



Early Soil Nitrogen and Greenhouse-Gas Responses to Reduced Tillage in Smallholder Maize- Bean Systems Across Contrasting Agro-ecological Zones of Western Kenya

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Abstract

Reduced tillage is increasingly being promoted in sub-Saharan Africa, yet early changes in soil nitrogen (N) cycling and greenhouse-gas (GHG) exchange remain poorly resolved under smallholder maize–bean systems. This three-year field experiment evaluated conventional tillage (CT), minimum tillage (MT), and no-till (NT) at Bungoma (lower altitude, warmer, two annual cropping seasons) and Trans-Nzoia (higher altitude, cooler, one principal cropping season) in western Kenya. Treatments were arranged in randomized complete blocks with four replicates. Potentially mineralizable nitrogen (PMN), mineral nitrogen, soil moisture, and chamber-based CO₂, CH₄, and N₂O fluxes were measured during long-rain, short-rain, and fallow periods. Site and season strongly structured biogeochemical responses. PMN and GHG fluxes were generally greater at Bungoma than Trans-Nzoia, and short-rain periods produced the largest CO₂ and N₂O fluxes. Reduced soil disturbance consistently lowered CO₂ flux. Relative to CT, NT lowered mean CO₂ flux from 79.5 to 64.5 mg CO₂-C m⁻² h⁻¹ at Bungoma and from 61.3 to 52.0 mg CO₂-C m⁻² h⁻¹ at Trans-Nzoia. In contrast, mean N₂O differences among tillage treatments were not statistically significant, indicating that mitigation responses were air and context-specific. CH₄ exchange was small and predominantly represented net uptake. The results show that early transition to reduced tillage can suppress soil CO₂ losses, while N₂O responses remain strongly conditioned by season and agro-ecological setting. These findings support locally adapted conservation agriculture strategies and caution against assuming uniform GHG benefits from reduced tillage alone.

Keywords: conservation tillage; carbon dioxide; nitrous oxide; methane oxidation; potentially mineralizable nitrogen; maize–bean intercropping; sub-Saharan Africa

Introduction

Smallholder cereal-legume cropping systems are central to food and livelihood security in sub-Saharan Africa (SSA), but repeated soil disturbance, residue removal, nutrient depletion, and increasing climate variability can accelerate soil degradation and constrain productivity. Conservation agriculture (CA) built around minimum soil disturbance, soil cover, and crop diversifications therefore promoted as a pathway to improve soil functioning and climate resilience. However, adoption and performance remain highly context dependent because residue availability, livestock competition, equipment, labour, soils, rainfall, and farmer priorities vary widely across SSA (Araya et al., 2024; Sithole and Olorunfemi, 2024). Recent evidence from East Africa further shows that farmer-observed improvements in infiltration, crusting, and workability under CA can correspond with measurable changes in soil condition, while responses still differ among locations and management histories.

Greenhouse-gas fluxes and labile N pools are sensitive indicators of early soil response to management. Tillage can alter aggregation, aeration, temperature, moisture, and substrate exposure, thereby affecting decomposition, nitrification, denitrification, and CH₄ oxidation. Contemporary syntheses demonstrate that the climate effects of reduced or no tillage are not

uniform: a 2024 global meta-analysis reported average reductions in N₂O under reduced and no tillage, but identified climate, soil pH, texture, N status, fertilizer rate, and experiment duration as major moderators (Meng et al., 2024). Conversely, a recent SSA meta-analysis found that residue-retaining climate-smart practices can increase soil nitrate and N₂O under some conditions, underscoring the importance of regional evidence (Namatsheve et al., 2024). A 2026 secondary meta-analysis likewise concluded that conservation tillage does not consistently reduce N₂O across cropping systems, whereas fertilizer and water-management interventions show more reproducible effects (Nyameasem et al., 2026). Evidence from smallholder maize-bean systems in humid and sub-humid East Africa remains limited, particularly during the first years after conversion when soil C and N pools are still adjusting. The present study therefore assessed early responses of soil PMN, inorganic N, and CO₂, CH₄, and N₂O fluxes to CT, MT, and NT across two contrasting agro-ecological settings in western Kenya. We hypothesized that reducing tillage intensity would decrease CO₂ losses and alter labile N dynamics, but that N₂O responses would depend strongly on season and site conditions. The study provides a three-year field-based test of these responses under management practices

representative of smallholder maize–bean production.

Materials and methods

Study Sites

Field experiments were conducted at Mabanga Farmers Training Centre in Bungoma County (00°35' N, 34°34' E; 1,433 m a.s.l.) and Manor House Agricultural Centre in Trans-Nzoia County (01°01' N, 35°00' E; 1,890 m a.s.l.), western Kenya. Bungoma lies in a warmer lower-midland zone with clay-loam Ferralsols, mean annual temperature of approximately 23 °C, and annual rainfall of about 1,100 mm. Trans-Nzoia is a cooler upper-midland zone with sandy-clay-loam Ferralsols, mean annual temperature of approximately 20 °C, and annual rainfall of about 1,300 mm. Rainfall is bimodal, with long rains generally occurring from March to August and short rains from September to November. Warmer conditions at Bungoma permit two cropping cycles annually, whereas the cooler Trans-Nzoia site is predominantly cropped during the long rains (Odhiambo et al., 2015).

Experimental Design and Treatments

The experiment used a randomized complete block design with four replicates and 10 × 10 m plots. Treatments were conventional tillage (CT), minimum tillage (MT), and no-till (NT). CT consisted of deep hand hoeing at Bungoma or animal-drawn mouldboard ploughing at Trans-Nzoia, with land prepared twice to approximately

20 cm depth. Minimum Tillage used shallow hand hoeing or an animal-drawn multi-functional implement, whereas NT avoided pre-plant soil disturbance. Maize hybrids H513 (Bungoma) and H6213 (Trans-Nzoia) were intercropped with Rosecoco GLP2 common bean. Maize was spaced at 0.75 × 0.25 m and beans were planted between maize rows at 0.15 m within-row spacing. At planting, maize received 57 kg P ha⁻¹ as diammonium phosphate and beans received 60 kg P ha⁻¹ as single superphosphate. Maize was top-dressed with 37.5 kg N ha⁻¹ as calcium ammonium nitrate when plants were approximately 45 cm tall. Weeds were controlled manually three times per 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 LR, 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 CO₂, CH₄ and N₂O 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 2mm 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°C in the dark inside an incubator (Sierra 2002). About 5g of the aerobically incubated soil samples were oven dried at 105°C 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 (NH₄⁺). Ammonium –N and nitrate –N (NO₃⁻) 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 NH₄⁺ (Weatherburn 1967) and inorganic NO₃⁻ (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 (2.0 mol L^{-1} KCL extracts) and incubated (4.0 mol L^{-1} KCL extracts) presented PMN levels.

Statistical Analysis

Data were analysed separately by site because the locations differed in altitude, temperature, soil properties, and cropping frequency. Homogeneity of variance was evaluated using the Fligner–Killeen test, and residual normality was assessed using Q–Q plots and the Shapiro–Wilk test. Effects of year, season, and tillage were evaluated by analysis of variance in R (R Core Team), with $\alpha = 0.05$. Where significant effects occurred, means were separated using Tukey’s honestly significant difference (HSD) procedure.

Results are reported with treatment means and standard errors. Because repeated measurements were made through time, interpretation emphasizes the magnitude and consistency of treatment patterns together with reported significance rather than treating individual sampling events as independent long-term emission inventories.

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 $\text{mg NH}_4\text{-N kg}^{-1}$ 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 ($20.4 \text{ mg NH}_4^+ \text{ kg}^{-1}$) were five times greater than the values obtained during the LR and FP (Fig. 2).

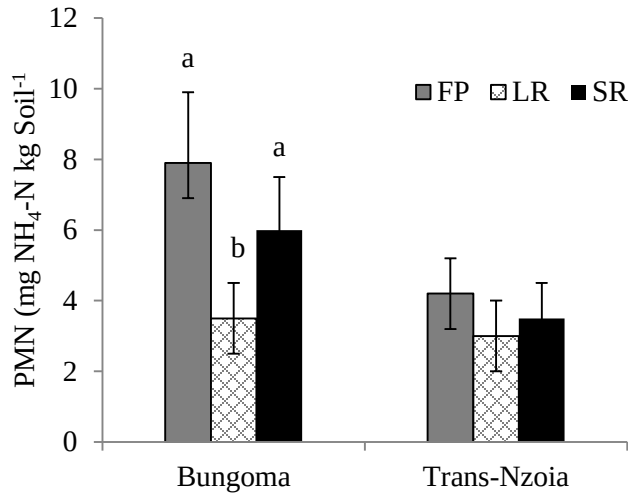


Figure 1. Potentially mineralizable nitrogen (PMN) as influenced by sampling time; fallow period (FP), long rains (LR) and short rains (SR). Lower case letters indicate significance differences in the means within each site ($p \leq 0.05$).

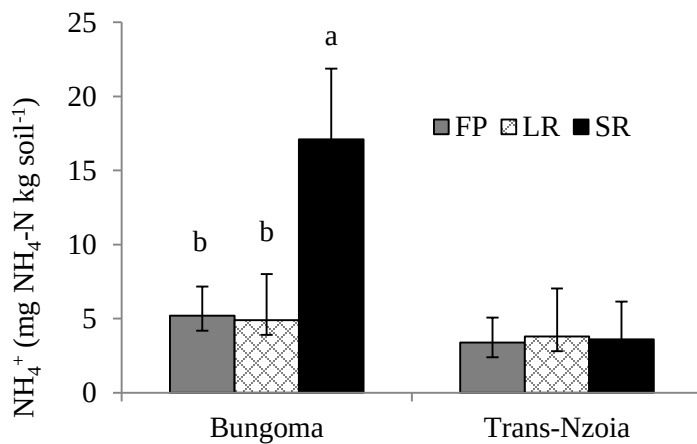


Figure 2. Soil ammonium (NH_4^+) concentrations as impacted by sampling time; fallow period (FP), long rains (LR) and short rains (SR)} and Tillage systems. Lower case letters indicate significant mean differences in each site ($p \leq 0.05$).

Nitrous Oxide (N_2O) Fluxes

Season significantly affected N_2O fluxes at both sites ($p \leq 0.05$), with generally greater fluxes at Bungoma than Trans-Nzoia. Tillage treatment means did not differ significantly (Table 2). At Bungoma, N_2O flux was lowest during the fallow period and highest during the short rains ($72.6 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$). At Trans-Nzoia, fallow and long-rain fluxes were comparable and lower than the short-rain value ($35.47 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$; Figure 3). Thus, seasonal conditions exerted a clearer control on N_2O than tillage during the three-year transition period.

Carbon Dioxide (CO_2) Fluxes

Season significantly influenced CO_2 flux at both sites ($p \leq 0.05$), and fluxes were generally greater at Bungoma than Trans-Nzoia (Table 2). At both sites, the short-rain period produced the largest seasonal CO_2 fluxes, whereas the fallow

period produced the lowest values (Figure 4). In Bungoma, CT produced the highest mean CO_2 flux ($79.5 \text{ mg CO}_2\text{-C m}^{-2} \text{ h}^{-1}$), while NT produced the lowest ($64.5 \text{ mg CO}_2\text{-C m}^{-2} \text{ h}^{-1}$; Table 2). Short-rain CO_2 flux was 57% greater than during the fallow period and 38% greater than during the long rains (Figure 4). Across years, NT remained lower than CT in corresponding annual comparisons (Figure 5a). In Trans-Nzoia, CT also produced the highest mean CO_2 flux ($61.3 \text{ mg CO}_2\text{-C m}^{-2} \text{ h}^{-1}$), while NT produced the lowest ($52.0 \text{ mg CO}_2\text{-C m}^{-2} \text{ h}^{-1}$; Table 2). Seasonal CO_2 fluxes were greatest during the short rains and lowest during the fallow period (Figure 4). Across years, CO_2 flux generally declined, although CT initially increased before declining in the third year (Figure 5b).

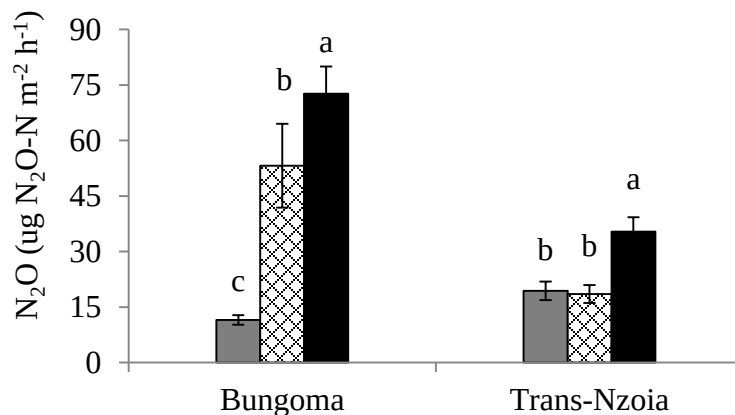


Figure 3. Nitrous oxide (N₂O) flux during different cropping seasons of fallow period (FP), long rains (LR) and short rains (SR) pooled across the experimental years in Bungoma and Trans-Nzoia. Bars within a site with same letters are not statistically different at $p \leq 0.05$.

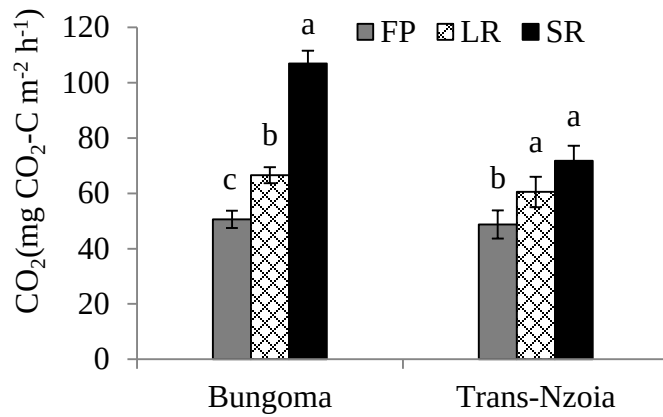


Figure 4. Carbon dioxide (CO₂) flux during different cropping seasons of fallow period (FP), long rains (LR) and short rains (SR) pooled across the experimental years in Bungoma and Trans-Nzoia. Bars within a site with same letters are not statistically different at $p \leq 0.05$.

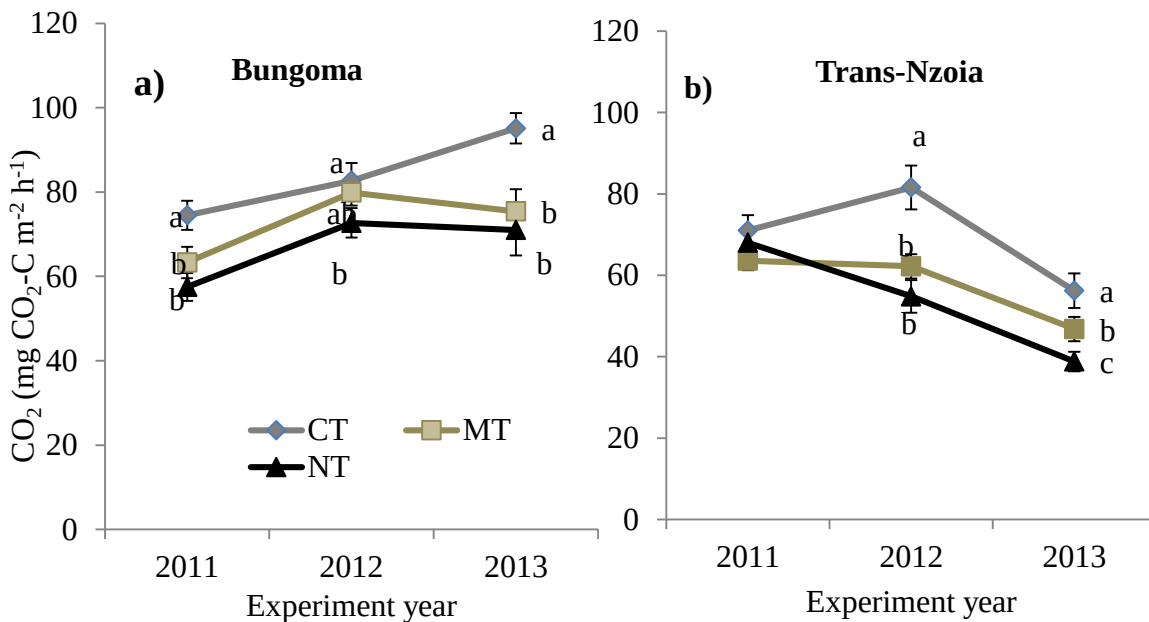


Figure 5. Annual CO₂ fluxes under different tillage systems; conventional tillage (CT), minimum tillage (MT) and no-till (NT) at Bungoma (a) and Trans-Nzoia (b). Lower case letters represent significant treatment separation within the year ($p \leq 0.05$)

Methane (CH₄) Fluxes

Soils at both sites generally acted as small CH₄ sinks, as indicated by negative flux values (Table 2). CH₄ uptake was greater at Bungoma than Trans-Nzoia. At Bungoma, NT showed lower CH₄ uptake than CT and MT; at Trans-Nzoia, differences among tillage treatments were small and not significant. These results indicate that CH₄ exchange contributed less to treatment differentiation than CO₂ or seasonal N₂O dynamics.

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 ($p \leq 0.05$).

Tillage	Bungoma			Trans-Nzoia		
	GHG Flushes			GHG Flushes		
	CO ₂ (mg m ⁻² hr ⁻¹)	CH ₄ (µg m ⁻² hr ⁻¹)	N ₂ O (µg m ⁻² hr ⁻¹)	CO ₂ (mg m ⁻² hr ⁻¹)	CH ₄ (µg m ⁻² hr ⁻¹)	N ₂ O (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

The experiment demonstrates that early biogeochemical responses to reduced tillage were strongly conditioned by agroecological setting and season. Bungoma, the warmer site with two annual cropping cycles, generally showed larger PMN and GHG fluxes than the cooler, higher-altitude Trans-Nzoia site. This pattern is consistent with faster decomposition and N turnover under warmer conditions and with the additional soil disturbance and residue turnover associated with a second cropping season. The pronounced short-rain peaks in CO₂ and N₂O at both sites further indicate that rainfall-temperature interactions and the timing of fresh substrates can dominate short-term GHG dynamics. Recent syntheses similarly identify precipitation, temperature, soil texture, pH, N availability, and management duration as major controls on tillage-related GHG responses (Meng et al., 2024; Matteau et al., 2024).

Reduced tillage produced the clearest mitigation signal for CO₂. Mean CO₂ flux under NT was about 19% lower than CT at Bungoma and about 15% lower at Trans-Nzoia, consistent with reduced physical disruption of aggregates and lower exposure of protected organic matter to rapid microbial decomposition. This agrees with recent evidence that conservation tillage can support SOC retention and, under suitable conditions, lower soil GHG losses (Meng et al.,

2024; Qin et al., 2024). However, the N₂O response was different: treatment means were not significantly separated and numerically tended to be slightly higher under MT and NT than CT. This is important because reduced disturbance can increase soil moisture and create microsites favourable to denitrification even while lowering CO₂ losses. Recent global and regional syntheses report similarly heterogeneous N₂O responses, including sensitivity to rainfall, texture, fertilizer N, residue retention, and duration of management (Matteau et al., 2024; Namatsheve et al., 2024; Nyameasem et al., 2026). Therefore, reduced tillage should not be presented as an automatic N₂O mitigation practice. The PMN and NH₄⁺ patterns reinforce the importance of seasonal N cycling. At Bungoma, elevated short-rain NH₄⁺ coincided with high CO₂ and N₂O, suggesting rapid mineralization followed by potential gaseous N loss when moisture and substrate conditions were favourable. By contrast, the cooler Trans-Nzoia system showed lower overall fluxes and a tendency for PMN to remain greater during fallow periods, consistent with slower turnover. For SSA, these findings have practical significance because CA benefits depend on how reduced tillage is combined with residue, nutrient, crop-diversification, and water management. A recent SSA meta-analysis found that CA can improve grain yield and N-use efficiency overall, but residue

retention may also raise nitrate availability and N₂O emissions in some settings (Namatsheve et al., 2024).

This supports locally adapted packages rather than single-practice recommendations. The study has limitations that should guide interpretation. Measurements represent a three-year transition period rather than a long-term equilibrium, and chamber observations were periodic rather than continuous annual inventories. The two sites also differed in cropping frequency as well as climate and soil properties, so site contrasts should not be attributed to a single factor. Nevertheless, the replicated field design across contrasting smallholder environments provides useful evidence of early transition dynamics. Longer-term measurements integrating yield, SOC stocks, full-season GHG budgets, residue management, and emission intensity per unit of crop output would strengthen assessment of the net climate value of reduced tillage in East African maize–bean systems.

Conclusion

Reduced tillage altered soil C and N dynamics within the first three years of transition, but the response differed among gases and agroecological settings. No-till consistently lowered soil CO₂ flux relative to conventional tillage at both western Kenya sites, indicating reduced short-term C loss from soil disturbance. In contrast, N₂O was governed

more strongly by season than by tillage treatment, and tillage means were not significantly different. Bungoma showed greater overall biogeochemical activity than Trans-Nzoia, highlighting the influence of warmer conditions and more frequent cropping. These findings support reduced tillage as one component of locally adapted conservation agriculture, while emphasizing that credible climate mitigation requires integrated management of soil disturbance, residues, N inputs, crop diversity, and seasonal water conditions. Future studies should quantify complete annual GHG budgets, SOC stocks, crop yields, and GHG intensity over longer periods before drawing conclusions about net climate benefits.

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