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Measurement and Modeling Nitrous Oxide Emissions from Ferric Luvisols in the Guinea Savanna Agro-ecological Zone of Ghana

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Authors' contributions

This work was carried out in collaboration between both authors. Author WKA wrote the protocol, designed the study, managed the analyses of the study and performed the statistical analysis and wrote the first draft of the manuscript. Author PKK reviewed the experimental design and all drafts of the manuscript and approved. Both authors read and approved the final manuscript.

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ABSTRACT

Agricultural sector in Ghana contributes to about 60% of Gross Domestic Product (GDP) and is mainly characterized by fertilizer application to improve depleting soil fertility. With the increase in population and demand for increased productivity, application of inorganic fertilizers will result in enhanced greenhouse gas emissions. As nitrogen (N) is among the most limiting soil nutrient in the Guinea Savanna, chemical/organic fertilizers are applied in significant amounts to maintain crop productivity. Because of increased fertilizer and manure application to replenish dwindling soil fertility, the region is likely to become a significant source of nitrous oxide (N_2O) emissions. To study the effect of fertilizer application on N_2O emissions, Denitrification decomposition model (DNDC), a process-base model of carbon (C) and nitrogen (N) biogeochemistry in agricultural ecosystems was calibrated with field data obtained in 2013 and was used to predict the impact of N fertilizer source and rate of application on N_2O emissions.

The linear equation between measured and modeled annual fluxes from ferric luvisols showed a

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positive relationship between observed N_2O fluxes from field experiments in the 2013 season and simulated N_2O flux with with a coefficient of determination (R^2) of 0.7773. For the validation period (2013) the predicted N_2O emissions simulation agreed practically well with the observed data. Plots without fertilization resulted in the lowest N_2O emissions in both measured and simulated data and the model was capable of simulating the highly dynamic changes in N_2O emissions most of the time at different N application. However, N_2O emissions on application of 120 kg N ha^{-1} as urea and sulphate of ammonia were underestimated by DNDC model. The results further showed that the DNDC model can be used to predict N_2O gas flux from the Guinea Savanna agro-ecological conditions of Ghana. Simulated results further indicate that, application of 120 kg N ha^{-1} as sulphate of ammonia and urea respectively would had higher global warming potential compared to application of same N source at 60 kg N ha^{-1}.

Keywords: Emissions; denitrification; decomposition; modeling; nitrous oxide.

1. INTRODUCTION

The parties to the United Nations Framework Convention on Climate Change (UNFCC) are committed to estimate their national N_2O budgets and to establish regional programmes of N_2O emissions reductions. Although Ghana is party to the Kyoto protocol, there is very little effort in researching into greenhouse gas emissions. The probable reason being that, fertilizer application rate are far below emission thresholds and therefore may have negligible impact on net atmospheric carbon.

Agricultural sector in Ghana contributes to about 60% of GDP and is mainly characterized by fertilizer application to improve depleting soil fertility. With the increase in population and demand for increased productivity, application of inorganic fertilizers will result in enhanced greenhouse gas emissions. Out of many greenhouse gases, N_2O is considered to play an important role in ozone depletion and counts for 6% of the global warming potential (GWP) [1].

The Guinea Savanna agro-ecological zone of Ghana is considered the breadbasket of the country where many crop and animal production occur. As N is among the most limiting soil nutrient in the Guinea Savanna, chemical/organic fertilizers are applied in significant amounts to maintain crop productivity. Because of increased fertilizer and manure application to replenish dwindling soil fertility, the region is likely to become a significant source of N_2O emissions. [2-4] reported similar phenomenon in grasslands in Ireland. The N_2O emissions from chemical/organic fertilizer application and animal deposition are estimated to be 35.6% of total agricultural greenhouse gas emissions in Ireland [5].

In soils, N_2O is mainly produced in the microbial processes of nitrification and denitrification [6]. These processes are influenced by several environmental factors such as soil temperature [7] and soil moisture [8], as well as by management practices, such as nitrogen application [9]. However, [8] reported that the controlling factors and soil properties interact at different temporal and spatial scales and make it difficult to estimate N_2O emissions accurately from the agricultural sector. It is therefore, necessary to fully understand the dynamics of N_2O emissions into atmosphere, and also identify the mechanisms and factors responsible for N_2O production in soils from the tropics.

Many studies on emissions from agricultural sources have been conducted in the tropics, but lacking or few of such studies of N_2O emissions measurements and modeling had been reported from tropical soils. [10,11,4] in Ireland have shown an increase in N_2O emissions rates which is directly influenced by intensive management practices such as increased N application and intensive grazing. For example [4] observed the emission rate range of 1.3 to 3.4%, with an average emission rate approximately 69% higher than the Intergovernmental Panel on Climate Change (IPCC) default value of 1.3%. In view of these results, there is the need for research efforts to understand the N_2O emissions from tropical soils where fertilizer application is on the increase to improve productivity and to develop mitigation strategies.

2. METHODOLOGY

The study was carried out at Akukayilli, N 9°23′ 38.2″ and W 1°00′ 18.4″ located in the Tolon district of the Northern region of Ghana. The climate of the region is relatively dry, with a single rainy season that begins in May and ends in October sometimes with few scattered rains in November. The amount of rainfall recorded annually varies between 750 mm and 1100 mm. The dry season starts in November and ends in March or April with maximum temperatures occurring towards the end of the dry season (March-April) and minimum night temperatures in December and January. The harmattan winds, which occur during the months of December to early February, have a considerable effect on the temperatures in the region, which may vary between 14℃ at night and 40℃ during the day. Humidity, however, which is very low at this time, mitigates the effect of the daytime heat. Vegetation cover ranges is mainly Guinea savannah. Farming forms the main occupation of about 70% of the people in the region. Among the crops grown are maize, rice sorghum, yams, tomatoes and tree crops such as shea-nut, cotton and kapok. The soil at the experimental site was classified as ferric Luvisols/ Kumayili series. The parent material was Voltaian clay; well to moderately drained. The top soil was strong brown with occasional iron and magnesium concretions. It has an average depth of 0-90 cm.

The Denitrification decomposition model (DNDC) model was used to predict the impact of N fertilizer source and rate on greenhouse gas emission with emphasis on N_2O. The model was calibrated and validated with N_2O fluxes obtained from field experiment in the 2013 season. Data sets used to run the model include soil texture, soil bulk density, organic carbon content, field capacity and water filled pore space. Climatic data also precipitation, maximum and minimum environmental temperature obtained from the Council for Scientific and Industrial Research (CSIR)-Savanna Agricultural Research Institute weather station situated 2.5 km away from the experimental site. Complete field management practices which include ploughing, harrowing, planting and harvesting dates, fertilizer application methods and rates were all defined appropriately. Calibration and validation of the DNDC model was done by adjusting model parameters to suit the Guinea Savanna agro-ecological zone conditions of Ghana. Also the impact of different N fertilizer application rate and source on global warming potential was determined after model was well calibrated and validated. Finally the model was used to determine the effect of soil depth, N fertilizer application rate and source on nitrification and denitrification.

2.1 Chamber Measurements of N_2O Fluxes

An improvised static chamber technique (Clayton et al., 1994) was used to sample gas from each plot. The chamber measured 0.050 m in length, 0.025 m width and a height of 0.017 m. It was fitted on to collars of 0.050 cm long, 0.025 cm wide and 0.006 m high covering an area of 0.1256 m^2, and used for CO_2 and N_2O flux. Collars were inserted into the soil permanently at a depth of 0.003 m, a week after planting in each experimental year. Chambers were fitted to the collars at the time of gas sampling each day and were removed after flux measurements. Four gas samples were taken during each measurement day at times 0, 20, 40 and 60 minutes respectively. Volume of 20 ml was collected with a syringe through a three-way stop cock which was fitted gas-tight to the chamber and transferred to a vial with septum. The syringe was flushed three times before sampling in order to mix the chamber air. Samples were transferred into vials with septum, which had been pre-evacuated of air using a vacuum pump of 0.3 mbar and a capacity of 3.5 m^3 h^{-1} and transported to the laboratory for analysis. Samples were analyzed for N_2O using a Clarus 580, PerkinElmer, Rodgau, Germany, fitted with an electron capture detector (detection limit: N_2O< 1 ppbV / 1 nl $^{l-1}$ or lower). Chamber closure and gas sampling were conducted between 09:00 and 16:00 h each gas sampling. Flux rates were calculated according to the following equations:

$$F_{N_2O} = \frac{b \text{ x } V_{ch} \times MW_{N_2O\text{-}N} \times 10^6}{A_{ch} \times MV_{corr} \times 10^9}$$

where F_{N2O} = N_2O flux rate (μg N m^{-2} h^{-1}), b = mixing ratio increase (ppb h^{-1}), V_{Ch} = chamber volume (m^3), $MW_{N2O\text{-}N}$ = molecular weight of N_2O-N (28 g mol^{-1}), A_{Ch} = base area of chamber (m^2), MV_{corr} = pressure and temperature-corrected molvolume of air (m3 mol^{-1}).

$$MV_{corr} = 0.0224 \times \left(\frac{273.15 + t}{273.15}\right) \times \left(\frac{po}{p1}\right)$$

where t = air temperature during measurements (˚C), $_{p0}$ = standard atmospheric air pressure (Pa), $_{p1}$ = air pressure during measurements (Pa).

Annual cumulative N_2O fluxes were calculated by interpolating the N_2O fluxes measured between sampling periods (Dong et al. 2000).

3. RESULTS AND DISCUSSION

Denitrification Decomposition model was calibrated with field data collected in 2013 (Fig. 1b) as well as soil and climatological information of the field.

The annual emissions for the different treatments estimated using the measured data were in the range of 0.5 to 4.5 kg N_2O -N ha^{-1} yr^{-1} from soils that received no fertilizer application and soil that was treated with urea at 120 kg ha^{-1} yr^{-1} (Fig. 1a). The DNDC simulation resulted in an annual flux range of between 2.27 to 5.25 kg N_2O -N ha^{-1} yr^{-1}, for plots that was not treated with fertilizer and plots treated with 120 kg N ha^{-1}. The linear equation between measured and modeled annual fluxes from ferric luvisols showed a positive relationship between observed N_2O fluxes from field experiments in the 2013 season and simulated N_2O flux with an R^2 of 0.7773.

For the validation period (2013) the predicted N_2O emissions simulation agreed practically well with the observed data (Fig. 2). For all six treatments the measured annual N_2O fluxes ranged from 0.3 to 4.2 kg N_2O -N ha^{-1} yr^{-1} (Fig. 1a). Mean annual N_2O fluxes varied considerably between N amount applied and source with maximum emission from soils treated with 120 kg N ha^{-1} in both measured and simulated data. Across all treatments, the mean N_2O flux ranged from 2.27 to 2.56 kg N_2O -N ha-1 y^{-1} for simulated data and from 0.31 to 4.3 kg N_2O -N ha^{-1} y^{-1} (Fig. 2). Time course of N_2O flux is presented in Fig. 1b. Plots without fertilization resulted in the lowest N_2O emissions in both measured and simulated data and the model was capable of simulating the highly dynamic changes in N_2O emissions most of the time at different N application. However, N_2O emissions on application of 120 kg N ha^{-1} as urea and sulphate of ammonia were underestimated by DNDC model. In both the simulated and measured data the peak fluxes occurred in the soon after N application and when soil moisture and soil temperature enabled fluxes to occur (Figs. 6 and 7).

The results showed that the DNDC model can be used to predict N_2O gas flux from the Guinea Savanna agro-ecological conditions of Ghana. Simulated results further indicate that, application of 120 kg N ha^{-1} as sulphate of ammonia and urea respectively would increase the heat trapping capacities of the atmosphere compared to application of same N source at 60 kg N ha^{-1} (Fig. 2).

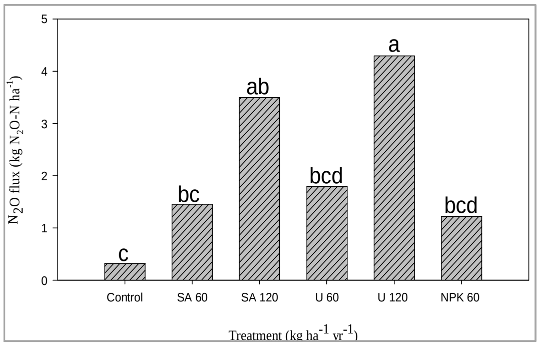

Fig. 1a. Observed N_2O flux (kg ha^{-1}) of fertilized and unfertilized maize field (Bars with the same letters are not significantly different (P >0.05) from each other)

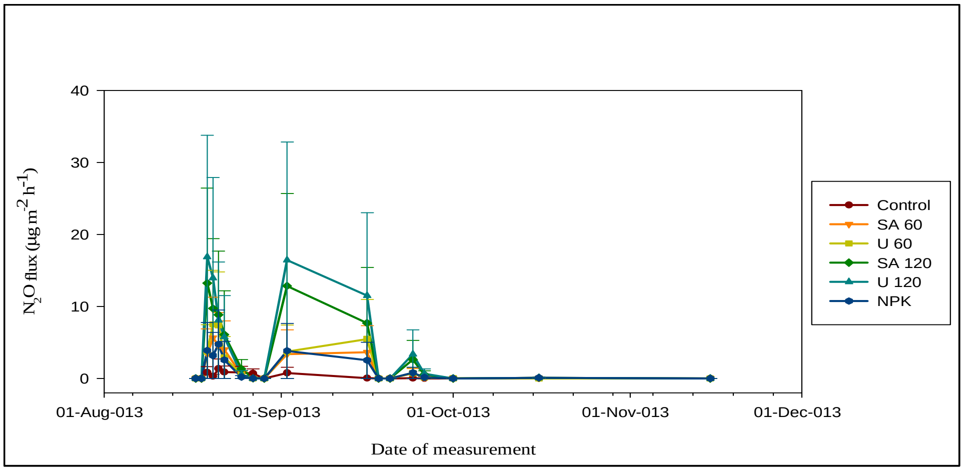

Fig. 1b. Time course of N_2O flux (µg N_2O-N m^{-2} h^{-1}) in the 2013 growing season (error bars represent standard deviation)

Application of 60 kg N ha^{-1} as urea and sulphate of ammonia resulted in improved crop N uptake compared with when 120 kg N ha^{-1} was applied (Fig. 3). This is was in agreement with results obtained from the field measurement where agronomic N use efficiency was higher on application of 60 kg N ha^{-1} urea and ammonia, respectively (Table 1).

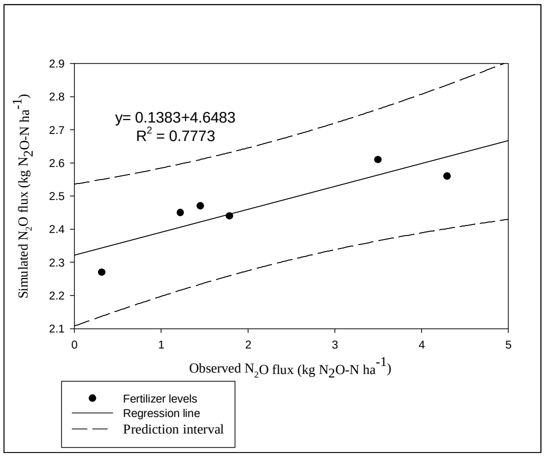

Fig. 2. Calibration of DNDC model to predict N_2O flux from N fertilized maize plots in the Guinea Savanna agro-ecological zone of Ghana

The lower crop N uptake and increased N leached from plots without N fertilization could be as a result of poor crop canopy that leaves the soil surface bare exposing it to intense rains which leached N beyond crop root zones.

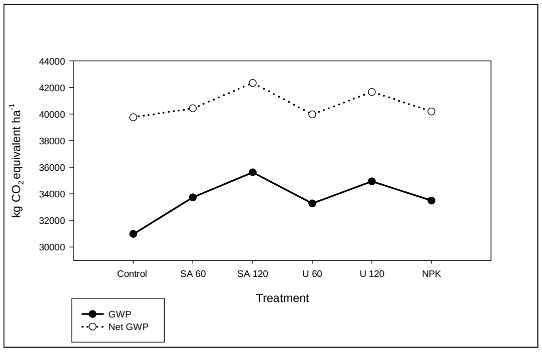

Fig. 3. Simulated Global Warming Potential (GWP) of N fertilized maize plots at Akukayilli

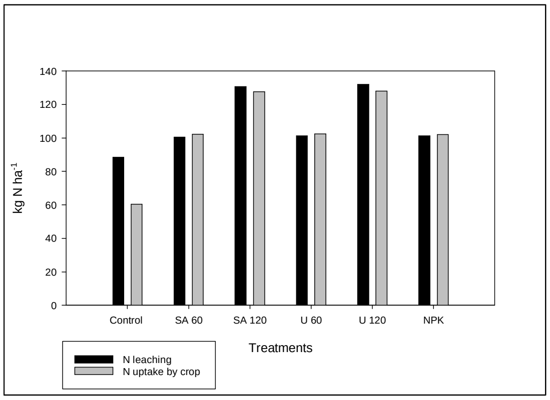

Fig. 4. Simulated N uptake and leaching from fertilized maize at Akukayilli

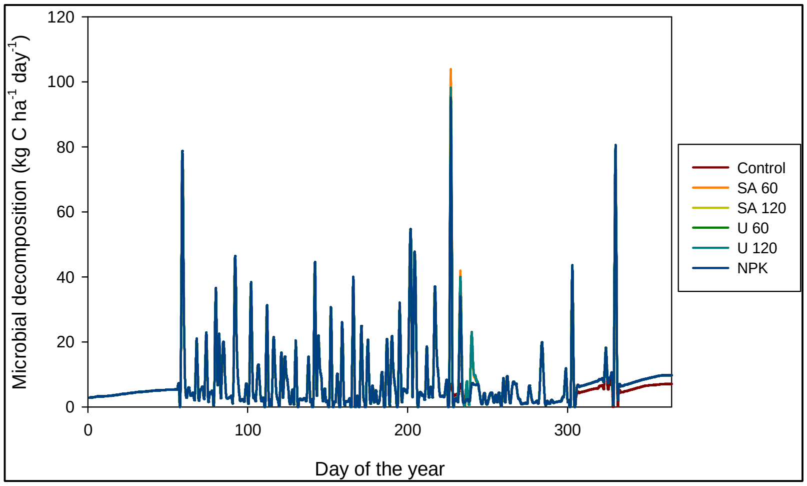

Fig. 5. Simulated microbial decomposition from fertilized maize at plots at Akukayilli

Microbial decomposition was found to be below 20 kg C ha^{-1} at the beginning of the year when precipitation was very low and environmental temperatures were high. It then peaked approximately on the 60th day of the year when there was enough moisture (Fig. 5). However, the highest simulated microbial decomposition was observed between 225th and 300th day of the year when fertilizer application occurred. The simulated results further showed intermittent microbial decomposition activity with onset of rainfall and declined after October when moisture was limited with application of 60 kg N ha^{-1} as sulphate of ammonia showing the highest response to microbial decomposition.

The pattern of daily nitrification rate was similar to microbial decomposition with application of 60 and 120 kg N ha^{-1} as urea and sulphate of ammonia being the highest (Fig. 5). The results further showed that, nitrification and denitrification occurs at different soil depth. Whereas nitrification occurs between soil surface and 10 cm depth, denitrification occurs between 10 and 20 cm depth of soil (Figs. 8 and 9). This results agrees with the suggestion that nitrification is more prominent when moisture available.

Table 1. Agronomic N use efficiency observed on fertilization

Treatments (kg ha^{-1} yr^{-1})	kg kg^{-1}
U 60	29.63
NPK 60-40-40	27.66
SA 60	27.5
U 120	16.19
SA 120	15.6

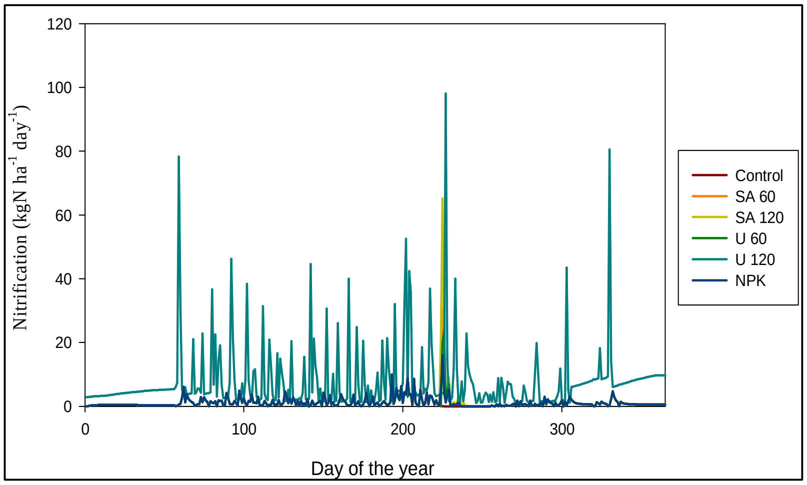

Fig. 6. Simulated nitrification from fertilized maize at plots at Akukayilli

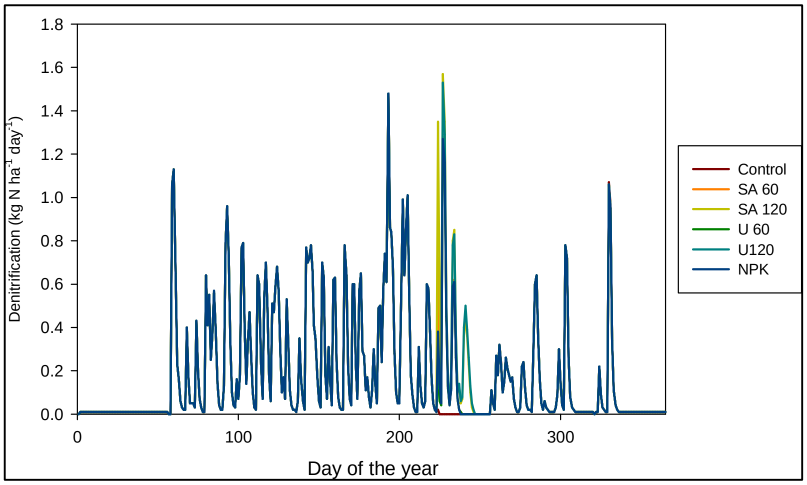

Fig. 7. Simulated denitrification from fertilized maize at plots at Akukayilli

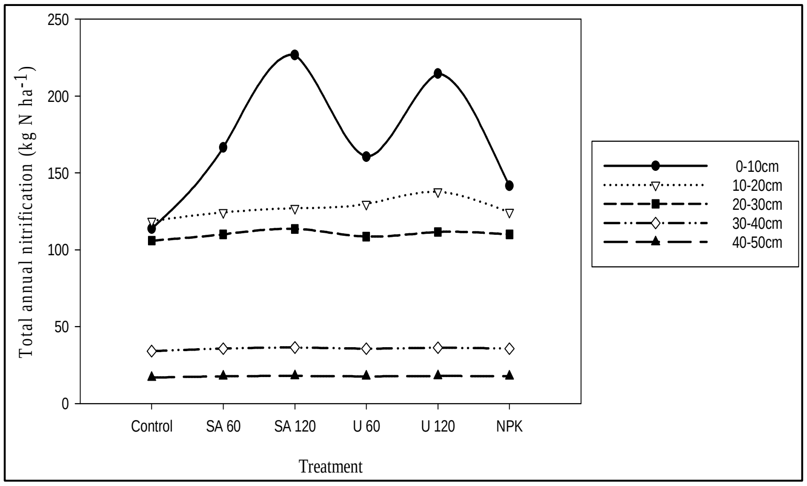

Fig. 8. Effect of soil depth and N fertilizer application on nitrification

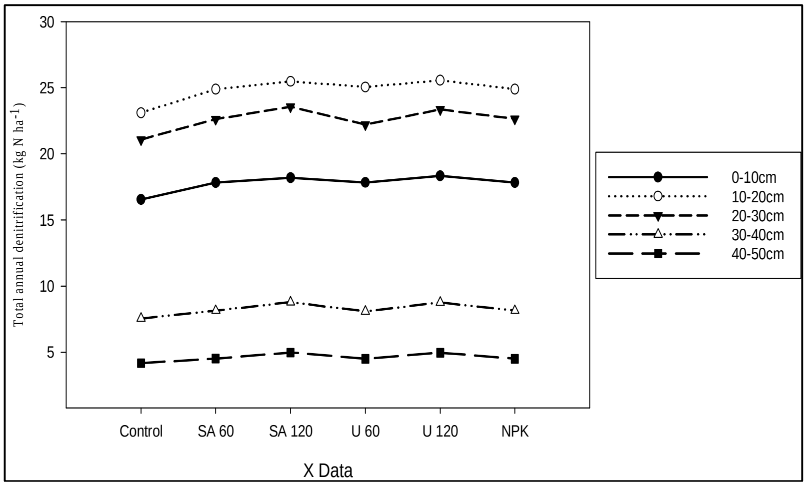

Fig. 9. Effect of soil depth and N fertilizer application on denitrification

4. CONCLUSION

Denitrification decomposition model predicted N_2O emissions in the Guinea Savanna agro-ecological zone of Ghana accurately with an R^2 of 0.7773. The model was able to predict N_2O emissions under different fertilizer application rates and sources. Furthermore, the modelled results were in close agreement with peak N_2O emissions periods after fertilizer application. The study further concludes that nitrification occurs within the soil at 0-10 cm depth whereas denitrification occurs at 10-20 cm within the soil.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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