characteristics of peat
Field studies were carried out in oil palm plantations in Riau Province from 2015 - 2018. The study location was a peatland basin in Siak Regency with an elevation of 20-26 masl and about 67 km from the nearest coastline. The climatic conditions in the study location are an average annual rainfall of around 2,100 – 2,400 mm, rainy days ranging from 48 - 128 days year⁻¹ with an average of 97 days year⁻¹ and an average annual temperature below 30 °C based on the rainfall station. rain that is located about 6-10 km from the study location. During the study period (2015 - 2018), the most extreme dry season rainfall occurred in 2015, namely the El-Nino phenomenon, where there was a rainfall deficit below 100 mm month⁻¹ [28]. The land use in the research location in mature oil palm plantations that were established in 2002. Before the establishment of oil palm plantations, the research location was the secondary forest. Oil palm trees are planted in agricultural blocks (300 × 1,000 m) with a density of 136 trees ha⁻¹.

![Figure 1. Location of research in oil palm plantations in the provinces of Riau.](image)
The drainage network is used to dry the plantation site through a canal system, 3-5 meters wide with a distance of 300 – 1,000 meters, to reduce the groundwater level to a level suitable for the growth of plantation crops. The water management system in the research location uses semi-permanent and permanent water structures consisting of overflow and water gates. Water-zoning systems are classified based on topographic information, where each zone has an elevation difference between 0.5 - 1 meter.

From the results of land surveys in locations study (table 1) that have been carried out by competent institutions, the classification of land in the study area consists of 4 types, namely organosol, gleisol, cambisol, and podsolic. Peat depth in the research location ranges from 0.5 - 7.5 meters, with peat maturity (Sapric, hemic, and fibric). Sampling to observe the depth and density of peat were carried out using a peat drill, while sampling Bulk Density used a sample ring, which was taken to a depth of 50 cm below the surface.

**Table 1. Summary of characteristics of the observation location.**

| Characteristic                        | Value             |
|---------------------------------------|-------------------|
| Site location (Lat/Long)              | 101.730/0.677     |
| Peat area                             | 2.178             |
| Peat depth                            | 4 ± 3.5           |
| Bulk density 50 cm on the surface     | 0.09 ± 0.08       |
| GWL depth                             | 0.7 ± 0.3         |

2.2. Groundwater level measurement
The depth of the water level was monitored using a 4 inch PVC pipe (piezometer) with a length of 4 meters, the position of the piezometer in the middle of the block (centroid), 1 piezometer per block (figure 2), with weekly monitoring. In the study location were 132 observation blocks (132 piezometers). Average water depth was calculated monthly and used in data analysis.

![Figure 2. Groundwater was measured with piezometer pipe.](image)

2.3. Peat subsidence measurements
The measurement of peat subsidence was observed through the use of the subsidence poles method, with subsidence poles made of galvanized pipe (2-inch diameter) inserted into the peat vertically to penetrate...
the mineral substrate layer ± 0.5 m so that the pipe was stable and not following peat fluctuations. For measurement of the decrease in peat, the pipe that has been plugged in was marked with a ring made of metal on the surface of the peat as the starting point/baseline (figure 3). To minimize measurement errors, a radius of 0.8 m in the location of the subsidence sticks was limited by a fence so that there is no compression on the peat surface due to repeated measurement activities in that location (figure 4). The location of the subsidence poles installation is in the middle of the block adjacent to the measurement of water depth. There were 16 blocks of subsidence observation (16 sticks). The initial measurement period was carried out after 2-3 months from the stick installation, to avoid measurement errors due to the influence of compression during the post-installation. Measurements were carried out at 1-month intervals. Data analysis was done by calculating the average monthly value, yearly value, and the value of cumulative subsidence in all locations as a comparison.

Figure 3. Subsidence was measured with subsidence poles.

Figure 4. Observation of the surface subsidence of the instrument with the subsidence poles method.

2.4. Rainfall
Rainfall information was observed through the AWS (Automatic Weather System) station located in each study location. Information about rainfall was recorded every half hour and collected as daily and monthly administration.

2.5. Dynamics observation of water level and peat moisture
Water level fluctuations were measured using a piezometer pipe in which there was a water level data logger (HOBO U20L-40, USA). The water level data logger measured the pressure of the water column (kPa) in hourly intervals. The data was then converted to the distance (meter) where the measurements were conducted. Recorded data were downloaded using a USB Base Station. The design of the measurement of water level and moisture in peat automatically (figure 5). The water level height from the land surface was calculated using the following equation:

\[ GWL = S - (H+X) \]  

(1)
Figure 5. The design of groundwater level and peat water content measurement.

Note: Where GWL = Ground Water Level Height (m); X = Height of water column recorded by the sensor (m); H= Height of piezometer pipe (m); S = Length of the sling to the sensor at the water level data logger (m).

Observations of peat moisture using soil moisture sensor (Decagon EC5 S-SMC-M005, USA), that can measure soil moisture content from 0 to 0.550 (v/v). Soil moisture sensors were installed at a depth of 10 cm from the soil surface. Each sensor retrieved data every one hour then the data was stored automatically into the micro station data logger (Hobo H21-USB Micro Station, USA). The soil moisture sensor was installed close to the water level data logger. Using the following equation the conversion of units of peat moisture can be done from a percent volume (% v/v) to a percent weight (% w/w) [29]:

Peat moisture content (% w/w) = Sensor moisture content (% v/v) x Bulk Density (w/w) x 100%

3. Results and discussion
3.1. Water table depth
The availability of water is an important benchmark as most oil palm cropping systems are rain-fed [30]. Water availability depends on rainfall and soil characteristics and is strongly site-specific [31-32]. Figure 6 shows seasons from year to year at the study location. In the rainy season (November - April) the GWL is increased to the peat surface, but in the dry season (July - October) the GWL decreases deeper below the surface. The average GWL at location studies is 0.5 m with a range from 0.31 to 0.96 m. In research locations, the drainage system was cut through the contour to remove excess water and encourage the proliferation of oil palm roots in deeper soil layers. The depth of the water was indeed maintained at the optimal level for oil palm plantations, namely between 45 - 60 cm.

During the rainy season (November - April) in the study location, rainfall is around 7.3 mm day$^{-1}$ reaching an average water level of 0.45 m below the peat surface. Meanwhile, during the dry season (July - October), the average rainfall is around 5.1 mm day$^{-1}$, where the average decrease in water level is quite high, which is about 0.67 m below the peat surface. In the dry season (July - October 2015), an El Nino year when there was almost no rain for 4 consecutive months, GWL dropped by -0.96 m below the surface. Prolonged low rainfall causes low groundwater levels in peatland, which creates a drier environment that is prone to fire hazards [33]. This shows that the canal bulkhead cannot maintain a high-water level during prolonged dry periods [34].
From Figure 6, there is a clear relationship between water depth and rainfall depth, where water depth fluctuates throughout the year depending on rainfall in each location. The results of the regression correlation indicate that GWL is positively related to rainfall indicated by $R^2 = 0.185$. An increase in the amount of rainfall is followed by an increase in GWL (Figure 7).

![Figure 6. Groundwater level and rainfall in the study area from 2015 – 2018.](image)

Figure 7. Relationship between GWL and rainfall from 2015 to 2018. N for GWL = 48; N for rainfall = 48. $Y = -60.43 + 0.08X$; $F = 10.46$; $P < 0.005$.

### 3.2. Subsidence rates

Peat soil subsidence measurements were carried out in the study locations after 18 years of plantation establishment. The measurement of peat subsidence in the first year is quite significant compared to the annual average where peat subsidence is about 4.69 cm, while the annual average decline (2015 - 2018) is only about 1.58 cm year$^{-1}$. The cumulative peat subsidence during the 4 years of observation was around 6.31 cm (Figure 8). If we look at 2015 when the El Nino phenomenon, it is clear that there was a significant decrease in peat in the research location.

![Figure 8. Cumulative subsidence at study location (2015 - 2018).](image)
The relationship between GWL fluctuations and changes of peat subsidence at the study site after 18 years of land clearing (see figure 9), the correlation regression results show that GWL is positively related to water level decline indicated by $R^2 = 0.26$ where there is a decrease in water depth (GWL) followed by land subsidence. Analysis of variance confirmed that the linear relationship between changes of subsidence and GWL was statistically valid at the $<0.05$ significance level.

**Figure 9.** Relationship between GWL (cm) and changes of subsidence (cm) from 2015 to 2018. N for GWL = 33; N for subsidence = 33. Y= 0.4+0.01X; F=11.09; P < 0.005.

### 3.3. Dynamic relationship between water levels and peat moisture

Peat moisture monitoring at research location was observed from June 2017 - December 2018, observing the relationship between peat moisture and the dynamics of water level shown in (figure 10), which showed a significant decrease in water level at the location of oil palm plantations in dry months namely the period (January - March) and (July - September) where the decrease in water level ranges from 0.90 - 0.94 m with water content in the 10 cm layer ranging from 243.5 - 267.0%. This shows that the fluctuations in soil moisture on the surface are greatly affected by water level conditions. Groundwater level reduction affects the distribution of soil moisture throughout the peat soil profile and results in the release of a volume of groundwater from the above layers [35].

**Figure 10.** Observation of groundwater level and peat moisture.
Figure 11. Relationship between ground water level (GWL) and soil moisture (SM) in location A from June 2017 to 2018, N for GWL = 561; N for SM = 561; P < 0.001.

We found a strong relationship between the surface moisture of peat (layer 10 cm) and the dynamics of groundwater, with a value of $R^2 = 0.65$ (Figure 11). This correlation shows that the fluctuations in water level to a depth of 1 m influence the peat moisture in the 10 cm layer. This might occur due to the density of the soil in location A which is already quite dense, between 0.09 - 0.15 g cm$^{-3}$ to a depth of 50 cm from the surface, so that the water is able to rise to the surface. Capillary water can also replace water lost by evapotranspiration in the upper layers [36-39] explained that capillary water is able to rise 40-50 cm while the results of this study were obtained on peat soil in subtropical regions which have different characteristics of peat from peat in the tropics. [4] explained that the capillary water in the oil palm plantation could rise from about 68 to 76 cm in tropical peatlands.

Capillary water on peatland during dry conditions (dry season) plays a very important role in providing water for the plant root zone. The actual groundwater level in the root zone is very dependent on the water level in areas with shallow water levels. Increased capillary water in the soil is a phenomenon that visualizes the movement of water through the soil pores from low to higher altitudes. [40] Capillarity is a common phenomenon in nature that occurs due to the presence of surface tension which causes water to rise higher than the ground level [40].

3.4. Relationship between groundwater level (GWL) and yield

Yield is a consequence of the interaction of genetics, environment, and management [41]. According to statistical model data and other work, every 100 mm of water deficit reduces yield by 8% - 10% in the first year, and 3% - 4% in the second year after the stress event [42-44]. Yield loss may even double, with each 100 mm increase in mean water deficit resulting in a 5.9 t/ha or about 20% decrease of a 30 t/ha yield over 2 years after the event [45]. Water excess, similar to water deficit, could depress future yield, and that extreme years where both water deficit and excess occurred had the greatest depressive effect on yield [46].
The impact of stresses on fruit (FFB) development only becomes visible 20 - 30 months after the occurrence because of the long development period between floral initiation and fruit maturity in oil palms [47]. The average production of oil palm FFB (tons/ha/month) planted on peatland in research locations is summarized in figure 12. We found a relationship between groundwater level and an increase in oil palm production with a value of $R^2 = 0.65$ (figure 13). This correlation compares the current water level condition with the production of FFB 20 months later, where the process of forming male / female flowers until the fruit is ready for harvest takes around 19.5 - 28 months.

Stress sensitivity varies throughout fruit development with three most critical periods due to their impact on productivity: sex determination (months 8 - 20 after leaf initiation), potential inflorescence abortion (months 28 - 32), and potential bunch failure (months 36 - 38) [48], a condition in which sparse or no fruit set is followed by complete drying or rotting of the affected bunches for a variety of reasons [49]. While water conditions [50-52] and defoliation seem to play an important role in fruit development [53], nutrition also clearly has a role to play.

Water management is an important aspect of oil palm cultivation because peat deficit or excess water will affect oil palm trees and reduce crop yields. Water management primarily aims to minimize the effects of droughts and floods by optimizing the use of rainwater and freshwater from the flow-through drainage, irrigation, and the practice of conservation of soil slopes [54].
3.5. Peatland management model

Despite the fact that the average age of plants in research locations is around 19 years (6 years before replanting), oil palm production on peatlands remains high, achieving an average yield of around 22 - 23 ton ha\(^{-1}\) year\(^{-1}\). Older palm oil trees will have higher yields.

![Figure 14](image)

**Figure 14.** Relative Frequency of occurrence of plots with GWL values in the same GWL range. The number of plots with GWL in the same range relative to all GWL values. Distribution pattern of GWL values from 139 selected blocks with ages range from 9 to 23 years old.

By operating water gates and canal blocks, GWL can be properly maintained with a water depth of around 40 - 60 cm to maintain peat moisture (250% to 350%) so that the potential for land fire and dryness causing irreversible drying due to drainage activities is avoided. This can be seen from Figure 14 where most of the GWL values are found in the range from 40 - 60 cm, followed by the range 60 - 80 cm, and 20 - 40 cm. These results indicate that the water management system has been successfully applied to control the water level; only a few GWL values are occupied lower than 80 cm.

By applying GWL in the range of 40 - 60 cm, the level of decline in peat surface can be minimized with the average subsidence of about 1.58 cm year\(^{-1}\) for 4 years of observation. These results indicate that peat soil subsidence is strongly influenced by GWL. Reducing the level of groundwater means that peat soil loses a certain amount of water which triggers organic matter to become denser and decomposed and therefore the peat surface becomes lower [20]. In conclusion, the peat management system implemented in the study area can ensure high yields and at the same time be able to maintain the water level as expected and can avoid excessive peat surface reduction, at least in the relatively short term.

4. Conclusion

The results showed that peat soil subsidence, water content, and yield were influenced by fluctuations in the groundwater table. There is a relationship between GWL fluctuation and changes in peat subsidence \((R^2 = 0.26)\), where the decrease in the water table increased the change in peat subsidence. A strong relationship is seen between the GWL and the water content of peat soil in the 10 cm layer in oil palm plantations \((R^2 = 0.65)\). Here capillary water in peatlands has a very important role in providing water for plant root areas even though the groundwater level is low but water capillaries are able to rise to the surface to keep the peat moist. A strong relationship was also found between the water table and oil palm yield 20 months later with a value of \(R^2 = 0.65\). By maintaining GWL at a depth of 40-60 cm, the peat moisture on the surface can be maintained so that the risk of irreversible drying and land fires can be reduced.
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