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Effects of forest conversion to oil palm plantation on soil erosion and surface runoff

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KEYWORDS

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Forest

Nutrient loss

Oil palm

Runoff

ABSTRACT

The vegetation type and its coverage in forest ecosystems are crucial in soil erosion and surface runoff. Cover crops provide significant protection to the soil aggregates, preventing damage caused by rainfall and runoff that might occur in the absence of these crops. However, changes in land use, such as converting forests into oil palm plantations, have resulted in changes to the land cover, which affect erosion, surface runoff, and, ultimately, the forest ecology of the watershed. This study aimed to provide an overview of erosion and runoff in forest areas and oil palm plantations. This field research was conducted to study erosion, runoff, and nutrient loss using plots measuring 15m x 25m, including oil palm plantation areas and forest areas. After each rain, sediment weighing and runoff volume measurements were carried out. Laboratory analysis was conducted for sediment and surface runoff water samples' N, P, and K elements. The study results showed that five-year-old oil palm plantation areas experience the highest levels of erosion and runoff, followed by three-year-old oil palm plantation and forest areas. Nutrients were found to be lost in sediment across all land cover types, with a minimal amount recorded in surface runoff.

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1 Introduction

Over the past decade, Indonesia has experienced notable growth in palm oil production, which has become the fastest-growing industry in the country. According to the Indonesian Ministry of Agriculture's 2010 report, the government had targeted increasing crude palm oil production to 40 million tonnes by 2020 from regions such as Sumatra, Kalimantan, and West Papua. However, the country exceeded its intended palm oil production target, producing over 44.67 million tonnes. The Riau Province in Sumatra is Indonesia's largest palm oil producer, accounting for approximately 19.62% of the total national production, followed by Central Kalimantan, which contributes around 12.89% of the national output. Additionally, between 2016 and 2020, Indonesia's palm oil cultivation area expanded by 30.3%, growing from 11.20 million hectares to 14.59 million hectares. The largest palm oil cultivation area is in Riau Province, followed by West Kalimantan and Central Kalimantan (Kurniawan et al. 2018; BPS 2020).

The palm oil industry plays a crucial role in Indonesia's economy, contributing 3.5% to the country's GDP as per GAPKI (2022). According to UNcomtrade (2022), Indonesia exported 25.94 million tons of palm oil, with a total value of USD 17.37 million, accounting for 55.48% of the global market share in 2020. Notably, Indonesia and Malaysia are the leading countries in palm oil exports (Tandra et al. 2022). Furthermore, palm oil cultivation can benefit smallholders without increasing economic risk (Suroso and Ramadhan 2014; Acosta and Curt 2019; Mehraban et al. 2021). The industry also contributes significantly to Indonesia's non-oil and gas exports.

Indonesia has seen a significant shift in land usage, particularly with the rapid expansion of the oil palm industry, which has negatively affected the environment and human health. Although the growth of the oil palm (OP) plantations has positively impacted the country's economy, it has also brought some unintended ecological and societal issues. Several previous studies (Oyarzun et al. 2007; Setiawan et al. 2016; Vijay et al. 2016; Austin et al. 2017) suggest that the spread of OP plantations has led to forest removal, resulting in reduced carbon stocks, deforestation, forest fires (Dadi 2021), and the destruction of biodiversity (Koh and Wilcove 2009; Lees et al. 2015; Linder and Palkovitz 2016; Dadi 2021), as well as water scarcity and the exploitation of soil and water resources (Safitri et al., 2018). Additionally, the development of OP has resulted in negative social impacts, including land grabbing, subpar working conditions on plantations (Dhiaulhaq et al. 2015; Gellert 2015), and disputes between migrants and locals due to social jealousy and ethnic migrants' dominance (Dadi 2021).

Compared to natural forests, oil palm (OP) plantations have a less dense, more uniform canopy, significantly affecting the local climate by raising air temperature, soil temperature, and humidity (Hardwick et al. 2015; Meijide et al. 2018). This change in canopy cover also affects hydrological aspects such as flooding, soil erosion, nutrient leaching (Dislich et al. 2017), and groundwater availability and levels. Water storage can also be reduced, annual water yield can increase, and water quality can decrease when forests are converted to OP plantations. However, the adverse effects tend to fall as plantations age (Comte et al., 2012) and can be mitigated by effective management practices (Yusop et al. 2007). Nonetheless, there is a lack of reliable data on the water problem in various locations. Some small-scale studies suggest that well-managed oil palm can regulate the essential hydrological characteristics of the catchments reasonably well.

Developing and managing plantations, such as forest clearing, building roads and drainage systems, using agricultural pesticides, and discharging wastewater, can cause soil erosion and affect groundwater quality (Environment Conservation Department, 2000; Goh et al. 2003). The water quality in aquatic ecosystems near plantations can also be affected by erosion and surface runoff. These effects cause the nutrients from water sources to dissolve in sediments. Applying fertilizers at high dosages to plantations can lead to declining water quality in nearby aquatic ecosystems and hydrological conditions (Sheil et al. 2009).

To control the surface runoff and drainage water from OP plantations, cover crops plantation or vegetation cover can retain excess water and nutrient-rich sediment. However, the decomposition of legume cover crops under a mature canopy releases nitrogen that previously occurred through nitrogen fixation (Goh et al. 2003; Breure 2003; Campiglia et al. 2011). Sandy soils see higher nitrate losses by leaching from legumes (Goh and Chew, 1995). The OP plantations have a closed canopy, which causes the understorey to vanish as the plantations age. As a result, changes in land use, especially when switching from forests to agricultural or grasslands, significantly impact the flow of nutrients in the watershed (Vitousek et al. 1997).

It's unclear how converting forests to plantations will impact nitrogen and phosphorus levels in Indonesian conditions. Generally, tropical forests are rich in available nitrogen, retain high levels of N and exhibit high rates of soil N cycling (Hedin et al. 2009). However, systems with high available N are prone to significant N losses (Veldkamp et al. 2008). When forests are converted to crops, there is an initial increase in the rate of N mineralization, which results in a rise in soil NO flux, N2O emissions and N leaching (Veldkamp et al. 2008). Over time, cultivated systems may experience a decrease in available N, alkaline cations and overall soil fertility. However, systems utilizing N-fixing tree species or N fertilizers do not undergo the same reduction in soil N availability (Corre et al. 2006). Conversely, they can experience N loss through leaching or emissions (Veldkamp et al. 2008). Vegetation substitution, such as logging, affects the forest floor and accelerates soil erosion and N mineralization (Nykvist et al. 1994).

This research aims to investigate the extent of erosion and surface runoff on forest and oil palm plantations of varying ages. The study will provide insights into the impact of forest-to-oil-palm conversion on a watershed, primarily due to soil erosion, surface runoff, and nutrient loss. The research will examine the relationship between land use, the amount of erosion and surface runoff, and the nutrients N, P, and K carried in sediments and surface runoff.

2 Materials and Methods

The research was carried out on forest land and OP plantations owned by PT. KHS is located in the Jalemu Watershed, Manuhing Subdistrict, Gunung Mas Regency, as shown in Figure 1. The study was conducted for six months, from May to October 2017. Erosion and runoff measurements were taken under field conditions, while sediment and water analysis was carried out at the Analytical Laboratory of the University of Palangka Raya in Indonesia.

During this research, field conditions were used to study the effects of different land use factors on erosion. The study involved three factors, i.e., forest, 3-year-old oil palm plantations, and 5-year-old oil palm plantations, with two replications. To achieve this, erosion plots were established, each with a width of 15m and length of 25m. Plates were planted on each side of the plot, 20cm above the soil surface, so all the water entering the erosion patch flows into the erosion reservoir and surface runoff. At the end of the plot, a box was installed to collect erosion and surface runoff. This box was 5m long, 0.5m wide, and 0.5m high. It has seven holes on the side facing outward, each with a diameter of 2.5 inches. A 2.5-inch pipe connects the centre hole to box B (Figure 2). The amount of erosion and surface runoff was measured after each rainfall event. Soil and sediment samples were taken and weighed in the field to determine their weight. The moisture content of sediment samples was determined by drying in an oven at 105ºC for 24 hours. The dry weight of soil/sediment in each erosion event was calculated as the moist weight of soil/sediment multiplied by (100-% water content). Sampling was also carried out to analyze the nutrient content in the surface runoff. The data collected were analyzed using descriptive analysis to compare each factor.

$$\text{Water content (\%)} = \frac{(\text{weight of moist soil sample(M)} - \text{weight of dry sample(D)})}{\text{weight of dry sample (D)}} \text{x } 100\%$$

Water and sediment analysis was conducted at the Analytical Laboratory of Palangka Raya University. The estimation of Total N (using the Kjeldahl method), while the Total P, and Total K was done with the help of 25 percent Ekstraksi HCl and a spectrophotometer, as described in Sulaeman et al. (2009). The water analysis included the estimation of NH3 (Kjedhahl) and NO_2 (measured using the sulpanilamide method, APHA Standard method 4500 NO_2-B). In an acidic environment, NO_2 reacts with sulfanilamide (SA) and N-(1-naphthyl) ethylene diamine dihydrochloride (NED dihydrochloride) to form red-purplish azo compounds. The absorbance of the color formed was measured spectrophotometrically at a maximum wavelength of 543 nm, as per Clesceri et al. (1998). Nitrate (NO_3) was analyzed using the colorimetric method with Brusin dye reagent and measured with a

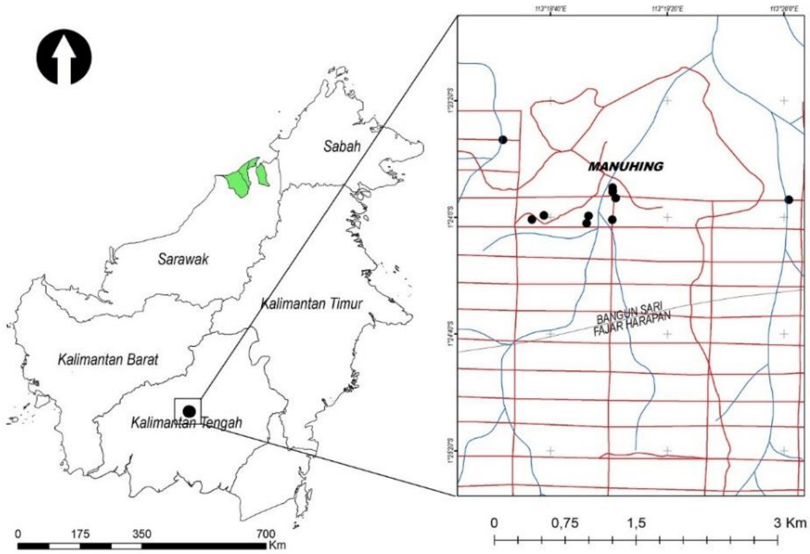
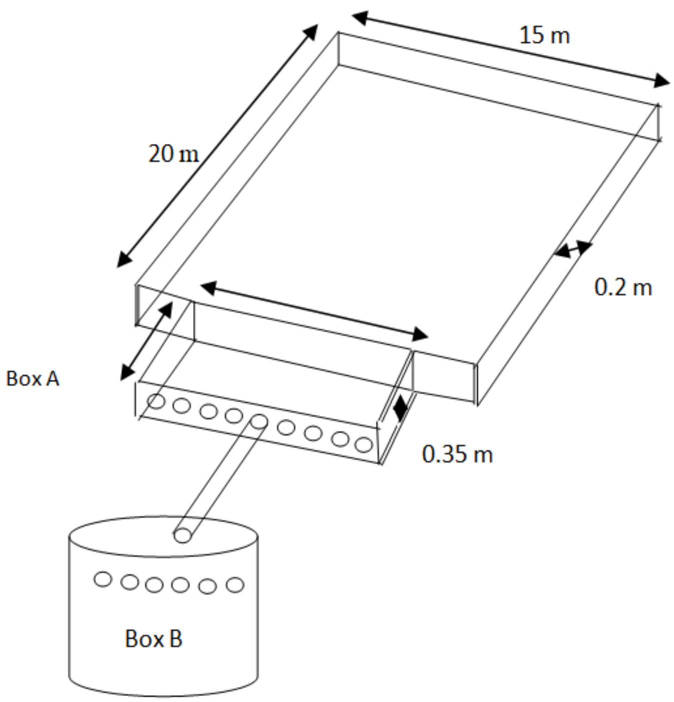


Figure 1 Map of research location in Jalemu Watershed which mainly dominated by OP plantation



(a)

(b)

Figure 2 (a) The collection box for erosion and runoff and (b) the condition of the erosion plots in the field

spectrophotometer at a wavelength of 432 nm. Phosphate (P) in water filtrate can be measured directly colorimetrically with a spectrophotometer at a wavelength of 889 nm, with the formation of a molybdate blue color. Potassium (K) concentration was determined using an Atomic Absorption Spectrophotometer (AAS). The results of the Total N, P, and K analysis through erosion or surface runoff can be calculated using the following equation:

$$X = Y \times E$$

where:

X = N, P and K losses due to erosion or surface runoff ($kgha^{-1}$)

Y = Total N (%), P (ppm) and K ($me100gr^{-1}$ soil) concentrations in sediment or surface runoff ($mg\ L^{-1}$)

E = Total soil erosion ($kgha^{-1}$) or volume of surface runoff (L)

2.1 Data Analysis

In-depth data analysis was conducted by comparing erosion and sedimentation values. A one-way ANOVA test was performed at a 5% significance level with IBM Statistics SPSS version 24 software to determine the variance in nutrient content between sediments and runoff.

3 Results

3.1 Rainfall

Rainfall data collected using a tipping bucket ombrometer during research and processing monthly results are presented in Figure 3. The observations indicate 117 rainy days between May 2017 and February 2018.

Figure 3 shows a noticeable decrease in rainfall during the dry season in May and June. The month with the highest precipitation was October 2017 with 459.5mm, while the lowest was reported in June 2017, with 86.5mm. Regarding rainy days, November had the highest number with 24 days, while May 2017 had the lowest with only 7 days.

3.2 Erosion and Surface Runoff

Figure 4 compares erosion calculations between forest areas and 3 and 5-year-old OP plantations after various rainfall events. The results show that erosion values are higher during rainy seasons in three-year-old oil palm plantations (0.10 tonnes ha^{-1}) compared to those in the five-year-old plantations (0.09 tonnes ha^{-1}) and forest areas (0.002 tonnes ha^{-1}). The erosion during rainfall events is closely related to the volume and intensity of rain on that particular date. The density of crop canopy cover is a critical factor influencing

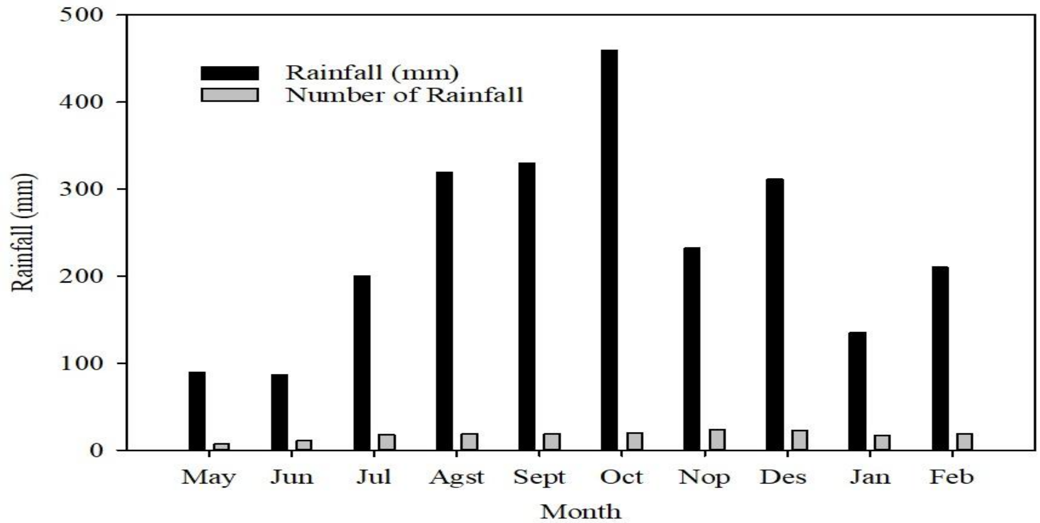


Figure 3 Amount of rainfall and number of rainy days at the research location

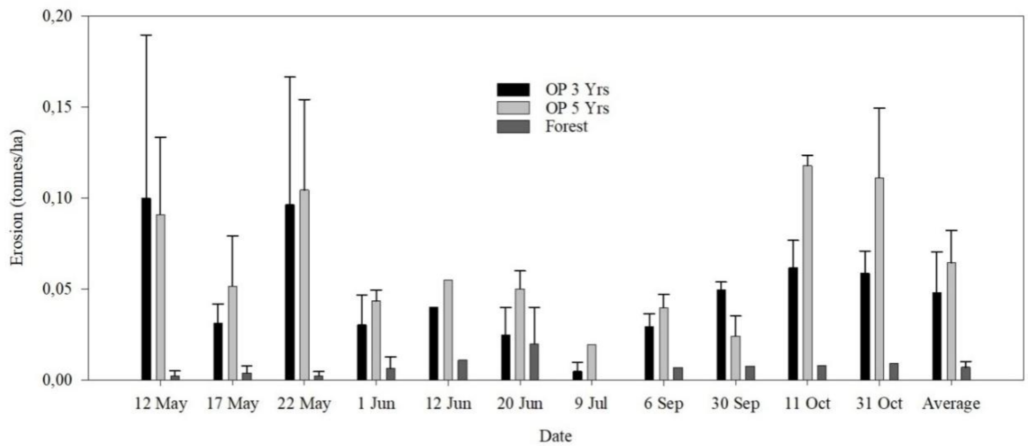


Figure 4 Erosion that occurs in forest areas and OP plantations aged 3 years and 5 years

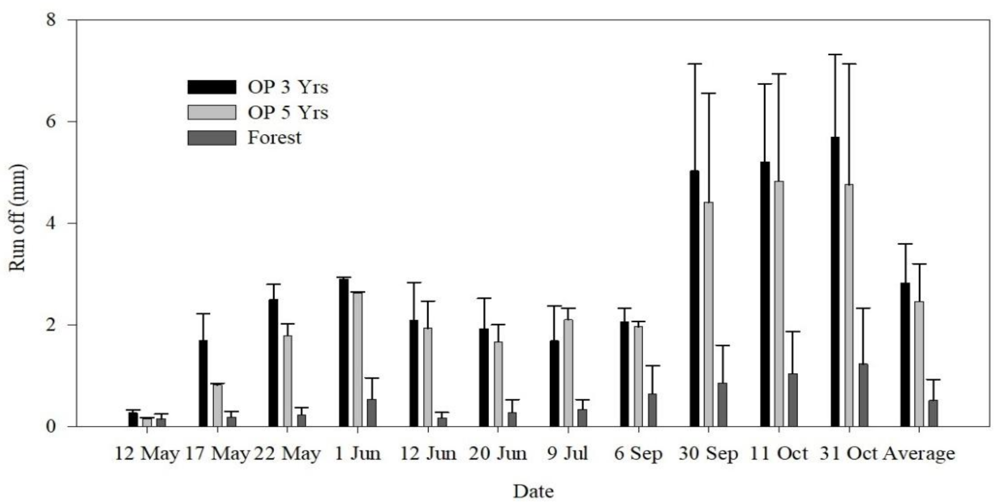


Figure 5 Surface runoff that occurs in forest areas and OP plantations

Table 1 Average results of laboratory analysis for N, P and K in eroded soils

Land use	N (%)	P (ppm)	K(me/100 g)
Oil Palm 3 yrs	0.19[a]	19.63[a]	0.09[a]
Oil Palm 5 yrs	0.21[a]	12.34[a]	0.08[a]
Forests	0.22[a]	60.01[a]	0.33[a]

Values without common letters differ significantly at LSD P<0.05

Table 2 Average results of laboratory analysis for N, P and K in surface runoff

Land use	NH_3 (mg L^{-1})	NO_2 (mg L^{-1})	NO_3 (mg L^{-1})	N-Total (mg L^{-1})	P total (mg L^{-1})	K Total (mg L^{-1})
Oil Palm 3 yrs	0.08	0.01	0.22	0.31[a]	3.71[a]	1.02[a]
Oil Palm 5 yrs	0.10	0.02	0.08	0.19[a]	0.04[a]	0.77[a]
Forests	0.05	0.02	0.11	0.17[a]	0.09[a]	2.36[a]

Values without common letters differ significantly at LSD P<0.05

erosion rates. The vegetation canopy in the 3 and 5-year-old OP plantation regions is less dense than the surrounding forest.

The results of the calculation of surface runoff during rainfall events for both forested areas and oil palm (OP) plantations aged 3 and 5 years are presented in Figure 5. Figure 5 shows that the surface runoff on a 3-year-old OP plantation is typically higher than that of a 5-year-old plantation and the forested area during most rain events. On average, the surface runoff in oil palm plantations that have been operating for three years is 2.83 mm; for those that are five years old, it is 2.46 mm, and in forest areas, it is 0.52 mm.

3.3 Nutrients losses in erosion and runoff

Tables 1 and 2 illustrate the average results of laboratory analyses for N, P, and K losses in erosion and surface runoff, respectively. Figure 6-11 displays the nutrients N, P, and K carried in erosion in each treatment plot. The table shows that the total N content in eroded soil for the three-year-old oil palm plantations was between 0.16 - 0.23% (average of 0.19%). In comparison, the five-year-old OP plantation reported between 0.15 - 0.30% (average of 0.21%), while the forest area ranged between 0.17 - 0.33% (average of 0.22%). Likewise, the highest total P content was reported in the three-year-old OP plantation, ranging between 10.09-29.39 ppm (average of 19.63 ppm). The five-year-old OP plantation reported 5.45-18.14 ppm (average of 12.34 ppm), while the forest area reported between 16.08-171.72 ppm (average of 60.01 ppm P). Total K in eroded sediments ranged from 0.03-0.19 me $100g^{-1}$ soil (averaged 0.09 me $100g^{-1}$) for three years of OP, from 0.05-0.14 me $100g^{-1}$ soil (averaged 0.08 me $100g^{-1}$ soil) for five years of OP, and 0.08-0.90 me $100g^{-1}$ soil (averaged 0.33 me $100g^{-1}$ soil) for the forest. The sediment or soil carried away by erosion from the forest areas appears to contain more N, P, and K than the 3 and 5-year-old OP plantations.

The data presented in Table 2 shows that the total nitrogen in surface runoff from three-year-old OP ranges from 0.02-0.86 mg L^{-1}, with an average of 0.31 mg L^{-1}. In contrast, the total nitrogen in surface runoff from five-year-old OP ranges from 0.02-0.69 mg L^{-1}, with an average of 0.19 mg L^{-1}. Most of the nitrogen is found in ammonia (NH_3), which ranges from 0.02-0.29 mg L^{-1}, with an average of 0.17 mg L^{-1} for forests. After three years of observation, the total phosphorus levels range from 0.02 to 22.57 mg L^{-1}, with an average concentration of 0.04 mg L^{-1}. On the other hand, after five years, the total phosphorus levels range from 0.01-0.12 mg L^{-1}, with an average concentration of 0.04 mg L^{-1}. The total phosphorus levels in forest areas range from 0.02-0.24 mg L^{-1}, with an average concentration of 0.09 mg L^{-1}. The total potassium concentration in surface runoff ranges from 0.01-4.18 mg L^{-1}, with an average value of 1.02 mg L^{-1} for three-year-old OP. In contrast, for five-year-old OP, the total potassium concentration ranges from 0.59-4.55 mg L^{-1}, with an average value of 2.36 mg L^{-1}. In summary, the results suggest that the nitrogen, phosphorus, and potassium levels delivered by surface runoff from forest regions are frequently higher than those of OP plantations three and five years old.

Based on Figure 6, the sediment eroded from the plantation areas contained a total of nitrogen ranging from 1.16 to 35 kg per hectare (with an average of 12.90 kg/ha) for three years. Over the same period, the sediment eroded from the plantation areas contained a total of nitrogen ranging from 1.19 to 39.48 kg per hectare (with an average of 13.04 kg/ha), while the sediment eroded from the forested areas contained a total of nitrogen ranging from 0.42 to 6.80 kg per hectare (with an average of 1.93 kg/ha).

Furthermore, Figure 7 showed that erosion rates were highest in the 3-year-old plantation areas, with a range of 0.30 to 5.01 kg per hectare (with an average of 2.65 kg/ha), followed by the 5-year-old plantation areas, with a range of 0.43 to 4.51 kg per hectare (with

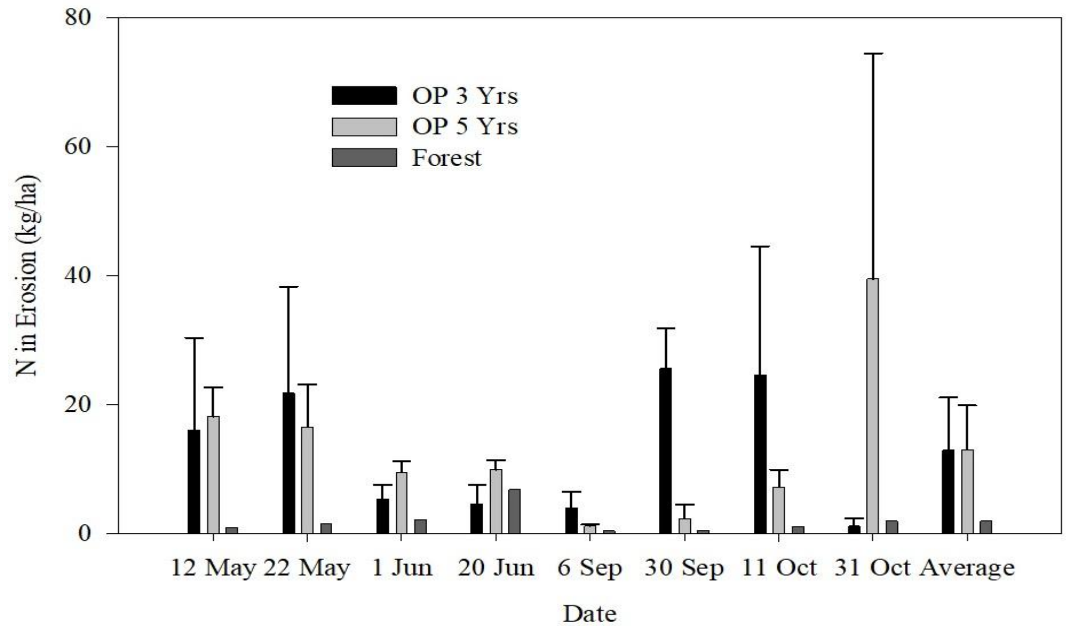


Figure 6 N in Erosion on 3 and 5-year-old OP plots and forest areas

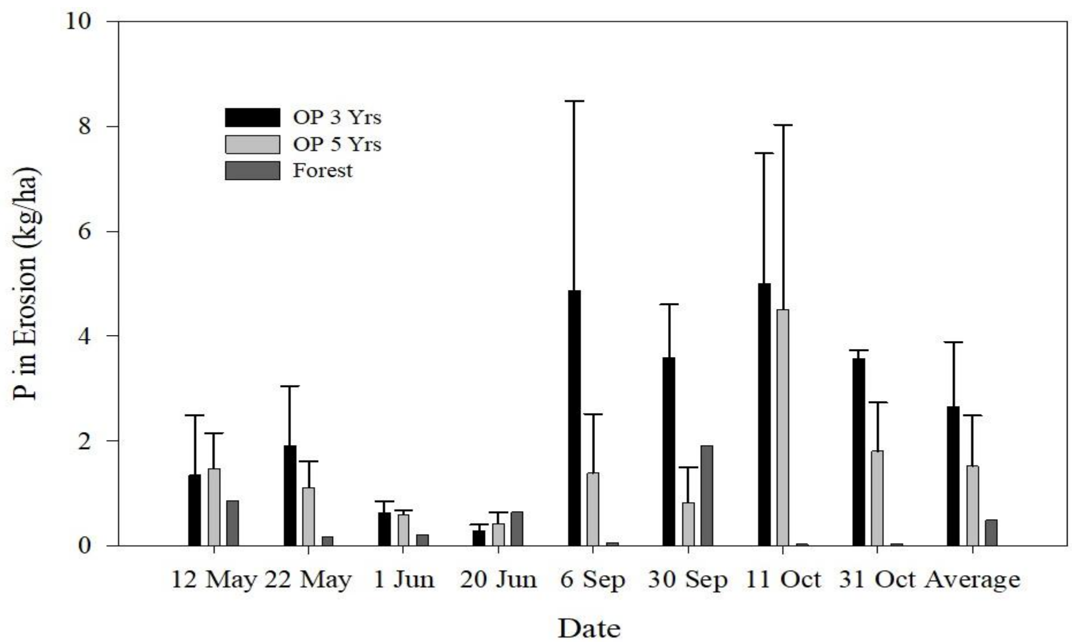


Figure 7 P in Erosion on 3 and 5-year old OP plots and forest areas

an average of 1.52 kg/ha), and the forested areas, with a range of 0.03 to 1.91 kg per hectare (with an average of 0.49 kg/ha).

Regarding the total potassium content in the eroded sediment, Figure 8 revealed that the highest loss of potassium was from the 5-year-old plantation areas, with a range of 0.92 to 62.82 kg per hectare (with an average of 15.17 kg/ha), followed by the 3-year old plantation areas, with a range of 0.45 to 32.38 kg per hectare (with an average of 10.46 kg/ha), and the forested areas, with a range of 0.33 to 3.42 kg per hectare (with an average of 1.61 kg/ha).

In conclusion, the soil erosion caused by the OP plantations resulted in a more significant loss of nitrogen, phosphorus, and potassium compared to the forested areas. This was particularly evident in the 3 and 5-year-old plantations.

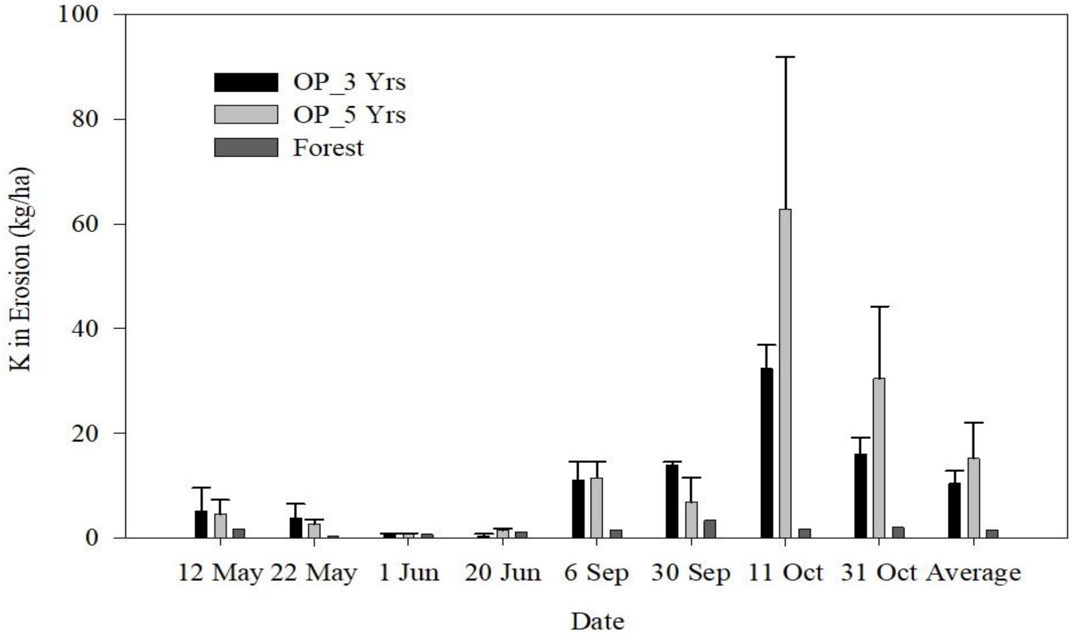


Figure 8 K in Erosion on 3 and 5-year-old OP plots and forest areas

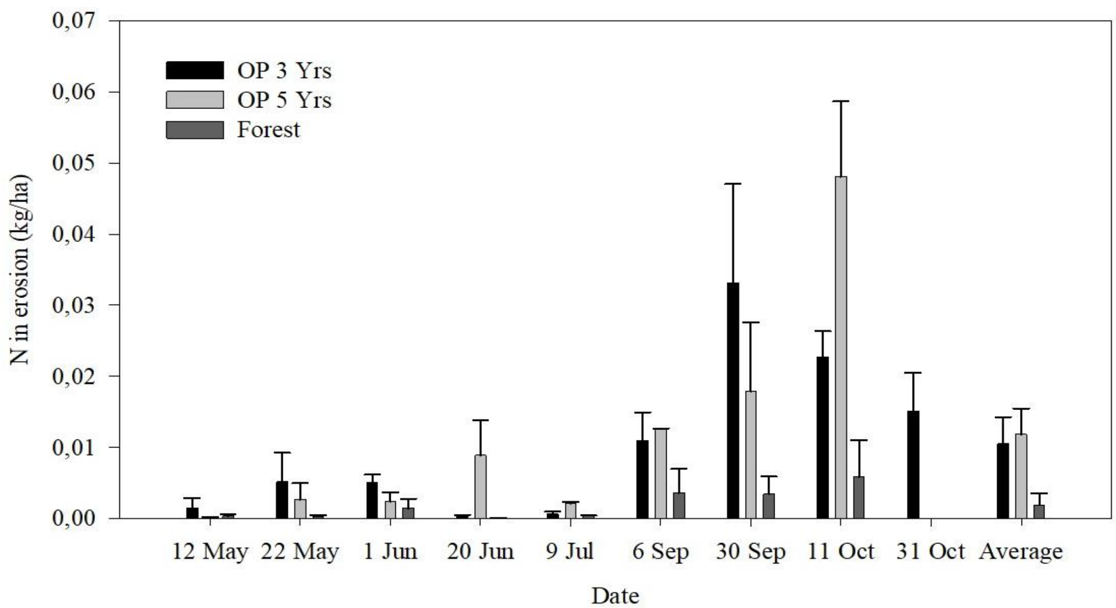


Figure 9 N in the surface runoff of 3 and 5-year-old OP plots and forest areas

When surface runoff occurs in a forest or an oil palm plantation, the nutrients N, P, and K are carried away with the water. The amount of nutrients lost through surface runoff is determined by the volume of the water and the nutrient content of N, P, and K in the water. Figure 9 shows that at 3 years OP, the total amount of nitrogen lost with surface runoff ranges from 0.004 to 0.0332 kg ha^{-1}, with an average of 0.0105 kg ha^{-1}. For 5-year OP, the range is from 0-0.481 kg ha^{-1}, with an average of 0.0105 kg ha^{-1}, while for forests, the range is from 0-0.0058 kg ha^{-1}, with an average of 0.0017 kg ha^{-1}. The majority of nitrogen losses occur in the form of ammonia (NH_3).

As for P-total, for an OP of 3 years, the amount lost ranges from 0 to 1.1105 kg ha^{-1}, with an average of 0.1691 kg ha^{-1}. For 5-year OP, the losses in surface runoff range from 0 to 0.5420 kg ha^{-1}, with an average of 0.1016 kg ha^{-1}. The losses in forests range from 0 to 0.017 kg ha^{-1}, with an average of 0.0058 kg ha^{-1}, as shown in Figure 10.

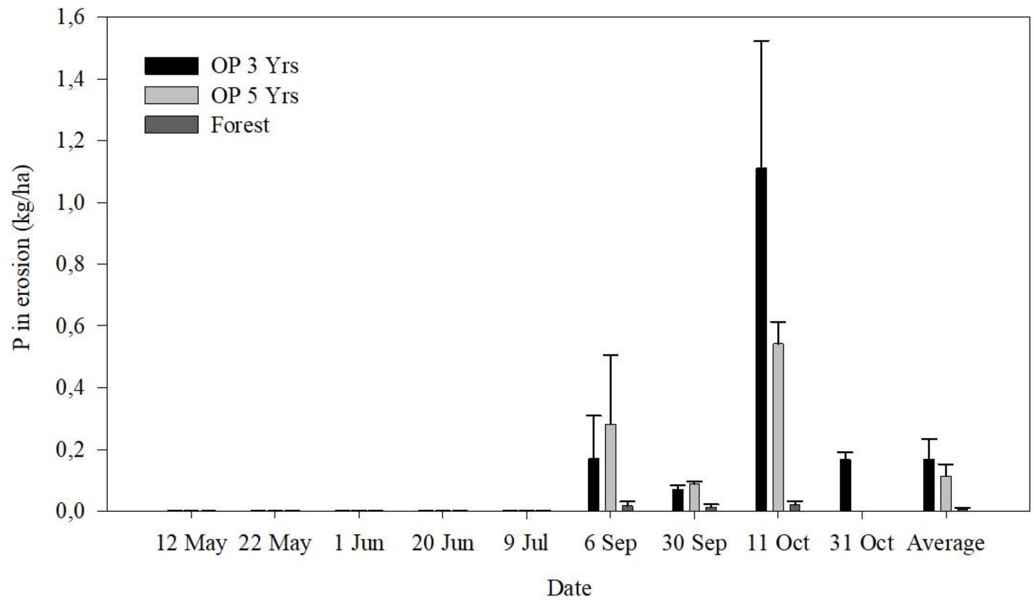


Figure 10 P in the surface runoff in 3 and 5-year-old OP plots and forest areas

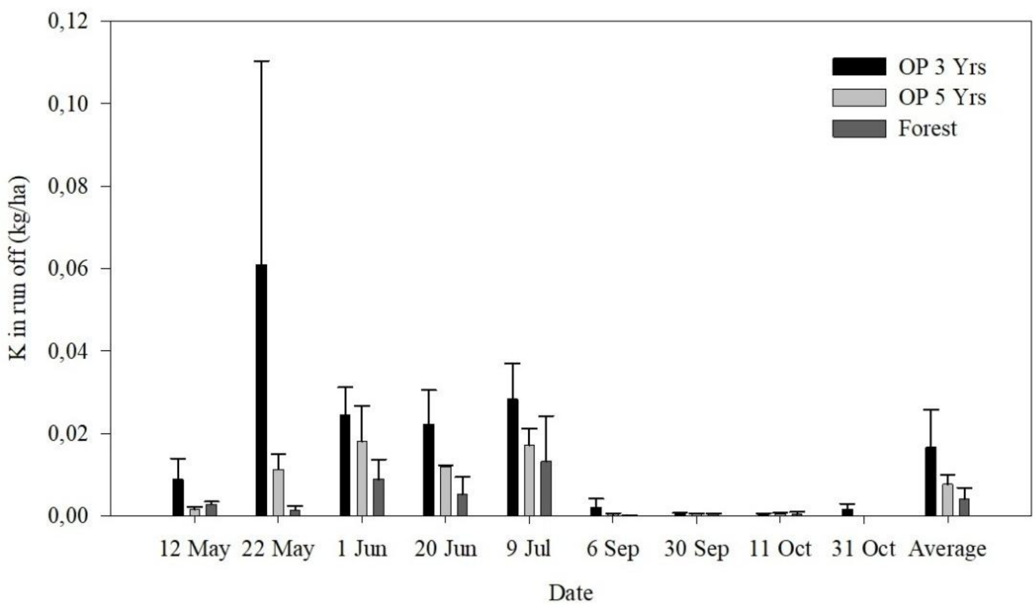


Figure 11 K in surface runoff in 3 and 5-year-old OP plots and forest areas

Figure 11 shows the total K content in the surface runoff for different studied parameters. The results showed that for a 3-year OP plantation, the total K content ranged from 0.0005 to 0.0610 kg ha^{-1}, with an average of 0.0167 kg ha^{-1}. For a 5-year OP plantation, the total K content ranged from 0 to 0.0181 kg ha^{-1}, with an average of 0.0068 kg ha^{-1}. Finally, the total K content for the forest area ranged from 0 to 0.0132 kg ha^{-1}, with an average of 0.0036 kg ha^{-1}. Overall, the 3-year OP plantation had a higher surface runoff in terms of N, P, and K content than the 5-year OP plantation and the forest area.

4 Discussion

Rainfall is a significant climate variable that impacts surface runoff and erosion. Various aspects of rainfall, such as its type, intensity, length, distribution, and direction, influence the amount of soil erosion and surface runoff (Haridjaja et al. 1990; Kee and Chew 1996). The volume and flow rate of surface runoff are directly proportional to rainfall intensity. Higher rainfall intensity generally increases surface runoff, but it depends on the soil's infiltration capacity. If the intensity of rainfall exceeds the soil's ability to

Table 3 Nutrient losses from erosion and runoff (kg ha^{-1}).

Nutrient	Sediment			Runoff			Total		
	3 yr-OP	5 yr-OP	Forest	3 yr-OP	5 yr-OP	Forest	3 yr-OP	5 yr-OP	Forest
N	12.900	13.000	1.900	0.011	0.011	0.002	12.911	13.011	1.902
P	2.650	1.520	0.490	0.169	0.102	0.006	2.819	1.622	0.496
K	10.460	15.170	1.610	0.017	0.007	0.004	10.477	15.177	1.614

absorb water, the surface runoff will increase proportionally. Moreover, the duration of rainfall also affects the amount of surface runoff (Sukartaatmadja 1998; Banabas et al. 2008). The longer the rainfall, the greater the surface runoff, depending on the strength and amount of rainfall.

According to the study results, the largest erosion and highest runoff occur in 3-year-old Oil Palm (OP) plantations, followed by 5-year-old OP plantations and forests. As many previous studies have reported, the amount of erosion is affected by vegetation coverage. Trees in forest areas can intercept falling rain and reduce the impact of raindrops on the soil, which can cause the dispersion of soil particles. Whereas in OP plantations, the percentage of canopy cover is lower, allowing more rain to fall through it.

Like OP plants, plants with fibrous roots are more effective in controlling erosion. This is because the fine threads on the fibre roots can bind soil particles into a solid soil aggregate. The growth phase or age of the plant also has a different effect on the erosion control process. Initially, the growth of canopy cover plants is still relatively open, causing rainwater to fall directly on the soil surface. This can accelerate the occurrence of surface flow because of the slow infiltration of water into the soil. Plant height also plays a key role in increasing the effectiveness of cover crops in reducing erosion. A lower and tighter plant canopy can change the energy of the rain that reaches the soil's surface (Arsyad 2006). In addition, vegetation can affect erosion due to (i) interception of rainfall by the canopy and absorption of rainwater energy, minimizing soil erosivity, (ii) influence on surface runoff, (iii) increase in soil biological activity, and (iv) increase in the speed of water loss through transpiration (Rahim 2003).

The level of erosion that occurs can be influenced by vegetation factors such as crop canopy cover and vegetation cover in the forest and oil palm (OP) plantations. In the studied OP plantations, which are 5-6 years old, the canopy cover levels are relatively close compared to younger OP but still more open than forests. This can be observed by the distance between canopies, which are close enough. The relatively close canopy cover levels enable plants to retain more falling rain. In addition to being intercepted by the plants, rainfall can flow through the stems and then be transferred to the soil surface, albeit with less force than at the point of origin. The reduced energy of rainfall that reaches the soil surface results in a lesser ability of raindrops to disperse the soil, ultimately reducing the amount of erosion. In forest areas, canopy stratification also has a decreasing effect on raindrops and surface runoff, which can reduce erosion (Arsyad 2006).

Based on the results presented in Table 3, it can be observed that nitrogen, phosphorus, and potassium are lost due to erosion and surface runoff. Therefore, it is crucial to implement measures to control erosion. In addition to the loss of N, P, and K minerals, erosion can introduce other nutrients and organic materials and change the composition of soil particles in the area. Sediment movement is stronger in fine particles, which can cause clay and dust to leave more sand in the soil. Previous studies have reported that a catchment area with native forests has a lower loss of NO_3 per year compared to areas with plantations where the river discharge output exceeds the rainfall input. Loss of nutrients on OP plantations can be influenced by various factors such as soil type, rainfall intensity, age of plantations, agricultural practices, type of fertilizers, water management, and level of fertilizer applications. Generally, OP plantations that receive chemical fertilizers have lower nutrient losses through leaching and concentrations of nutrients in groundwater quality. However, larger nutrient losses are expected in mature plantations due to reduced nutrient absorption by palm roots and higher use of fertilizers. These factors can contribute to an overall increase in nutrient loss. This study found that the forest lost 1,050 g ha^{-1} of nitrogen, 21.69 g ha^{-1} of phosphorus, and 1,084 g ha^{-1} of potassium. Compared to Ariesca's (2004) findings, nitrogen loss was substantially more significant. Similarly, the total loss recorded in Papua New Guinea was between 0.3 and 2.2 kg Nha^{-1} $year^{-1}$, lower than the 15-22 kg Nha^{-1} $year^{-1}$ reported in Malaysia. Smallholder OP plantations have experienced increased leaching losses of potassium and other nutrients such as sodium, calcium, magnesium, and total aluminium since applying inorganic fertilizers and liming.

Conclusion

The study showed that the highest rainfall occurred in October, with a total of 459.5mm, while the lowest rainfall was recorded in June. November had the most wet days, with 24, while May had the lowest, with only 7 days. Erosion and runoff were found to be higher in 3- and 5-year-old oil palm (OP) plantations compared to forest areas. The largest surface runoff was observed in 3-year-old oil palm plantations with a recorded value of 2.83mm, followed by 5-year-old oil palm plantations with 2.46mm, and forest areas with

0.52mm. The study also found that nutrients are lost due to erosion and runoff from 3- and 5-year-old OP plantations, which is higher than in forest areas. Nutrients are mostly lost along with sediment; only a small percentage is lost in water surface flow. The total nitrogen content in eroded sediments and surface runoff in OP plantations aged 3 years, 5 years and forests are 12.91 $kgha^{-1}$, 13.05 $kgha^{-1}$, and 1.94 $kgha^{-1}$, respectively. The total phosphorus content lost in erosion and runoff was 2.82 $kgha^{-1}$, 1.62 $kgha^{-1}$, and 0.50 $kgha^{-1}$, while the average potassium loss was 10.48 $kgha^{-1}$, 15.18 $kgha^{-1}$, and 1.61 $kgha^{-1}$ for 3 years, 5 years, and forests, respectively.

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