Effects of long-term nitrogen fertilization on soil CO_2 and N_2O fluxes in a tropical peatland

（熱帯泥炭地における長期窒素施肥が土壌CO_2およびN_2Oフラックスに及ぼす影響）

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CHAPTER 8

Summary

Introduction

Tropical peat swamp forests are largely composed of coarse woody material from fallen trees, branches, and dead roots which develop under conditions of near continuous soil saturation that leads to anaerobic conditions which dramatically slows decomposition. Thus, tropical peat swamp forests are seen to be an important role in the global carbon (C) cycle and has contribution to climate change. The conversion of tropical peat swamp forest into oil palm plantation requires drainage and fertilization which typically accelerates the rate of peat mineralization and enhances soil CO_2 and N_2O emissions to the atmosphere. While effects of nitrogen (N) fertilizers from cultivated tropical peatland are still limited, the understanding of this subject is essential to develop the mitigation approach for sustainable management of tropical peatland for agriculture. Long term studies are essential as environmental conditions and peat characteristics with time could display a different response of the greenhouse gases to N addition. Besides, finding a suitable N rate for optimum oil palm growth and yield whilst maintaining low environmental impact is also crucial for the economic growth of the oil palm sector in Malaysia. Long-term field measurement was conducted (i) to quantify soil N_2O emissions by varying the rates of N fertilizers and the key factors influencing the response of soil N_2O emissions under N fertilization were identified (ii) to quantify the annual soil CO_2 emissions from an oil palm plantation on a tropical peat soil from different N rates, to identify the regulatory factors affecting soil CO_2 fluxes over time and to understand the temporal effect of groundwater level (GWL) on CO_2 fluxes. On the other hand, incubation study was conducted to (iii) investigate the effect of N fertilizer on peat decomposition under different water-filled pore space (WFPS).

Materials and methods

Field experiment: A field experiment was conducted to quantify the CO_2 and N_2O emissions from soil in an oil palm plantation (*Elaeis guineensis* Jacq.) located in a tropical peatland in Sarawak, Malaysia. The study was conducted from January 2010 to December 2013 and resumed from January 2016 to December 2017. Gas measurements were done in the first week of every month on a non-rainy day, 1 week after fertilization, using a closed chamber method. The experiment used a randomized complete block design with four different N rates; control (T1, without N fertilization), low N (T2, 31.1 kg N ha^{-1} yr^{-1}), moderate N (T3, 62.2 kg N ha^{-1} yr^{-1}), and high N (T4, 124.3 kg N ha^{-1} yr^{-1}) in three blocks (three replications). Air temperature, relative humidity, soil temperature at 5 cm and 10 cm, GWL, and rainfall were also measured. Soil properties such as bulk density, soil porosity, WFPS, soil pH, nitrate (NO_3^-), sulphate (SO_4^{2-}), ammonium (NH_4^+), loss on ignition (LOI), total C and total N were also measured. Oil palm yield, parameterized as the fresh fruit bunch (FFB) in each palm of each treatment block, were harvested, weighed, and recorded.

Incubation study: Peat soil was incubated with four fertilization treatments at two different soil moisture (50% and 80% WFPS) were arranged by a randomized complete design. The treatments are; T1 (control- 0 mg N kg^{-1} soil), T2 (780 mg N kg^{-1} soil), T3 (1,550 mg N kg^{-1} soil) and T4 (3,110 mg N kg^{-1} soil) under 50% WFPS and 80% WFPS. Concentration of CO_2, N_2O, soil pH, water extractable organic carbon (WEOC), nitrite (NO_2^-), NO_3^-, NH_4^+, SO_4^{2-}, total C, total N and microbial biomass carbon (MBC) were measured in weekly basis at initial stage, 1,2,3,4,5,6,7,8,9,10,11 and 12 weeks. Gross N mineralization (GM), net N mineralization and nitrification were also calculated.

Soil N_2O emissions under different N rates in an oil palm plantation on tropical peatland.

Application of the N fertilizer significantly increased annual cumulative N_2O emissions for T4 only in the years 2010 (p = 0.017), 2011 (p = 0.012), 2012 (p = 0.007), and 2016 (p = 0.048). The highest average annual cumulative N_2O emissions were recorded for T4 (41.5 ± 28.7 kg N ha^{-1} yr^{-1}), followed by T3 (35.1 ± 25.7 kg N ha^{-1} yr^{-1}), T1 (25.2 ± 17.8 kg N ha^{-1} yr^{-1}), and T2 (25.1 ± 15.4 kg N ha^{-1} yr^{-1}), indicating that the N rates of 62.2 kg N ha^{-1} yr^{-1} and 124.3 kg N ha^{-1} yr^{-1} increased the average annual cumulative N_2O emissions by 39% and 65%, respectively, as compared to the control. The N fertilization had no significant effect on annual oil palm yield (p = 0.994). Alternating between low (deeper than −60 cm) and high GWL (shallower than −60 cm) enhanced nitrification during low GWL, further supplying NO_3^- for denitrification in the high GWL, and contributing to higher N_2O emissions in high GWL. The emissions of N_2O ranged from 17 µg N m^{-2} hr^{-1} to 2447 µg N m^{-2} hr^{-1} and decreased when the WFPS was between 70% and 96%, suggesting the occurrence of complete denitrification. A positive correlation between N_2O emissions and NO_3^- at 70%–96% WFPS indicated that denitrification increased with increased NO_3^- availability. Oil palm yield was negatively correlated with annual cumulative N_2O emissions, and NO_3^- (p<0.05). At the same time positive correlation was found between WFPS and oil palm yield (p<0.001). These suggest that higher NO_3^- uptake by oil palm in higher WFPS and reduced NO_3^- concentration, resulting in decrease of N_2O emission in higher WFPS. Based on their standardized regression coefficients, the effect of GWL on N_2O emissions increased with increased N rate (p < 0.001). Both nitrification and denitrification increased with increased N availability, making both processes important sources of N_2O in oil palm cultivation on tropical peatland.

Effect of ground water level control and N fertilization on CO_2 fluxes from oil palm plantation on tropical peatland.

Application of N fertilizer had no significant effect on annual cumulative CO_2 emissions in each year (p=0.448), ranging from 7.7 to 16.6 t C ha^{-1} yr^{-1} for T1, 9.8 to 14.8 t C ha^{-1} yr^{-1}1 for T2, 10.5 to 16.8 t C ha^{-1} yr^{-1} for T3 and 10.4 to 17.1 t C ha^{-1} yr^{-1} for T4 which possibly due to high C/N ratios and increased with time (20 to 37). Soil CO_2 fluxes were positively correlated with N_2O fluxes, rainfall, soil porosity, air temperature, soil temperature, soil pH, and NO_3^--N while negative correlations were obtained between CO_2 fluxes and oil palm yield, WFPS, GWL, relative humidity and C/N ratio. By using the overall data, CO_2 flux showed significantly positive correlation with both WFPS ($p<0.001$) and N_2O fluxes ($p<0.05$) with WFPS as the strongest predictor. Negative slope of the CO_2 flux to the WFPS was steeper in T4 than other treatments while positive slope of the nitrous oxide (N_2O) emissions to the CO_2 emission was steeper in T3 and T4 than T1 and T2, implying that 62.2 kg N ha^{-1} yr^{-1} (T3) represents the threshold in changes of WFPS on CO_2 flux and changes of CO_2 emissions on N_2O emissions. GWL had significant effects on WFPS and CO_2 fluxes only during young stage of oil palm (2010 and 2011) ($p<0.05$), which due to the disturbance of capillary rise by the increase of oil palm water uptake. Constant peat decomposition after drainage and compaction would decrease soil porosity and increase WFPS over time which led to decrease in CO_2 fluxes over time. Positive relationship between oil palm yield and WFPS ($p<0.001$) and negative relationship between WFPS and CO_2 fluxes suggest that higher WFPS is better to increase oil palm yield and decrease CO_2 emissions as the palms getting mature. This study suggests that N rates less than 62.2 kg N ha^{-1} yr^{-1} with higher WFPS is better to optimize oil palm yield and reduce CO_2 emissions from tropical peatlands.

Incubation study: Effect of different N rates on peat decomposition under different soil moisture level.

There were no significant differences between CO_2 fluxes in IF and OF (p=0.489) but N_2O fluxes in OF was significantly higher than IF (p<0.001), indicating that N fertilizers most likely leached from IF to OF. Higher slope near oil palm trunk would probably cause fertilizers easily leached to lower slope. The width of circumference fertilizer area was approximately 0.15 m but it was shown that fertilizers affected area would likely to be larger than fertilized area (2 m away from palm) particularly on N_2O emissions. Thus, measurements taken in the fertilized area exclusively likely overestimate actual plot scale emissions induced by fertilization. Thus, the calculation of amount of N fertilizers for incubation study was based on area which was affected by fertilization application where N rates are ten times higher than the average calculated based on field experiment. Results showed that there was no significant effect of N fertilization on cumulative CO_2 and N_2O emissions under 50% WFPS (CO_2; p=0.3670, N_2O; p=0.1689) and 80% WFPS (CO_2; p=0.8865, N_2O; p=0.9032), corresponding with results from field studies. Although N fertilization has been added into the peat soil, C/N ratios in all treatments were still high (>20) which not able to support decomposition explained the insignificant effects of N fertilization on CO_2 and N_2O emissions. Only N_2O emissions from fertilized treatments were significantly affected by soil moisture where cumulative N_2O emissions in 80% WFPS were significantly higher than 50% WFPS in fertilized treatments (p<0.001) which in contrast with field measurements where WFPS more than 70% would decrease N_2O fluxes. These could be due to the presence of plant N uptake in field experiment where higher NO_3^- uptake by oil palm in higher WFPS decreased N_2O fluxes. Positive correlation between CO_2 fluxes and N_2O fluxes were found in both field and laboratory results, suggesting that N_2O emission closely related to peat soil organic matter decomposition. Slope of N_2O emissions to the CO_2 emissions in field experiment was larger than incubation which may due to the presence of plant NO_3^- utilization and likely stimulated root exudation, increasing both CO_2 and N_2O emissions in field. Linear positive relationship was obtained between MBC and GM ($p<0.001$) indicates that greater MBC enhanced gross N mineralization which resulted in higher N_2O production. This study suggests that without N uptake by oil palm, N fertilizers application on tropical peatland would result in larger magnitude of N_2O production in higher soil moisture (80%). However, magnitude of peat decomposition on N_2O emissions would be larger in the presence of plant roots which probably due to utilization of NO_3^- by oil palm roots would likely stimulate root exudation which then stimulate microbial activity.

Conclusions

High C/N ratio (>20) after N fertilizers application explained the insignificant effect of N fertilization on cumulative CO_2 and N_2O emissions in both field experiment and incubation study under 50% WFPS ($p>0.05$), suggesting that quality of organic matter play significant roles in peat decomposition. However, N fertilizers application particularly beyond 62.2 kg N ha^{-1} yr^{-1} resulted in larger effects of GWL on N_2O fluxes, WFPS on CO_2 fluxes and CO_2 emissions on N_2O emissions, implying that N rates less than 62.2 kg N ha^{-1} yr^{-1} would be recommended in an oil palm planted on tropical peatland to mitigate the effects of N fertilization on CO_2 and N_2O emissions but able to optimize oil palm yield. Increased of WFPS with time (>70%) reduced both N_2O and CO_2 emissions and increased oil palm yield, suggesting that bulk density and soil porosity are important for mitigation strategies in cultivated tropical peatland. Significant relationship between GWL and WFPS and CO_2

fluxes were found only during early stage of oil palm showed that water uptake by oil palm plantation would play significant roles in affecting the relationship between GWL, WFPS and CO_2 fluxes. Presence of plant roots are likely affecting the relationship between WFPS and N_2O emissions and relationship between CO_2 emissions and N_2O emissions which need future investigation.