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Changes in Microbial Populations and Chemical Properties of Undisturbed and Disturbed Secondary Forests Converted to Oil Palm Cultivation

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ABSTRACT

Conversion of natural forests into monoculture oil palm plantations may result in detrimental effects on soil microbial population and the physical properties. In this study, data on soil microbial populations and soil chemical properties were collected from three different areas namely, undisturbed secondary forest (USF), disturbed secondary forest (DSF) and oil palm cultivated area (OP) at three different sampling times (June 2012, January 2013, June 2013). Results showed that microbial populations were significantly affected by location and time of sampling. The OP had the highest populations of bacteria (6.57 $\log_{10}$cfu g^{-1} soil) and fungi (5.57 $\log_{10}$cfu g^{-1} soil) in June 2013. Population of phosphate-solubilising bacteria was consistently low at the OP compared to that in the secondary forests (USF and DSF) at all sampling times. Most of the soil chemical properties were affected by time changes. Soil moisture was higher in the secondary forests (USF and DSF) in June 2012 and June 2013. Total C (4.09%) and N (0.31%) were higher in USF compared to DSF and OP in January 2013. The findings demonstrate that cultivation of oil palm did not diminish the overall microbial population and physico-chemical properties of the soil. However, differences in soil attributes between the secondary forests (USF and DSF) and oil palm OP denote that oil palm cultivation did have some adverse effects on soil microbial population.

Key words: Soil quality, secondary forest, oil palm cultivated area, soil microbial population, soil chemical properties.

INTRODUCTION

The expansion of oil palm plantations in the past few decades has been a subject of much debate due to deforestation, increase in greenhouse gas (GHG) emissions and loss of biodiversity (Khatiwada *et al.* 2018). Malaysia is the world's second largest producer and a major exporter of oil palm with a planting area of 5.81 million hectares or 17.7 % of the total 32.86 million hectares of land area of Malaysia (MPOB, 2018).

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However, oil palm is largely grown on highly weathered tropical soils which are less fertile and have low pH (< 5) with the soil consisting mainly of sesquioxides and kaolinite. Under these circumstances, the availability of phosphorus is severely limited and the acidity of tropical soils may accelerate the loss of basic cations (Ca^{2+} and Mg^{2+}) which can reduce biological N fixation and crop yield (Teh 2017).

External inputs such as fertiliser and pesticides are commonly introduced to improve plant productivity and protect the plants against diseases. However, the application of pesticides and fertilisers in agriculture has been known to reduce soil biota activities and diversity. Accumulation of metal contaminants from the fertiliser can lead to long-term chronic toxicity. Further, nitrogen-fixing rhizobia are more sensitive to metal toxicity (Bitew and Alemayehu, 2017). Hernández *et al.* (2018) state that in the short-term period, glyphosate usage decreases the bacterial population. Paraquat causes disruption in bacteria and actinomycetes population, whereas fungi are most affected by glyphosate (Masirah *et al*. 2013).

Soil chemical and biological properties are considerably critical, since they are closely related to various functional processes of soil (Lu *et al.* 2013). Soil microbial properties serve as a sensitive indicator providing useful insights on short-term changes of land use (Moeskops *et al.* 2010). It has been shown that changes in the composition of soil microbial community can lead to either a decline or an improvement in management practices. Studies have shown that oil palm cultivation in Borneo has led to the extinction of ectomycorrhizal fungal communities and the loss is attributed to the absence of leaf litter to support organic horizon, interference of heavy vehicles which causes the soil to be compacted and chemical inputs from fertilisers and limes which disrupt the pH (McGuire *et al.* 2015). However, under different circumstances, oil palm cultivation promotes more diversity for certain bacteria such as *actinobacteria* when compared to forest soil, where there is less availability of carbon and nitrogen ratio (Lee-Cruz *et al.* 2013; Tripathi *et al*. 2012).

To know more about converting forests to oil palm plantations, there is a need to evaluate the changes in microbial population and soil physico-chemical properties (Allen *et al*. 2011). It is known that oil palm plantations have an adverse impact on the microbial communities as well as physico-chemical properties of the soil. Hence, the study used secondary forests as a reference to compare the changes that occur in an oil palm plantation. The objectives of this study are: (1) to determine the populations of bacteria, actinomycetes, fungi and functional microbes (phosphate-solubilising bacteria and N-fixing bacteria) from secondary forests and oil palm cultivated areas in Belaga, Sarawak at different sampling periods; and (2) to determine the relationships between the changes in microbiological properties and the soil physical and chemical properties in secondary forests and oil palm cultivated areas.

Site Description

Soil sampling was carried out at three different areas, namely undisturbed secondary forest [Biodiversity strip 1 (USF)] (longitude: 113º 956688'–113º 962620'E, latitude: 2º 2991894'- 2º 2985677'N), disturbed secondary forest [Biodiversity strip 2 (DSF)] (longitude: 113º 973298'-113º 957065'E, latitude: 2º 999828'- 2º 992196N) and oil palm cultivated area (OP) (longitude: 113º 953327'- 113º956999'E, latitude: 2º 985197' - 2º986037'N) in Sungai Asap, Belaga, Sarawak. All of the sampling areas were adjacent to each other, where USF and DSF were 6.0 km and 6.7 km apart, respectively, from OP cultivated area. Sampling was conducted at 6-month intervals (June 2012, January 2013, June 2013). Oil palm was cultivated on a total area of 106.4 ha in 2009 by smallholders. The age of the oil palm tree was 5 years (June 2012), 5½ years, (January 2013) and 6 years (June 2013) respectively. Sarawak is categorised as having a tropical rainforest climate, with the wettest period being from November to February during North-East Monsoon season and dry season from June to August. Soil sampling was carried out during both the wet and dry seasons. The average annual temperature ranged from 26.7ºC to 27.9ºC while the rainfall ranged from 92 to 327 mm as shown in Table 1.

TABLE 1
Total rainfall(mm) during sampling period

Sampling time	Month/Year	Total rainfall(mm)	Temperature (ºC)	Relative humidity (%)
1	June 2012	92.19	27.0	84.5
2	January 2013	327.66	26.7	85.8
3	June 2013	98.89	27.9	83.4

Sampling Design and Collection

This study was arranged in a completely randomised design. Soil sampling was carried out at 10 GPS point from each site at depths of 0 – 10 cm. The distance between one sampling point to another was 100 m apart. Three replications of soils were taken from each sampling point and composited to represent one sampling point. The samples were kept in sterile plastic tubes and transported in polystyrene boxes containing ice to the laboratory.

Soil Microbial Population Analysis

A series of tenfold dilutions of the soil suspension were made up to 10^{-6}. Aliquots of 0.1 mL from the prepared dilution were spread on respective Nutrient Agar (NA) (Merck Cat # 1054500500) for bacteria, Actinomycete Agar (AA) for actinomycetes (BD DIFCO Cat #212168), Rose-Bengal Streptomycin Agar (RBSA) for fungi, nitrogen-free malate medium for nitrogen-fixing bacteria and National Botanical Research Institute's phosphate growth medium (NBRIP) for phosphate-solubilising bacteria. A spread plate technique was used and the plates were incubated for 24 h at 28ºC.

Soil Chemical Analysis

Soil pH was measured using a pH meter (Beckman digital pH meter) of 1:2.5 soil/water ratios. Determination of total carbon and total nitrogen contained in the soil samples was carried out by using LECO CNS machine, with 1 g of soil. Soil Extractable Phosphorus (P) was determined by using extraction reagent of Bray 2 (0.03N NH4F + 0.5N HCL) by an auto-analyzer (Lachat instrument, WI, USA). Cation Exchange Capacity (CEC) was measured using ammonium acetate method (NH_4 OAC) at pH 7 followed by displacement of 1N K_2 SO_4; the value was then determined by an auto-analyzer (Lachat instrument, WI, USA).

All statistical analyses were carried out using SAS 9.4 Significant differences of all the measured soil attributes among different land use types were tested with two-way ANOVA followed by Tukey's HSD differences at $P<0.05$.

RESULTS

Soil Microbial Population

Bacterial populations were significantly higher in undisturbed secondary forest (USF) and in disturbed secondary forest (DSF) in January 2013, compared to that in oil palm cultivated area (OP). However, opposite trends were observed in June 2013 where populations of bacteria were highest at OP (6.57 log10cfu g^{-1} soil) compared to that in both the secondary forests (Table 2).

The actinomycetes population was also significantly affected by location and time indicating that actinomycetes are highly sensitive towards environmental changes (Table 3). Table 2 shows that the populations of actinomycetes decreased with time in both the secondary forests (USF and DSF) and OP. Populations of actinomycetes were consistently highest at USF in January 2013 and June 2013 although, the populations of actinomycetes in DSF was about the same with OP.

Table 2 shows that the fungal populations in DSF (3.65 log10cfug^{-1} soil) and OP (3.64 log10cfug^{-1}soil) were the lowest in June 2012 compared to that in January 2013 and June 2013 sampling times. On the other hand, the populations of fungi were highest (5.57 log10cfug^{-1} soil) in OP compared to that in secondary forests (USF and DSF). Differences in fungi population were observed with respect to time and location (Error! Reference source not found.).

The population of nitrogen-fixing bacteria showed the significance of time (Table 3). It can be seen from Table 2 that a significant difference in nitrogen-fixing bacteria populations was only found at OP January 2013, with the populations being the lowest (4.49 log10cfu g^{-1}soil) compared to June 2013; but it is to be noted that there was no difference compared to June 2012.

TABLE 2
Soil microbial population of undisturbed and disturbed secondary forests (USF and DSF) and oil palm cultivation area (OP) in three sampling periods in Belaga, Sarawak

	June 2012 (mean ± std. err) (n=10)	January 2013 (mean ± std. err) (n=10)	June 2013 (mean ± std. err) (n=10)
Bacterial population (log_{10}cfu g^{-1} dry soil)			
USF	5.90 ± 0.03abA	6.18 ± 0.13aA	5.48 ± 0.21bB
DSF	5.89 ± 0.01abA	6.57 ± 0.37aA	5.74 ± 0.14bB
OP	5.90 ± 0.01bA	5.35 ± 0.09bB	6.57 ± 0.29aA
Actinomycetes population (log_{10}cfu g^{-1} dry soil)			
USF	6.85 ± 0.01aA	4.97 ± 0.09bA	5.02 ± 0.24bA
DSF	6.83 ± 0.02aA	4.43 ± 0.07bB	3.64 ± 0.13cB
OP	6.84 ± 0.01aA	4.18 ± 0.04bB	4.33 ± 0.37bAB
Fungal population (log_{10}cfu g^{-1} dry soil)			
USF	3.88 ± 0.29aA	4.94 ± 0.52aA	4.90 ± 0.18aB
DSF	3.65 ± 0.03cA	5.25 ± 0.10aA	4.19 ± 0.17bC
OP	3.63 ± 0.03cA	4.62 ± 0.29bA	5.57 ± 0.14aA
Nitrogen-fixing bacterial population (log_{10}cfu g^{-1} dry soil)			
USF	5.56 ± 0.18aA	5.03 ± 0.29aA	5.61 ± 0.18aA
DSF	5.51± 0.21aA	5.47 ± 0.32aA	5.45 ± 0.19aA
OP	5.68 ± 0.36aA	4.49 ± 0.30bA	5.86 ± 0.39aA
Phosphate-solubilising bacterial population (log_{10}cfu g^{-1} dry soil)			
USF	5.89 ± 0.18aA	5.34 ± 0.15aA	5.45 ± 0.19aA
DSF	5.23 ± 0.21aA	4.86 ± 0.15aA	5.27 ± 0.13aA
OP	3.89 ± 0.36aB	3.79 ± 0.21aB	3.75 ± 0.20aB

Notes: USF= Undisturbed Secondary Forest, DSF= Disturbed Secondary Forest, OP= Oil Palm Cultivated Area. Values followed by different uppercase letters within a column indicate difference (p<0.05) among locations. Values followed by different lowercase letters within a row indicate difference (p<0.05) in times.

The population of phosphate-solibilising bacteria was significantly affected by the difference in location (Table 3) shows that in June 2012, the population was at the lowest (3.89 log10cfu g^{-1} soil) in OP compared to that in secondary forests (USF and DSF). Similar differences were recorded consistently in January 2013 (3.79 log10cfu g^{-1} soil) and June 2013 (3.75 log10cfu g^{-1} soil), suggesting that phosphate-solubilising bacteria were significantly affected by differences in management of soil.

TABLE 3
P values of 2-way ANOVA showing effect of time, location, and their interaction on soil microbial populations across all locations and times of sampling

	$P_{location}$	P_{time}	$P_{location*time}$
	(df = 2)	(df = 2)	(df = 4)
Bacterial	NS	NS	<.0001
Actinomycetes	<.0001	<.0001	<.0001
Fungi	NS	<.0001	0.013
Nitrogen-fixing bacteria	NS	0.0097	NS
Phosphate-solubilizing bacteria	<.0001	NS	NS

Variables: Total bacterial population; Total actinomycetes population; Total fungal population; Total Nitrogen-fixing bacterial population;, Total phosphate-solubilising bacterial population

Soil Chemical Properties

Soil chemical characteristics varied significantly between land uses (Table 4). Notably, pH was significantly lowest in January 2013 compared to June 2012 and June 2013. Significant differences among location were observed in June 2012 where OP had the lowest pH (5.48). However, in June 2013 pH recorded in DSF was the highest (5.34) compared to USF (4.64) but not significantly different from OP area (5.03). Overall, significant differences were observed at different times and locations (Table 5).

A significant interaction of location and time was detected for soil moisture content (MC) (Table 5). MC was significantly lower in oil palm cultivated area at all sampling times. A significant difference with respect to time was detected where DSF had significantly the highest MC in June 2013 (32.99%) compared to June 2012 and January 2013 (Table 4).

Total C appears to be affected by time, location and interactive effect between time and location (Table 5). The significance was more pronounced in January 2013 where total C (4.09 %) and total N (0.31%) were higher in USF compared to DSF and OP (Table 4).

There were significant differences in total S as shown in Error! Reference source not found.. In June 2012, total S in OP was higher (0.008%) compared to DSF but there was no difference compared to USF. However, in January 2013, total S in USF was higher (0.030%) compared to DSF and OP (Table 5).

Available P was observed to be higher in USF (11.56 mg kg^{-1} and 12.86mg kg^{-1}) compared to DSF and OP in June 2012 and June 2013 (Table 4). Inconsistent values of available P were observed through all sampling times. Available P in USF was the highest (19.39mg kg^{-1}) in January 2013 compared to June 2012 and June 2013 while available P in DSF and OP were the highest (16.04 mg kg^{-1} and 20.90 mg kg^{-1}, respectively) in June 2013 compared to June 2012 and January 2013.

Cation Exchange Capacity (CEC) was significantly affected by location. As shown in TABLE 4, significant differences were detected in June 2012 where USF was higher (16.94 $cmol_{(+)}$ kg^{-1}) compared to DSF and OP.

TABLE 4
Chemical properties of undisturbed and disturbed secondary forests (USF and DSF) and oil palm cultivation area (OP) in three sampling periods in Belaga, Sarawak

	June 2012 (mean ± std. err) (n=10)	January 2013 (mean ± std. err) (n=10)	June 2013 (mean ± std. err) (n=10)
pH			
USF	6.36 ± 0.06^{aA}	4.22 ± 0.20^{bA}	4.64 ± 0.09^{bB}
DSF	6.30 ± 0.04^{aA}	3.83 ± 0.11^{cA}	5.34 ± 0.08^{bA}
OP	5.48 ± 0.03^{aB}	4.33 ± 0.16^{bA}	5.03 ± 0.19^{aAB}
Moisture content (%)			
USF	25.78 ± 2.47^{aA}	20.55 ± 1.90^{aA}	27.35 ± 1.55^{aA}
DSF	21.23 ± 2.05^{bA}	19.35 ± 2.37^{bA}	32.99 ± 1.86^{aA}
OP	14.28 ± 0.97^{aB}	14.22 ± 1.19^{aA}	16.92 ± 3.04^{aB}
Total C (%)			
USF	1.77 ± 0.02^{bA}	4.09 ± 0.47^{aA}	1.52 ± 0.25^{bA}
DSF	1.86 ± 0.50^{aA}	1.35 ± 0.03^{aB}	1.31 ± 0.01^{aA}
OP	1.11 ± 0.16^{aA}	1.16 ± 0.14^{aB}	1.14 ± 0.13^{aA}
Total N (%)			
USF	0.18 ± 0.01^{bA}	0.31 ± 0.03^{aA}	0.16 ± 0.01^{bA}
DSF	0.25 ± 0.03^{aA}	0.17 ± 0.02^{aB}	0.16 ± 0.01^{aA}
OP	0.17 ± 0.03^{aA}	0.12 ± 0.02^{aB}	0.13 ± 0.01^{aA}
Total S (%)			
USF	0.006 ± 0.0009^{aAB}	0.030 ± 0.004^{aA}	0.024 ± 0.001^{aA}
DSF	0.005 ± 0.001^{aB}	0.012 ± 0.002^{aB}	0.009 ± 0.001^{aA}
OP	0.009 ± 0.002^{aA}	0.014 ± 0.002^{aB}	0.036 ± 0.002^{aA}
Available P (mg kg^{-1})			
USF	11.56 ± 0.28^{bA}	19.39 ± 1.00^{aA}	12.86 ± 1.05^{bA}
DSF	9.49 ± 0.71^{bB}	10.23 ± 1.66^{aB}	16.04 ± 1.86^{aA}
OP	9.86 ± 0.35^{bB}	10.24 ± 1.73^{bB}	20.90 ± 4.00^{aA}
CEC ($cmol_{(+)}kg^{-1}$)			
USF	16.94 ± 0.58^{aA}	18.23 ± 0.88^{aA}	14.43 ± 1.66^{aA}
DSF	9.16 ± 1.30^{aB}	12.82 ± 0.89^{aA}	13.74 ± 2.08^{aA}
OP	8.30 ± 1.54^{aB}	11.37 ± 3.41^{aA}	9.29 ± 0.90^{aA}

Notes: USF= Undisturbed secondary forest; DSF= Disturbed secondary forest; OP= Oil palm cultivated area. Values followed by different uppercase letters within a column indicate difference ($p<0.05$) among locations. Values followed by different lowercase letters within a row indicate difference ($p<0.05$) in time. Variables: pH, Moisture Content (MC); Total Carbon (C); Total Nitrogen (N); Total Sulphur (S);Available Phosphorus (P); Cation Exchange Capacity (CEC)

Correlations Between Microbial Population and Chemical Properties

Soil properties played an important role in determining the distribution of the various microbial groups enumerated (Table 6). It can be observed that fungi were sensitive to soil chemical properties and changes in pH(r= -0.46). In a similar way, actinomycetes abundancy was also controlled by pH (r=0.62).

TABLE 5
P values of 2-way ANOVA showing effect of time, location, and their interaction on soil chemical properties across all locations and times of sampling

	$P_{location}$ (df = 2)	P_{time} (df = 2)	$P_{location*time}$ (df = 4)
pH	NS	<.0001	<.0001
Moisture content	<.0001	<.0001	0.02
Total C	<.0001	0.001	<.0001
Total N	NS	NS	NS
Total S	0.03	0.01	NS
Available P	NS	0.0007	0.0007
CEC	<.0001	NS	NS

Variables: pH; Moisture Content (MC); Total Carbon (C); Total Nitrogen (N); Total Sulphur (S); Available Phosphorus (P); Cation Exchange Capacity (CEC)

TABLE 6
Correlations between microbial populations vs chemical properties across all locations and times of sampling

Correlations	BAC population	ACT population	FUN population	NFB population	PSB population
pH	-0.18	0.62**	-0.46**	0.12	0.155
MC	0.023	-0.10	-0.044	0.023	0.41**
TC	0.011	0.055	0.17	-0.07	0.28**
TN	0.019	0.13	0.023	-0.03	0.16
TS	0.27**	-0.093	0.30**	0.17	-0.13
AP	0.28*	-0.29**	0.14	0.10	-0.0016
CEC	-0.09	-0.097	0.087	0.04	0.41**

* and ** indicate the significance of the Pearson correlations at $p<0.05$ and $p<0.01$ respectively; n=90
Variables: pH; Moisture Content (MC); Total Carbon (C); Total Nitrogen (N); Total Sulphur (S); Available Phosphorus (P); Exchangeable Potassium (K), Exchangeable Calcium (Ca); Exchangeable Magnesium (Mg); Cation Exchange Capacity (CEC); Total bacterial (BAC) population; Total Actinomycetes (ACT) population; Total fungal (FUN); Total nitrogen-fixing bacterial (NFB) population; Total phosphate-solubilising bacterial (PSB) population.

DISCUSSION

Population of bacteria was higher in the secondary forests (USF and DSF) compared to OP in January 2013. This finding is supported by Miah *et al*.(2010) where the bacteria population was lower in shifting cultivation than in forest soil. Response to environmental features such as sparse vegetation, less litter and leaving the soil exposed to full sunlight may contribute to the decline in bacterial population in the oil palm cultivated area. Large sized tree species in forests giving full canopy coverage may favour bacterial population in secondary forests areas (USF and DSF) compared to OP. However, there is evidence that bacteria are also well adapt to a cultivated environment (Tripathi *et al.* 2012). The population of bacteria was also observed to be higher in OP soil compared to secondary forests soils (USF and DSF) in June 2013. Alori *et al*.(2017) reported that adding small amounts of inorganic phosphate to the rhizosphere could drive mineralisation by bacteria. It

was also inferred that new individuals and groups might be introduced in moderate disturbance, therefore promoting competition and diversity of the community and establishing a more stable community in cultivated soils (Shange *et al.* 2012). The development of regenerating stands with young trees may have induced a gradual increase in community composition and activity which resulted in an increase in the bacteria population in OP in June 2013; the change in bacteria population in both secondary forests (USF and DSF) may mostly be due to nutrient availability (Mikkelson *et al*. 2016). Significant differences in chemical properties were also observed in this study.

Acosta-Martínez *et al*. (2008) suggest that actinomycetes are more prevalent in non-disturbed systems compared to soils under agriculture; this is in agreement with our study where populations of actinomycetes were consistently the highest in the USF, although the populations of actinomycetes in the DSF were about the same as in OP. Research findings of Hill *et al*.(2011) also suggest that there is no statistically significant evidence that cultivation increases the actinomycetes populations. Furthermore, actinomycetes were more commonly found in cultivated areas than in forested areas (Lee-Cruz *et al.* 2013; Shange *et al*. 2012). This may due to its capability of surviving under extreme environments (Ghorbani-Nasrabadi *et al*. 2013). Therefore, it is noted that the difference in soil chemical properties with the intervention of natural variables in DSF and OP may be the reason for the differences seen in USF. Positive correlation between pH was observed in this study. Generally, phosphate-solubilisation refers to the solubilisation of organic phosphorus and the degradation of the remaining portion of the molecule (Tamburini *et al*. 2014). Since actinomycetes also exhibit phosphate solubilisation capacity, the decomposition of phosphorus is expected to be carried out by actinomycetes. The pH of most soils where there are phosphate activities ranges from acidic to neutral values (Alori *et al.* 2017) whereas most soil actinomycetes show their optimum growth in neutral and slightly alkaline conditions (Garcia-Franco *et al*. 2015). In this study, it was observed that in soils with a pH of 5.48 and above, the populations of actinomycetes ranged from 6.83 to 6.85 log10cfu g^{-1}. But in soils with a pH below 5.34, the populations of actinomycetes ranged from 3.83 to 5.03 log10cfu g^{-1}. This scenario may explain the abundance of actinomycetes in June 2012 compared to January 2013 and June 2013.

Response of soil fungi against perturbation was rapid considering the brief period of time; fungal populations were affected in DSF and OP, whereas in USF, it was relatively stable throughout the sampling times suggesting that fungal populations exhibit a negative response to present and past agriculture management such as fertilisation in oil palm plantation and persistence in DSF (Guillaume et al. 2016; McGuire *et al*. 2015). Adversely the populations of fungi in this study have been shown to have a preference for human activity. Indeed Castaneda *et al*.(2015) also found that fungal communities flourished more in vineyards than in forested areas. Fungal populations were higher in OP compared to secondary forests (USF and DSF) although no significant differences were

observed in the first two sampling times. The differences may be attributed to the several chemical properties such as soil pH and total S, observed in the present study. The increase in soil acidity was probably brought about by an increase in fungal population and the variety of fungal populations. As observed, pH values were highest in June 2012 compared to January 2013 and June 2013. This scenario may explain the disruption in the number of most fungal populations at that particular time. The abundance of fungal populations could be attributed to their ability to proliferate at low pH (Okonkwo 2010). The increase in fungal population in the OP area was due to the activities performed for cultivation such as crop residue which can either promote or ease competition resulting in a more diverse community (Lee-Cruz *et al.* 2013; Shange *et al*. 2012).

Significance differences of nitrogen-fixing bacteria populations were only found in OP area in January 2013which had the lowest populations compared June 2012 and June 2013. This is expected, given the occurrence of heavy rainfall in January 2013 (327.66 mm) and which may have contributed to the decline in the populations of nitrogen-fixing bacteria. According to Allen *et al*.(2011), seasonal distribution of rainfall may affect the health of the soils and this has an impact on soil biological processes.

The population of phosphate-solubilising bacteria showed a consistent decrease in OP area compared to secondary forests (USF and DSF) suggesting that phosphate-solubilising bacteria have lesser preference for profileration in cultivated areas. This is in line with a study by Stanley *et al*.(2013) where these bacteria were found to be susceptible to an environment where there is paraquat use. Besides, the population of phosphate-solubilising bacteria may have an affiliation for the bioavailability of growth-promoting substances (Bhattacharyya *et al*. 2013). Thus, it can be concluded that phosphate-solubilising bacteria in this study were heterotrophic (Vikram *et al*. 2007).

The differences in soil pH among the locations and different sampling times were presumably due to differences in fertilisation levels and quality and quantity of plant litter produced (Hazarika *et al*. 2014) and natural processes such as carbon dioxide evolution from plant roots or soil microbial respiration. These processes are believed to be responsible for controlling soil pH (Lauber *et al.* 2009).

Moisture content (MC) was significantly lower in the OP area at all sampling times. This is in agreement with the study of Firdaus *et al*.(2010) which found that moisture content in OP area was lower than in forest soils (USF and DSF) due to evaporation from the soil surface.

Significant reductions in concentrations of total C, N and CEC recorded in DSF and OP could be due to natural environmental factors such as forest canopy and amount of litter available to protect the soil (Dawoe *et al*. 2013). The decline in these factors was expected to speed up the mineralisation process that was observed in DSF and OP area compared to that USF in January 2013. Similar factors were in play in USF where the total C and N saw a decline in June 2012 and June 2013.

As has been observed, inconsistent values of available P were obtained from USF and DSF through the sampling times. Differences in soil physico-chemical properties are associated with vegetation structures due to the differences in quantity and quality of leaf or root litter which control the mineralisation processes (Zhang *et al.* 2015). The higher value of total S in the OP area may be attributed to the cover cropping practices in oil palm cultivation (Ahamadou and Huang 2013).

CONCLUSION

Our study results suggest that most microbial populations and biochemical properties responded to chemical properties in soils as a consequence of human-induced land use alteration. The detectable changes in biological activities in OP area and USF and DSF can be attributed to the decrease in total population of bacteria, phosphate-solubilising bacteria, microbial biomass C (MBC), FDA hydrolysis, phosphatase, pH, MC, total C and total N. It must also be noted that there were strong effects of location, time and interactions of location and time in actinomycetes populations, MBC, and MC and total C. This finding is supported by significant positive correlations between soil microbial populations and chemical properties. Soil degradation which occurred in OP area shows that soils are generally sensitive to disturbance but are resilient, a prerequisite for soil to recover from perturbations. Based on this study, further experimentation is necessary since differences in biological and physico-chemical properties across different land use sites are likely due to obvious limitations of several factors that have not been measured in this study.

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