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Nitrous Oxide Emissions from Different Fertilizer Management of Cassava Cultivation in Thailand

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Application of nitrogen fertilizers for food crop production is the important source of atmospheric nitrous oxide (N_2O). The direct measurements of N_2O emissions under tropical environments where turnover of nitrogen is rapid are relatively rare, particularly in Southeast Asia. This study aims to measure the direct N_2O emission from managed soil in Thailand. It was performed in a long–term experimental field (47 y) of cassava cultivation with different fertilizations; variations in chemicals (nitrogen [N], phosphorus [P], and potassium [K]) and organic (crop residue [CR] and compost [CP]) fertilizers. The application rate of N, P (P_2O_5), K (K_2O), CR, and CP were 100, 50, 100, 6,250, and 18,750 kg ha^{-1}. A closed chamber method was used to investigate the emissions for 400 d during November 2021 to December 2022. The results show that the application of N from both chemical and organic fertilizers were the key factor inducing a significant fraction of N_2O emissions. The amount of N_2O emissions during these measurement periods ranged from 0.84–3.37 kg N_2O ha^{-1}, its average was 2.21 kg N_2O ha^{-1}. The nutrients provision by fertilizers directly resulted in increased cassava yield production. It was observed that the application of NPK or NK produced the greater yield, and these were additionally enhanced when CR or CP was applied together. Long–term soil management influenced soil characteristics based on the properties of materials applied to the soil. High pH and C content in CP increased soil alkalinity and soil organic carbon (SOC) sequestration. High nutrients in fertilizers affected the greater soil nutrients accumulation. Soil management with NPK+CR appeared to be the most suitable in this study when considering among environment, food security, and SOC aspects.

1. Introduction

Nitrous oxide (N_2O) is one of the major greenhouse gases (GHG), its global warming potential (GWP) is 273 times compared to carbon dioxide (CO_2). It is mostly released from soil management with fertilization in agricultural sector. Managed soils for food crop production are the crucial N_2O source of agricultural countries (IPCC, 2021). The mitigation to support the net zero GHG emissions goal with maintaining food security is challenging. The studies of N_2O emissions using a direct measurement and country-specific emission factors under tropical environments are relatively rare, particularly in Southeast Asia. This is one of the major barriers to build the effective mitigation measures or policies (Gerber et al., 2016). It indicates the urgent need to increase the number of studies in this region, including Thailand. The results of such studies also help to establish the appropriate approaches in response to the international climate change policies such as carbon trade measures (TPSO, 2022). The current estimates of direct N_2O emissions from managed soils for the year 2018 in Thailand was 8,715 Gg CO_2–eq, accounted for 14.9 % of GHG emissions in agricultural sector (ONEP, 2022). This was based on the use of emission factor (EF) of the Intergovernmental Panel on Climate Change (IPCC). This has

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been suggested to be inappropriate in several aspects. It has a high uncertainty ranged of 0.001–0.018 kg N_2O–N (kg N)$^{-1}$ for aggregation case (IPCC, 2019). Charles et al. (2017) concluded that N_2O EF for agricultural soils in 12 countries around the world were lower than IPCC's default value. Lesschen et al. (2011) reported that N_2O emission in each area should be calculated using a specific EF value consistent with environment conditions, crop production, and soil management. Albanito et al. (2017) demonstrated that N_2O emissions and N_2O EF values from managed soils in different sites differed. Shcherbak et al. (2014) reported that the relationship of increasing N_2O emission and increasing N input rate was not linear, contradicting the IPCC assumptions. It is to measure the emissions of N_2O as the important entry point towards establishing the specific N_2O EF. The production and emission of N_2O are varied with land uses characteristics, geographical characteristics, and spatial variations (Hayashi et al., 2015). Thailand has a few studies on N_2O emission using a direct measurement. A first old study of Watanabe et al. (2000) revealed that N_2O EF of soil management for maize cultivation in Nakhon Sawan, Saraburi, Khon Kaen, and Chiang Mai provinces ranged of 0.08–0.44 %. A recent study of Yuttitham et al. (2020) exhibited that maize cultivation soil in Nakhon Ratchasima province had N_2O EF 40 % lower than IPCC's default value. These results are still not sufficient to formulate the specific N_2O EF for Thailand. The increase in N_2O emission studies covering areas and crops should be conducted. This study aims to measure the direct N_2O emission from soil management for cassava cultivation in Thailand.

2. Materials and methods

2.1 Study site

A long–term experimental field at the Rayong Field Crop Research Center of the Department of Agriculture (DOA), Ministry of Agriculture and Cooperatives (12 °44 '00 '' N & 101 °08 '11 '' E, 50 m above mean sea level) was used in this study. It is situated in Mueang district, Rayong province of Thailand. The soil of this field was classified as Ultisols according to the soil taxonomy of the United States Department of Agriculture (USDA) with loamy sand texture (82 % of sand, 6 % of silt, and 12 % of clay). The basic properties of soil at 20 cm depth in each treatment prior to this study are shown in Table 1. The cumulative rainfall and average daily maximum and minimum air temperatures during the study period were 2340 mm, 32.3 °C, and 24.4 °C.

Table 1: Basic soil characteristics prior to this study

Property	NO	CR	N	NK	NP	NPK	NPK+CR	NPK+CP
WFPS (%)	47.0 a	44.7 a	50.0 a	41.2 a	42.9 a	44.4 a	50.7 a	43.0 a
pH [H_2O]	4.70 b	4.48 bc	3.63 d	3.88 cd	3.85 cd	4.03 bc	4.25 bc	6.05 a
OM (%)	0.85 c	1.29 c	1.01 c	1.07 c	1.17 c	1.33 bc	1.89 ab	2.45 a
OC (%)	0.49 c	0.75 c	0.58 c	0.62 c	0.68 c	0.77 bc	1.09 ab	1.42 a
Total C (%)	2.45 c	3.21 ab	2.23 c	2.61 bc	2.74 bc	2.93 b	3.22 ab	3.41 a
Total N (%)	0.15 b	0.20 ab	0.18 ab	0.18 ab	0.19 ab	0.22 a	0.23 a	0.26 a
NO_3^- (mg kg^{-1})	18.7 c	28.7 bc	28.4 bc	35.4 b	26.7 bc	65.2 a	68.3 a	72.0 a
Avail. P (mg kg^{-1})	18.5 b	21.0 b	22.5 b	20.3 b	92.0 b	74.5 b	84.0 b	647 a
Exch. K (mg kg^{-1})	14.0 c	22.5 bc	13.0 c	17.3 bc	18.0 bc	22.0 bc	37.0 b	133 a
EC (dS m^{-1})	0.05 a	0.05 a	0.05 a	0.05 a	0.05 a	0.06 a	0.06 a	0.06 a
CEC (cmol kg^{-1})	3.80 d	3.51 d	4.58 c	3.88 d	4.26 c	5.00 b	6.25 a	5.20 b
Bulk density (g cm^{-3})	1.71 a	1.74 a	1.78 a	1.65 a	1.70 a	1.71 a	1.77 a	1.73 a
SOC stock (Mg ha^{-1})	16.7 b	25.9 b	20.8 b	20.3 b	23.1 b	26.4 b	38.7 a	49.1 a

2.2 Experimental design and crop management

This study included 8 treatments of different soil management: no amendment (NO), crop residue application (CR), nitrogen fertilization (N), N and potassium oxide (K_2O) fertilization (NK), N and phosphorus pentoxide (P_2O_5) fertilization (NP), N+P+K fertilization (NPK), combination of N+P+K fertilization and CR (NPK+CR), and combination of N+P+K fertilization and compost (NPK+CP). The application rates of N, P_2O_5, and K_2O were 100, 50, and 100 kg ha^{-1} season^{-1}. This study used municipal compost at rate of 6,250 kg ha^{-1} season^{-1}. The properties of the municipal compost are; pH [H_2O] 9.00, organic matter (OM) 39.2 %, organic carbon (OC) 22.8 %, total carbon (C) 26.1 %, total N 2.45 %, ammonium (NH_4^+) 480 mg kg^{-1}, nitrate (NO_3^-) 64.0 mg kg^{-1}, phosphorus (P) 180 mg kg^{-1}, potassium (K) 11,150 mg kg^{-1}, electrical conductivity (EC) 10.7 dS m^{-1}, and cation exchange capacity (CEC) 50.2 cmol kg^{-1}. The crop residue of cassava (leaves and stems) was applied at rate of 18,750 kg ha^{-1} season^{-1} (265 kg N ha^{-1} season^{-1}). The experiment was conducted with 4 replications with randomized complete block design (RCBD). Cassava (*Manihot esculenta* Crantz, Rayong 9 variety) was planted with spacing of 1 x 1 m in the plot size of 8 x 10 m. It was cultivated under rain–fed condition with the cropping during of 384 d. Crop residue was incorporated into the soil by tillage that was implemented for 1 month before planting. Compost and chemical fertilizer were applied once per season on 71 and 75 d after planting (DAP). All treatments were managed the same and weeding chemicals were used when needed.

2.3 N_2O emission measurement

Emissions of N_2O was sampled from soil surface using a closed rectangular chamber technique (Sriphirom et al., 2021). The used chamber size was 31 (width) x 31 (length) x 30 (height) cm, 10 cm of chamber base was buried in the soil throughout the study period to minimize the soil interference. Gas sampling was performed every 14 d throughout the study period (400 d, Nov. 2021 to Dec. 2022). Four samples were taken at each time during 09:00–11:30, collected at 0, 10, 20, and 30 min after chamber closure. The collected air samples were analyzed the concentration using a gas chromatograph (7890B GC, Agilent Technologies, Inc., USA) equipped with an electron capture detector (ECD) and helium was used as a carrier gas. The measurement of N_2O emissions was conducted according to the protocol in De Klein and Harvey (2012). The flux and cumulative emission were calculated using the equations given by Yuttitham et al. (2020). The scales of N_2O emission per yield was estimated from the released N_2O amount to a kilogram of yield production (Tran et al., 2015).

2.4 Soil properties and cassava yield analysis

Cassava height and tuber yield were measured and weighed after harvest. The percentage of starch in tuber yield was analyzed using Riemann scale balance technique. Soil samples were collected at 20 cm depth before and after the cropping to analyze the characteristics. The following variables were analyzed; pH [H_2O] using pH meter (HI5222, Hanna Instruments, USA), OM and OC using Walkley & Black, total C and N using dry combustion (CHN 628C Series Elemental Analysis, LECO, USA), NO_3^-–N using an ion chromatography (761 Compact IC, Metrohm, Switzerland) equipped with Metrosep A Supp 5 (150 x 4.0 mm) and using 1.0 mM $NaHCO_3$ + 3.2 mM Na_2CO_3 as eluent, available P (avail. P) using Bray II (Spectroscopy, UV–VIS), exchangeable K (exch. K) using ammonium acetate and atomic absorption spectrophotometer (AAS), EC using electrical conductivity meter, and CEC using ammonium saturation according to the protocol in LDD (2010). Soil samples were dried to analyze moisture content and bulk density (BD) using an oven (Forced Air Convection Drying Oven, Redline RF 53, Germany). The percentage of water–filled pore space (% WFPS) was computed by using the equation as described in Yuttitham et al. (2020). The content of OC and BD were used to estimate soil organic carbon (SOC) stocks using the equation in Schrumpf et al. (2011).

2.5 Statistical analysis

Data were reported as mean value (n=4) with 3 digits. The different letters after data in Tables 1–4 indicated the significant differences among treatments. One–way analysis of variance (ANOVA) with Tukey's honesty significant difference (HSD) at a confidence level of 95 % (p<0.05) was used for the significant difference indication. The statistical analysis was performed using the SPSS version 22.0.

3. Results and discussion

3.1 Direct N_2O emissions

Most of N_2O production in agricultural soils are related to biotic activities that known as nitrification and denitrification processes and most of them are released through soil surface (Hayashi et al., 2015). Soil conditions (e.g. moisture content and texture) and pH in this study indicates that nitrification was a major source of N_2O over denitrification (Sahrawat, 2008). Nitrogen is a key factor contributing to N_2O production and emission (Hayashi et al., 2015). The application of N from chemical and organic fertilizers increased N_2O emission from cassava plantation soil. As relative to no amendment soil (NO), the practices of CR, N, NK, NP, NPK, NPK+CR, and NPK+CP significantly stimulated N_2O emission by 2.02, 0.95, 1.01, 0.99, 1.13, 2.30, and 2.53 kg N_2O ha^{-1}. Wang et al. (2020) reported that nitrifiers abundances and nitrification potential were stimulated at topsoil when fertilizer was applied. The results were observed that higher rate of N input (CR, NPK+CR, and NPK+CP) emitted more N_2O than lower N input rate (N, NK, NP, and NPK) significantly. The similar finding was reported in a meta-analysis of global N_2O emission by Charles et al. (2017) and a sugarcane study in Australia by Takeda et al. (2021). The availability of C from crop residue and compost can also increase N_2O production and emission (Lazcano et al., 2021). The combination of both chemical and organic fertilizers that increased N and C substrates contributed to higher N_2O than applying them separately (Table 2). Hayashi et al. (2015) reported that availabilities of N and C significantly increased N_2O production of nitrifiers and denitrifiers. The scales of N_2O emission per cassava yield production shows that NK, NPK, and NPK+CR soils lowered emission per yield and starch yield production significantly as compared to no amendment soil (Table 2). They are suitable to be suggested when considering the balance of environmental and food security aspects. Albanito et al. (2017) used Generalized Additive Mixed Model (GAMM) to show different net N_2O–N emissions in tropical and sub–tropical regions, Thailand was in the group of low N_2O emissions. Thailand should increase the number of studies to develop the country–specific N_2O EF instead of calculating using IPCC's default value that may be overestimated in relation to this study.

Table 2: Cumulative N_2O emissions and scales of N_2O emission per yield and starch yield

Treatment	Direct N_2O emission ($kg\ N_2O\ ha^{-1}$)	Yield–scaled N_2O emission ($g\ N_2O\ kg\ yield^{-1}$)	Starch yield–scaled N_2O emission ($g\ N_2O\ kg\ yield^{-1}$)
NO	0.84 d	0.70 b	2.74 bc
CR	2.86 b	0.72 b	2.67 bc
N	1.79 c	0.98 a	3.98 a
NK	1.85 c	0.41 c	1.56 d
NP	1.83 c	0.68 b	2.89 b
NPK	1.97 c	0.47 c	1.80 d
NPK+CR	3.14 ab	0.40 c	1.54 d
NPK+CP	3.37 a	0.63 b	2.48 c
Average	2.21	0.62	2.46

3.2 Cassava yield

The provision of nutrients to soil is the important factor increasing crop growth and yield production (Lazcano et al., 2021). Different fertilizer applications induced the changes in cassava growth and yield. Providing more nutrients from both chemical and organic fertilizers stimulated greater cassava height and yield than single fertilizer application and no amendment soil. Regarding yield amount, the application of organic fertilizer as crop residue is suitable to use with NPK fertilizer more than compost that contains high content of P and K. Single fertilizer application in the practice of NK, NPK, and CR produced more growth and yield as compared to other single applications (Table 3), indicating N and K is needed for cassava growth. Wilson and Ovid (1994) revealed that N and K are more important nutrients for cassava growth and yield than P. Excessive residue P in NPK+CP soil (Tables 1 and 4) can suppress cassava yield production (Aliyu et al., 2019). This study demonstrates that chemical fertilizer is still required for effective crop yield production. The combination of chemical and organic fertilizers, particularly NPK+CR, should be suggested for yield production aspect. The actual yield of Rayong 9 cassava when cultivated in suitable soil and weather conditions is about 13.2 $t\ ha^{-1}$ (DOA, 2021), indicating all treatments in this study produced lower yield than expected. This because soil environments have changed due to the repeated management for a long time, making it unsuitable for the cassava growth (Table 4).

Table 3: Cassava growth and yield

Treatment	Plant height (cm)	Tuber yield ($kg\ ha^{-1}$)	Starch (%)	Starch yield ($kg\ ha^{-1}$)
NO	131 d	1,200 d	26.0 abc	310 d
CR	194 abc	3,990 bc	27.1 a	1,090 bc
N	133 d	1,820 d	24.8 cd	454 d
NK	189 bc	4,530 b	26.2 abc	1,190 b
NP	151 cd	2,680 cd	24.0 d	642 cd
NPK	190 bc	4,210 bc	25.7 abc	1,090 bc
NPK+CR	235 a	7,800 a	26.6 ab	2,070 a
NPK+CP	222 ab	5,340 b	25.4 bcd	1,360 a

3.3 Soil characteristics

Different fertilizer applications in the past (47 y) and a current year affected soil quality changes (Tables 1 and 4). Chemical fertilizer acidified soil and increased nutrients accumulation according to those that were provided (N, P, and K). Alkalinity and high contents of P and K in compost increased soil pH and accumulation of P and K in soil. Similar findings were reported by Wang et al. (2019) who reported that 20 years applications of chemical fertilizer decreased soil pH and organic fertilizer increased soil pH. The strong soil acidification in all treatments was the important cause of cassava yield decrease (Ge et al., 2018). The ideal soil pH for the growth of cassava is between 5.5–7.5, although it can tolerate pH as low as 4.0–4.2 (CARDI, 2021). Application of organic matter (CR and CP) could enhance soil OM and OC, resulting in improved SOC sequestration. SOC stock was increased in CR by 48.9 % compared to NO and in NPK+CR and NPK+CP by 18.5 % and 35.9 % compared to NPK. Soil management with the same practices for long–term in this study may have caused damages to soil fertility, particularly high acidity (Table 4). Soil fertility improvement should be considered, such as using dolomite (Shaaban et al., 2015) or lime (CARDI, 2021) to raise soil pH.

Table 4: Soil characteristics after crop harvest

Property	NO	CR	N	NK	NP	NPK	NPK+CR	NPK+CP
WFPS (%)	41.1 a	43.4 a	36.6 a	39.5 a	46.6 a	45.2 a	42.3 a	47.4 a
pH [H_2O]	4.12 b	4.01 b	3.51 c	3.94 b	3.55 c	3.49 c	4.26 b	5.22 a
OM (%)	0.87 d	1.29 c	1.03 cd	1.06 cd	1.23 c	1.50 bc	1.75 ab	2.03 a
OC (%)	0.51 d	0.75 c	0.60 cd	0.61 cd	0.71 c	0.87 bc	1.02 ab	1.18 a
Total C (%)	2.75 bc	3.45 ab	2.28 c	2.67 bc	2.85 b	3.06 b	3.34 ab	3.72 a
Total N (%)	0.16 c	0.22 b	0.19 bc	0.18 bc	0.20 b	0.25 ab	0.24 ab	0.31 a
NO_3^- (mg kg^{-1})	17.0 d	36.8 c	28.4 cd	33.9 c	30.4 cd	54.0 b	69.1 a	77.1 a
Avail. P (mg kg^{-1})	23.7 e	60.8 d	163 c	26.0 e	359 b	359 b	368 b	785 a
Exch. K (mg kg^{-1})	7.07 c	10.8 bc	9.38 bc	14.1 b	10.9 bc	14.6 b	15.4 b	62.5 a
EC (dS m^{-1})	0.05 a	0.05 a	0.06 a	0.05 a	0.06 a	0.06 a	0.05 a	0.06 a
CEC (cmol kg^{-1})	3.69 cd	3.32 d	4.32 c	3.88 cd	4.24 c	5.28 b	6.38 a	5.04 b
Bulk density (g cm^{-3})	1.72 a	1.73 a	1.72 a	1.72 a	1.73 a	1.71 a	1.74 a	1.72 a
SOC stock (Mg ha^{-1})	17.4 c	25.9 b	20.6 bc	21.1 bc	24.7 b	29.8 b	35.3 a	40.5 a

4. Conclusions

Fertilizers are the major source of global N_2O emission. Their uses are still required for food crop production to satisfy yield and maintain food security. This study shows that the direct N_2O emission from cassava plantation with NO, CR, N, NK, NP, NPK, NPK+CR, and NPK+CP in Thailand are 0.84, 2.86, 1.79, 1.85, 1.83, 1.97, 3.14, and 3.37 kg N_2O ha^{-1}. Higher N input from both inorganic and organic sources contributes to larger N_2O emission. The addition of direct measurements of N_2O emissions in the field should provide more spatial coverage to determine the appropriate country–specific EF. This will lead to accurate N_2O estimation and using suitable mitigation measures or policies of Thailand. When considering a sustainable development approach (environment, social, and economic), the application of NPK+CR is the best practice in this study as it releases lowest N_2O per yield production unit and receives highest yield amount as well as maintains food security. Improving soil fertility (specially to resolve soil acidity) to increase cassava yield and mitigating N_2O emission in NPK+CR soil should be further studied to develop it in contributing to the achievement of net zero GHG emission of Thailand and other agricultural countries.

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