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Soil Nitrogen and Greenhouse Gas Fluxes in Response to Reduced Tillage Practices under Maize-Bean Intercropping in Western Kenya

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Abstract

Smallholder farmers in western Kenya produce maize (*Zea mays*) intercropped with common bean (*Phaseolus vulgaris.*) using inversion-type deep tillage. Crops are grown twice per year during long rains (LR) and short rains (SR) at low altitude and only once during the LR at high altitude areas. Conservation tillage or reduced tillage is being promoted in these areas as important alternatives to help enhance soil quality and mitigate increasing climate variability. Information on early agroecosystem responses to farmers' adoption of reduced tillage strategies is however, limited. The objective of this study was to assess the impact of reduced tillage practices on soil nitrogen (N) mineralization and greenhouse gas (GHG) fluxes at low altitude (Bungoma) and high altitude (Trans-Nzoia) locations during the transition period. Soil and air samples were collected during LR, SR and fallow period (FP) for a period of three years under three tillage practices; conventional (CT), minimum (MT) and no-till (NT) in a maize-common bean intercrop. Experimental design was a complete randomized block design replicated four times. In general, Potential Mineralizable Nitrogen, and greenhouse gas fluxes were higher in Bungoma than Trans-Nzoia. Introducing MT and NT reduced carbon dioxide (CO2) and nitrous oxide (N2O) fluxes in both locations. These observations indicate early signs of improved retention of soil organic N in less labile N pools, and greater N availability to plants rather than loss to N gas emissions.

Key words: Reduced tillage, carbon dioxide; methane; nitrous oxide; potentially mineralizable nitrogen

Introduction

Smallholder farmers in Sub-Saharan Africa (SSA) rely on frequent inversion deep tillage and continuous planting of maize (*Zea mays* L.) intercropped with common beans (*Phaseolus vulgaris* L.). Increasing demand for food in support of rapidly growing population puts a pressure on natural resources and challenges the sustainability of crop production in this region (Ehui and Pender, 2005). Solutions rely on emerging conservation agriculture (CA) strategies designed to produce sufficient yields while improving soil health (FAO, 2008). Little is known however, on the impact of the CA strategies on soil fertility and specifically, soil organic matter (SOM) in SSA. This knowledge would help understand the long-term benefits of CA to soil sustainability.

Greenhouse gas (GHG) fluxes are indices that can well reflect soil response to changes. These gases are produced in soil as byproducts of soil organic matter (SOM) decomposition and mineralization and soil disturbance may hasten soil microbial processes elevating the GHGs production. Anthropogenic activities such as intensive cropping, frequent tillage and high fertilizer inputs are also known to contribute to elevated GHGs emissions (Abdalla, *et al.*, 2013). For instance, tillage is known to increase SOM mineralization and hence, GHG fluxes from soils (La Scala *et al.*, 2008). Reicosky and Archer (2007), in their study found out that, the magnitude of CO_2 fluxes increase with tillage depth and frequency. Nitrous oxide (N_2O) which is the product of both nitrification and denitrification (Skiba and Smith, 2000) with relatively greater relative lifespan has much greater global warming potential relative to CO_2. Contributing factors to N_2O production are soil management related and include fertilizer inputs, tillage, irrigation (Parkin and Kaspar, 2006) and residue management (Baggs *et al.*, 2003). Conservation agriculture strategies that involve reducing tillage frequency and intensity, improving soil surface cover and crop rotation results in SOM accumulation and decline in GHG emissions (Cunningham *et al.*, 2004). However, information on GHG emissions from introduced CA practices in SSA region is limited. Products of microbial-mediated processes such as soil inorganic N and GHGs are indices sensitive to detect early responses of change during transition to alternative soil and crop management strategies. Therefore, conversion to CA systems to restore SOM will also influence the magnitude of GHG fluxes (Sainju *et al.*, 2008). However, there is lack of information on immediate agroecosystem responses from the SSA region where the knowledge of the immediate benefits of the CA systems would bring rapid positive response and successful farmers' adoption. The main objective of this study was to evaluate a series of selected CAPs designed to combine reduced tillage and inclusion of a cover crop on soil water content, N mineralization and GHG emissions in locations under unimodal (one growing season) and bi-modal (two growing seasons) in Western Kenya.

Materials and Methods

Study sites

Field studies were conducted for three years between May 2011 and April 2014 at two locations in western Kenya: Mabanga Farmers Training Center (00˚35′N, 34˚ 34′E, and 1433 m elevation) in Bungoma county henceforth called "Bungoma" and Manor House Agricultural Centre (010°01′ N, 350°00′ E, 1890 meters elevation) in Trans-Nzoia county henceforth called "Trans-Nzoia". Bungoma is located in lower midland agro-ecological zone with predominantly clay loams, high in kaolinite clay and classified as ferralsols (Jaetzold and Schmidt, 1983). Mean average temperature for the location is 23˚C and the site receives 1100 mm of rainfall annually. Trans-Nzoia is located in the upper midland agro-ecological zone characterized as sandy clay loams also in the ferralsol series (Jaetzold and Schmidt 1983). The site receives annual average rainfall of 1300 mm with mean average temperature of 20˚C. The two locations are characterized by bimodal rainfall pattern with long rains (LR) between March and August and short rains (SR) between September and November (Odhiambo *et al.*, 2015). Warmer temperatures in Bungoma allow for two cropping cycles annually while high altitude and cooler temperatures in Trans-Nzoia allow for one cropping season only.

Experimental design and treatments

The study was arranged in a randomized complete block design replicated four times and each plot measuring 10 m x10 m. The treatments were conventional tillage (CT) applied with deep hand hoeing or animal drawn moldboard plough; minimum tillage (MT) applied with shallow hand hoeing or animal drawn Multi-Functional Implement (MFI®) and no-till (NT). Land preparation before planting was done in accordance with local farming practices, such that plots were tilled twice to a depth of 20 cm using a hand hoe in Bungoma and animal drawn moldboard plough in Trans-Nzoia. Seeds were sourced from Kenya Seed Company Ltd. Maize hybrids H513 and H6213 were planted in Bungoma and Trans-Nzoia, respectively. Same variety of common bean (Rosecoco-GLP2) was planted in both locations. Planting using a hand hoe was done in mid-March for LR seasons and in mid-September for SR in Bungoma while planting in Trans-Nzoia was done in mid-March for LR only in every cropping year. Maize was planted at a spacing of 0.75 m by 0.25 m and common bean planted in between maize rows with intra row spacing of 0.15 m. Maize plots at both locations received 57 kg phosphorous (P) ha^{-1} as Double Ammonium Phosphate, DAP (18 % N, 46 % P_2O_5) and common beans received 60 kg P ha $^{-1}$ as single super phosphate, SSP (18 % P_2O_5, 24 % CaO) at planting. Maize plots also received 37.5 kg N ha^{-1} Calcium Ammonium Nitrate, CAN (28% N) as top dress when plants were 45 cm high. Manual weeding using a hand hoe was done to control weeds and was carried out three times in each growing season.

Field sampling

Basic soil characteristics of bulk density, pH, soil particle size, percent total carbon, total nitrogen and total phosphorous were determined at the beginning of the experiment using known procedures (Blake and Hartge 1986; Ghimire *et al.*, 2014). Soil and gas sampling was performed during long rains (LR), short rains (SR) planting and fallow period (FP). An enclosed static chamber method (Hutchinson and Mosier, 1981) was used for gas sampling. Specifically, 24 hours prior to sampling, four rings (10 cm high and 25 cm diameter) made of polyvinyl chloride (PVC) were permanently installed in each plot. Measurements were initiated by inserting chambers caps (10 cm high and 25 cm diameter) made of PVC with an additional thin-walled aluminum layer on the outside surface fitted with butyl rubber septa on top of the previously installed PVC rings and the entire chamber was immediately sealed with rubber gaskets. Air samples were withdrawn from chamber headspace using a 60-ml plastic syringe fitted with a needle. The first sample was taken immediately after each chamber was sealed and then at 15 and 30 minutes. At each time, a 30-ml of the air aliquot was injected into a previously evacuated 12-ml Labco® glass vial sealed with butyl rubber septa. Gas samples were analyzed for CO_2, CH_4 and N_2O by gas chromatography using Varian® gas chromatograph at the Agricultural Research Service Soil Science Lab in Fort Collins, Colorado, USA. Best flux was calculated from the rate of change of the individual gas species concentrations in the chamber headspace using chamber volume and Fick’s Gas Law (Hutchinson and Mosier, 1981).

Concomitantly with air sampling, air and soil temperatures were taken manually at the beginning and end of each sampling period using stainless soil thermometer probe inserted next to the chamber. Soil samples (0-10 cm) were collected near each chamber. Samples were homogenized and oven dried at 105°C for 48 hours to calculate gravimetric water content (GWC) at the time of sampling (Gardner, 1986). The remaining soil were air dried, sieved through a 2 mm sieve, packed and shipped to the University of Wyoming, USA for further analyses. Approximately 20 g of air dried soil was wetted to 23% moisture content, covered with perforated aluminum foil to allow gas exchange but minimize water loss and then aerobically incubated for 14 days at a constant temperature of 30^0C in the dark inside an incubator (Sierra, 2002). About 5g of the aerobically incubated soil samples were oven dried at 105^0C for 48 hours to calculate gravimetric water content as described above. Potentially Mineralizable Nitrogen (PMN) was determined using 14- day anaerobic incubation method (Keeney, 1982; Waring and Bremner, 1964). Five-gram air incubated soil samples were placed in 45 ml plastic centrifuge tubes with 12.5ml deionized water, and surfaces flushed with nitrogen gas to drive off oxygen (Hart et al., 1994), the tubes were then capped tightly and incubated in the dark at room temperature for 14 days. Anaerobic incubated samples were extracted using 12.5 ml of a 4.0 mol L^{-1} potassium chloride (KCl), filtered through Q5 filter paper (Fischer Scientific, Atlanta, GA and extracts analyzed for ammonium-N (NH_4^+). Ammonium –N and nitrate –N (NO_3^-) were also determined in the fresh aerobic incubated soil samples by extracting 10g of each sample with 50 ml of a 2.0 mol L^{-1} KCl. Both the inorganic NH_4^+ (Weatherburn, 1967) and inorganic NO_3^- (Doane and Howarth, 2003) were analyzed calorimetrically using BioTek inorganic N analyzer instrument (BioTek, Inc., Winooski, VT).The different in NH_4^+ levels in fresh (2.0mol L^{-1} KCL extracts) and incubated (4.0 mol L^{-1} KCl extracts) presented PMN levels.

Statistical analysis

All data were subjected to Fligner –Killeen test to determine the homogeneity of variance and normality tested using Q-Q plots and Shapiro Wilk test and data analyzed separately for each site. The effect of year, season and tillage were analyzed using ANOVA Model procedures of R (R core version 2.15.3, 2013) at significance alpha level of 0.05. Post-hoc analysis was done using Tukey's Honest Significant Difference (HSD).

Results

Baseline soil characteristics

The soils in Bungoma with clay-loam characteristics were generally more acidic with higher bulk density than those in Trans-Nzoia with sandy clay loam characteristics (Table 1). Bungoma soils had relatively low total C%, total N% and total P% compared to Trans-Nzoia soils.

Table 1. Baseline soil characteristics for Bungoma and Trans-Nzoia.

Soil properties	Bungoma	Trans-Nzoia
Bulk density (mg m^{-3})	1.7	1.6
pH	4.9	5.3
Clay %	36	28
Silt %	16	20
Sand %	48	52
Soil texture	Clay loam	Sandy clay loam
Total C %	2.3	2.4
Total N %	0.21	0.31
Total P %	0.03	0.05

Soil labile nitrogen

Soil PMN was generally higher in Bungoma than Trans-Nzoia and was significantly influenced by season in Bungoma only (Table 2). In Bungoma, soil PMN was comparable between FP and SR seasons and was 48.0% and 57.0 %, respectively greater compared with 3.53 mg NH_4-N kg $^{-1}$ obtained in the LR season (Fig. 1). In Trans-Nzoia, soil PMN was higher in FP than either SR or LR, however the differences were not significant. Soil NH_4^+ concentrations were also higher in Bungoma than Trans-Nzoia (Fig. 2). The effect of season was significant in determining soil NH_4^+ concentrations in Bungoma site only ($P \leq 0.05$). At this site, soil NH_4^+ concentrations in the SR (20.4 mg NH_4^+ kg^{-1}) were five times greater than the values obtained during the LR and FP (Fig. 2).

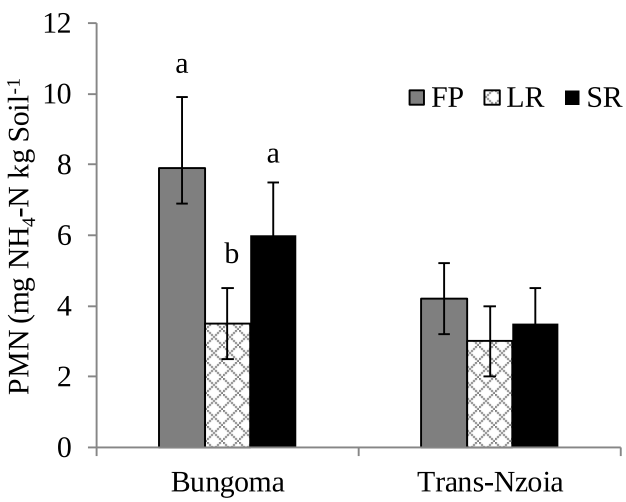

Figure 1. Potentially mineralizable nitrogen (PMN) as influenced by sampling time; fallow period (FP), long rains (LR) and short rains (SR). Lower case letters indicate significance differences in the means within each site *(*p ≤ 0.05*)*

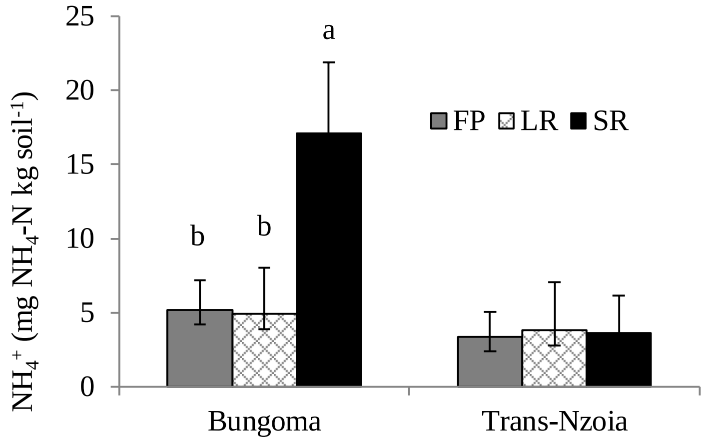

Figure 2.Soil ammonium (NH_4^+) concentrations as impacted by sampling time; fallow period (FP), long rains (LR) and short rains (SR) and Tillage systems. Lower case letters indicate significant mean differences in each site (*p ≤ 0.05*)

Nitrous oxide (N_2O) fluxes

The effect of season on N_20 fluxes was significant at both sites ($P \leq 0.05$). Generally more N_2O fluxes were reported in Bungoma compared to Trans-Nzoia. In terms of tillage approach, lowest N_2O fluxes was found in CT while highest fluxes was in FP at both locations, however the differences were not significant (Table 2). In Bungoma, Lowest N_2O flux was observed during FP season and was 84.0% lower than the highest fluxes observed in the SR season (72.6 7 µg N_2O-N m^{-2} h^{-1}) with intermediate fluxes during the LR (Fig. 3). In Trans-Nzoia, nitrous oxide fluxes were lowest and comparable during the FP and LR and were 46.0% lower than the 35.47µg N_2O-N m^{-2} h^{-1} fluxes produced during the SR (Fig. 3).

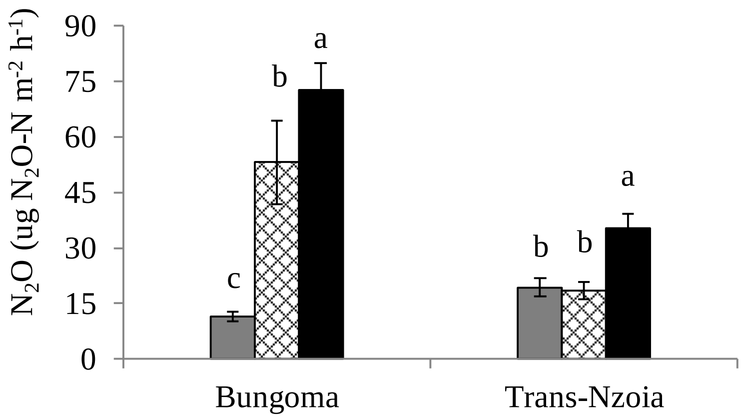

Figure 3. Nitrous oxide (N_20) flux during different cropping seasons of fallow period (FP), long rains (LR) and short rains (SR) pooled across the experimental years in Bungoma and Trans-Nzoia. Bars within a site with same letters are not statistically different at p≤0.05

Carbon dioxide (CO_2) fluxes

The main effect of season was also significant in explaining the variability in CO_2 flux at both sites (P≤ 0.05). Carbon dioxide fluxes were generally higher in Bungoma compared to Trans-Nzoia (Table 2). Likewise, seasonal impact on CO_2 production indicated significantly greater CO_2 fluxes during the SR season and lowest fluxes during FP seasons at both sites (Fig. 4).

In Bungoma, soils in CT produced highest CO_2 fluxes (79.5 mg CO_2-C m^{-2} h^{-1}) while the lowest CO_2 flux was recorded in NT (64.5 mg CO_2-C m^{-2} h^{-1}) (Table 2). Seasonal impact on CO_2 production indicated significantly 57% and 38% greater CO_2 fluxes during the SR season than FP and LR seasons respectively (Fig. 4). Annual variability indicated increases in CO_2 fluxes across the years in all tillage systems with consistently less fluxes from NT in any corresponding year (Fig. 5a).

In Trans-Nzoia, soils in CT produced highest CO_2 fluxes (61.3 mg CO_2-C m^{-2} h^{-1}) while the lowest CO_2 flux was in NT (52.0 mg CO_2-C m^{-2} h^{-1}) (Table 2). Season impact indicated CO_2 fluxes were greatest during SR season and were comparable to LR season but were significantly lowest during FP season (Fig. 4). All tillage systems resulted in a decrease in soil CO_2 fluxes across the years except CT with initial increase before dropping in the third year of the experiment (Fig. 5b).

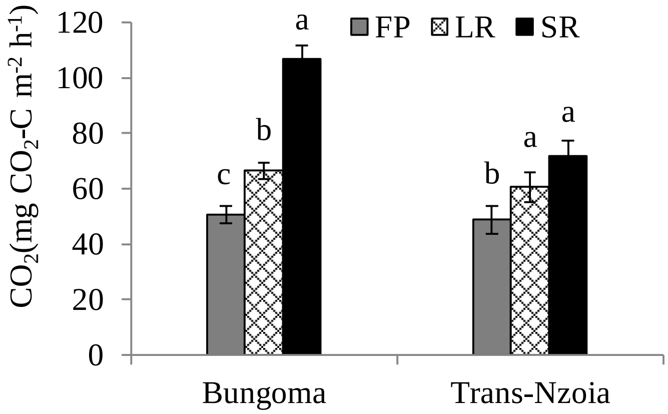

Figure 4. Carbon dioxide (CO_2) flux during different cropping seasons of fallow period (FP), long rains (LR) and short rains (SR) pooled across the experimental years in Bungoma and Trans-Nzoia. Bars within a site with same letters are not statistically different at $p \leq 0.05$

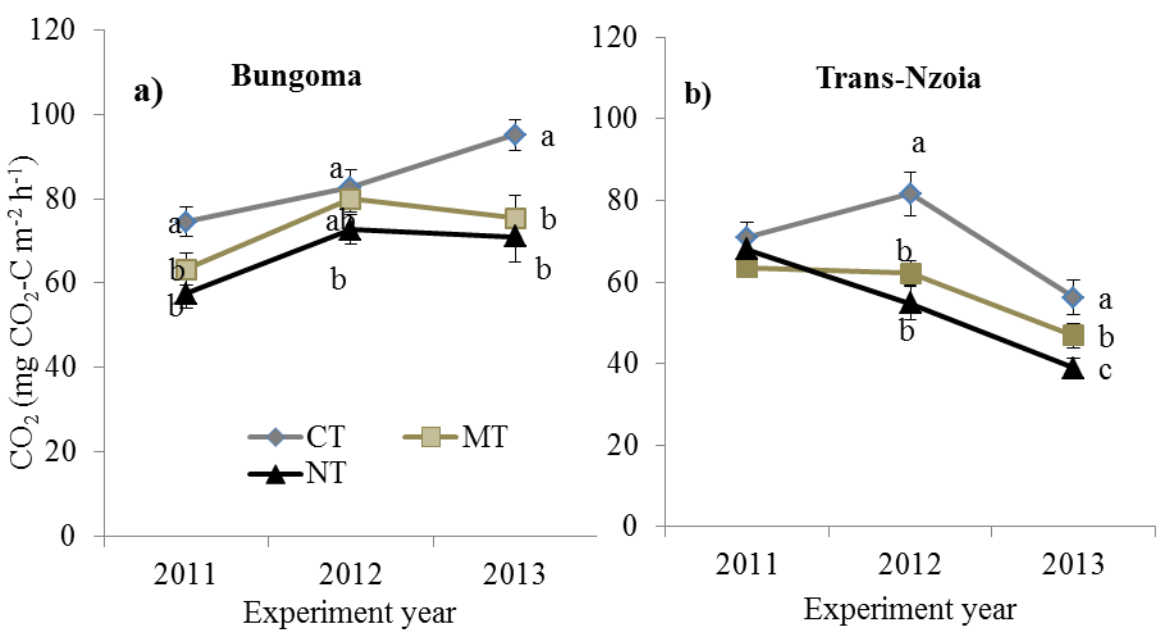

Figure 5. Annual CO_2 fluxes under different tillage systems; conventional tillage (CT), minimum tillage (MT) and no-till (NT) at Bungoma (a) and Trans-Nzoia (b). Lower case letters represent significant treatment separation within the year ($p \leq 0.05$)

Methane (CH_4) fluxes

A general trend of greater CH_4 consumption was recorded in Bungoma compared to Trans-Nzoia (Table 2). In Bungoma, the lowest CH_4 assimilation was recorded in NT which was 19.0% less compared to comparable consumptions in MT and CT. In Trans-Nzoia, lowest but non-significant CH_4 assimilation were reported in NT.

Table 2. Effect of tillage in the GHG fluxes in Bungoma and Trans-Nzoia averaged across the three experimental years. Values in parenthesis indicate mean standard errors. Means with different lower case letters within a column at each site are significantly different ($p \leq 0.05$)

	Bungoma GHG Flushes			Trans-Nzoia GHG Flushes		
Tillage	**CO_2 (mg m^{-2} hr^{-1})**	**CH_4 (µg m^{-2} hr^{-1})**	**N_2O (µg m^{-2} hr^{-1})**	**CO_2 (mg m^{-2} hr^{-1})**	**CH_4 (µg m^{-2} hr^{-1})**	**N_2O (µg m^{-2} hr^{-1})**
CT	79.5 (10.3)a	-5.7 (0.9)a	35.2 (15.6)	61.3 (8.8)	-2.9 (1.1)	22.7 (3.7)
MT	72.8 (14.0)ab	-5.9 (0.7)a	36.4 (11.4)	55.7 (6.6)	-2.9 (1.0)	24.4 (3.4)
NT	64.5 (3.9) b	-4.7 (0.6)b	38.9 (16.3)	52.0 (9.0)	-2.8 (1.0)	24.9 (3.4)

Discussion

Climatic conditions in both locations create low fertility soils which are prone to high N mineralization and subsequent losses to N leaching or GHG emissions. This scenario was even more exacerbated during SR especially in Bungoma as indicated by higher CO_2 and N_2O fluxes compared with Trans-Nzoia. Increased frequency of tillage associated with two cropping seasons in Bungoma is likely to increase continued seasonal soil nutrient loss in this region. Higher soil PMN concentration coupled with low NH_4^+, CO_2 and N_2O fluxes during FP in Trans-Nzoia is an indication of a build -up of soil organic C and N reserves also observed by Mikha *et al.*, (2006).

More frequent tillage in Bungoma likely resulted in more soil pulverization and enhanced mineralization and, therefore, increased availability of PMN and NH_4^+ and greater CO_2 and N_2O fluxes. The enhanced GHG fluxes during the SR were likely associated with disturbance-driven process and decomposition of crop residues under warm weather conditions, which was also observed by Ellert and Janzen (2008). These fluxes were likely triggered by rapid decomposition of plant residues left in soil from the earlier LR crop season, which was also proposed by Omonode *et al.* (2007). In addition, elevated CO_2 fluxes could also be attributed to root respiration (Atarashi-Andoh *et al.*, 2012). Oorts *et al.* (2007) found an increase in CO_2 emissions just before and after crop harvest in both no-till and conventional plots. Thus second season crop production in Bungoma appeared to negatively impact the ability of soil to store SOM and, instead, contributed to C and N losses to atmospheric GHG. Lower NO_3^- in Bungoma confirmed more losses of soil nitrogen to gaseous forms, especially N_2O, as deduced in our study. A second possibility is immobilization of soil NO_3^- by the more active microbial communities in such soils (Steenwerth and Belina, 2008).

Conclusions

Reducing soil disturbance through tillage resulted in early indication of soil quality improvement and decline in GHG emissions. Lack of tillage, especially during the fallow period in both locations and during SR in Trans-Nzoia is critical to conserve soil N for the next crop. There is a need to reconsider second crop production during SR in low altitude regions. Early indicators of change such as inverse between PMN and inorganic N or low CO_2 and N_2O fluxes are reliable proxies of increased agroecosystem efficiency in soil C and N retention. Within three years of transitioning to Conservation tillage, NT has shown a promising trend of reducing soil mineralization indicated with low fluxes of CO_2.

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