Original Research Article

Soil Carbon and Nitrogen Mineralization and Crop Parameters in Typical Maize-Bean Intercropping in Western Kenya

ABSTRACT

Smallholder farmers in Sub-Saharan Africa face many challenges associated with nutrient-poor soils and frequent weather-related crop failures. Little is known about the impact of current tillage intensive crop management on seasonal changes in soil organic matter (SOM)mineralization and renewal. Farmers in western Kenya intercropmaize (*Zea mays L.*) and common beans (*Phaseolus vulgaris L.*) usinginversion-type tillage and low fertilizer inputs. At high elevation crops are grown during one long growing season and twice per year during long and short rains at low elevation. Growing crops twice necessitates frequent land preparation and soil disturbance.The aim of this study was to assess SOM mineralization and crop performance in typical maize-bean production under double cropping (Bungoma) and single cropping (Trans-Nzoia)systems during long rains (LR), short rains (SR) and fallow period (FP). Sites in Bungoma and Trans-Nzoia were sampled three times per year for three years. Soils were analyzed for potentially mineralizable nitrogen (PMN), ammonium (NH_4), nitrate (NO_3), water filled pore space (WFPS), nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2). Results demonstratedsignificant increases in PMN, NH_4 N_2O and CO_2 during SR in Bungoma suggesting that additional tillage in support of the second crop facilitated SOM mineralization and potential losses. Soils in Trans-Nzoia also showed increases in NH_4, NO_3 and N_2O during SR but the magnitude of these changes were lower compared with Bungoma. High carbon (C) and nitrogen (N) mineralization likely did not support annual SOM renewal and crop productivity further

demonstrated by low soil total C and N and low cumulative crop yields in Bungoma. Typical crop production may become unsustainable in the long-term, thus considering alternatives such as edible cover crops and reducing tillage should become a necessity. Particular attention should concentrate on designing appropriate management strategies for growing crops during SR in Bungoma.

Keywords: long rain season; nutrient cycling; short rain season; soil disturbance; Sub-Saharan Africa; Sustainability of crop production; tillage disturbance

1. INTRODUCTION

Smallholderfarmersin Sub-Saharan Africa (SSA) face numerouschallengesassociated with nutrient-poor soils and high climatic variability[1].These challenges can impactagroecosystemcapacity to maintainand restore soil fertility in support of annual maize (*Zea mays L.*) and common bean (*Phaseolus vulgaris L.*) production. Better understanding of how typical, widespread farming practices driveseasonal changes to soil organic matter (SOM) mineralization is needed to support the development of alternative cropping strategies for better soil resource protection[2].

In much of SSA, maize and common beans are intercropped and managed with intensive deep tillage using hand hoes and animal drawn moldboard plows. Farmers intercropmaize with beans to intensify production and benefit from diverse plant life strategies of the two crops [3]. For example, beans fix atmospheric nitrogen (N) that ultimately contributes to soil N and benefits maize [4] while maize provides shading and protection of bean plants from occasional hailstorms.Majority of the area has bimodal rainfall that delivers on average 1000 to 1600 mm of rain annually. Low elevation areas (below 1500 meters) experiencewarm temperatures which allow maize and beans complete their growing cycles much faster than athigh elevation [5]. This in combination with bimodal rainfall, permit farmers to plant crops twice per year, during two rainy seasons known as the “long” and “short” rains. Planting during short rains occurs despite high variability of a rainfall that often results in frequent crop loss [6]. However, growing crops twice a year necessitates more frequent land cultivation for planting and weeding, which may ultimately result in limited land rest and annual SOM recovery[7]. Research in SSA has shown that deep tillage contributes to low nutrient retention of already nutrient depleted acidic soils[8]. For example, Smalling and Fresco [9] reported loss of 30kg ha^{-1} N in form of NO_3annual from cultivated fields in SSA. Many factors may affect high soil nutrient variability in these regions and factors such as topography and management are one of the leading causes[10].

Soil inorganicand labileorganic N in conjunction with greenhouse gas (GHG) fluxesare robust indices of soil nutrient status and soil response to disturbance [11]When coupled with soil inorganic N concentrations, the measurements of potentially mineralizable N (PMN), carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)fluxesare of particular value becauseall these compounds are biogenically produced by soil microorganisms that use SOM as their substrate during decomposition and mineralization[12].

The aim of this study was to assess SOM mineralization and crop performance in typical maize-bean production under double cropping and single cropping systems during long rains (LR), short rains (SR) and fallow period (FP). Our overall hypothesis wasthat double cropping drives much greater SOM mineralization compared withsingle cropping and the C and N losses are much higher during the short rains.Better understanding of the consequences of typical crop growing on soil will facilitate development of alternatives aiming to improve soil quality, crop productivity and ultimatelyagroecosystem health.

2. MATERIALS AND METHODS

2.1 Site Description

The experiment was carried out for three years starting in May 2011 at two research stations in western Kenya: the lowland Mabanga Farmers Training Centre in Bungoma Countyand highland Manor House Agricultural Centre in Trans-NzoiaCounty.The Bungoma study site(00°35′N, 34°34′E; 1200 mm MAP; 27°C MAT; referred to here as Bungoma) is located at 1433 meters elevation in the lower midland agro-ecological zone suitable for two crop growing seasons annually [13].The Trans-Nzoia study site(010 01′ N, 35° 00′ E; 1300 mm MAP; 20°C MAT; referred to here as Trans-Nzoia)is located at 1890 meters elevation in the upper midland agro-ecological zonesuitable for one crop growing season annually [13].Soils in both locations are clay loams or sandy clay loams classified as ferralsolsdominated by kaolinite clays with high iron and aluminum oxides contents[14-15]. Soil physical and chemical properties are presented in Table 1.

Long rains occur between late March through July, and short rains occur from August through November. Approximately 60 to 70% of annual precipitationoccurs during the LR [16]. December through March is referred to as the fallow period (FP) and receives very little rainfall. More information on seasonal climate and associated farming practices are shown in Fig.1. Daily precipitation, maximum and minimum air temperatures were monitored during the experiment using weather stations equipped with data loggers (Hobo® Weather Station, Onset Computer

Corp, Cape Cod, Massachusetts) at each location. Cumulative monthly precipitation and monthly average air temperatures for the study periods are shown in Fig. 2.

Table 1 Soil (0-15 cm) physical characteristics for Bungoma and Trans-Nzoia sites.

Soil Properties	Bungoma	Trans-Nzoia
Bulk density (g m^{-3})	1.7	1.6
Clay (%)	36	28
Silt (%)	16	20
Sand (%)	48	52
Soil texture	Clay loam	Sandy clay loam

At each study site a series of experimental plots (0.36 hectares in size) were managed in accordance with typical farmer practices. Land preparation involvedinversion-type tillage usingan animal drawn moldboard plow and a hand hoe(Trans-Nzoia) or a hand hoe only (Bungoma). These two tillage implementsexert comparable soil disturbance by inverting soil to 20 to 25 cm depth.All fields were planted with recommended maize and common bean varieties sourced from Kenya Seed Company Ltd.Maize hybrid H513suitable for low elevation was intercropped with Rosecoco-GLP2 bean (locally known as ‘Nyayo’) in Bungoma during LR and SR seasons. Maize hybrid 614D suitable for high elevation was intercropped with Rosecoco-GLP2 bean in Trans-Nzoia.

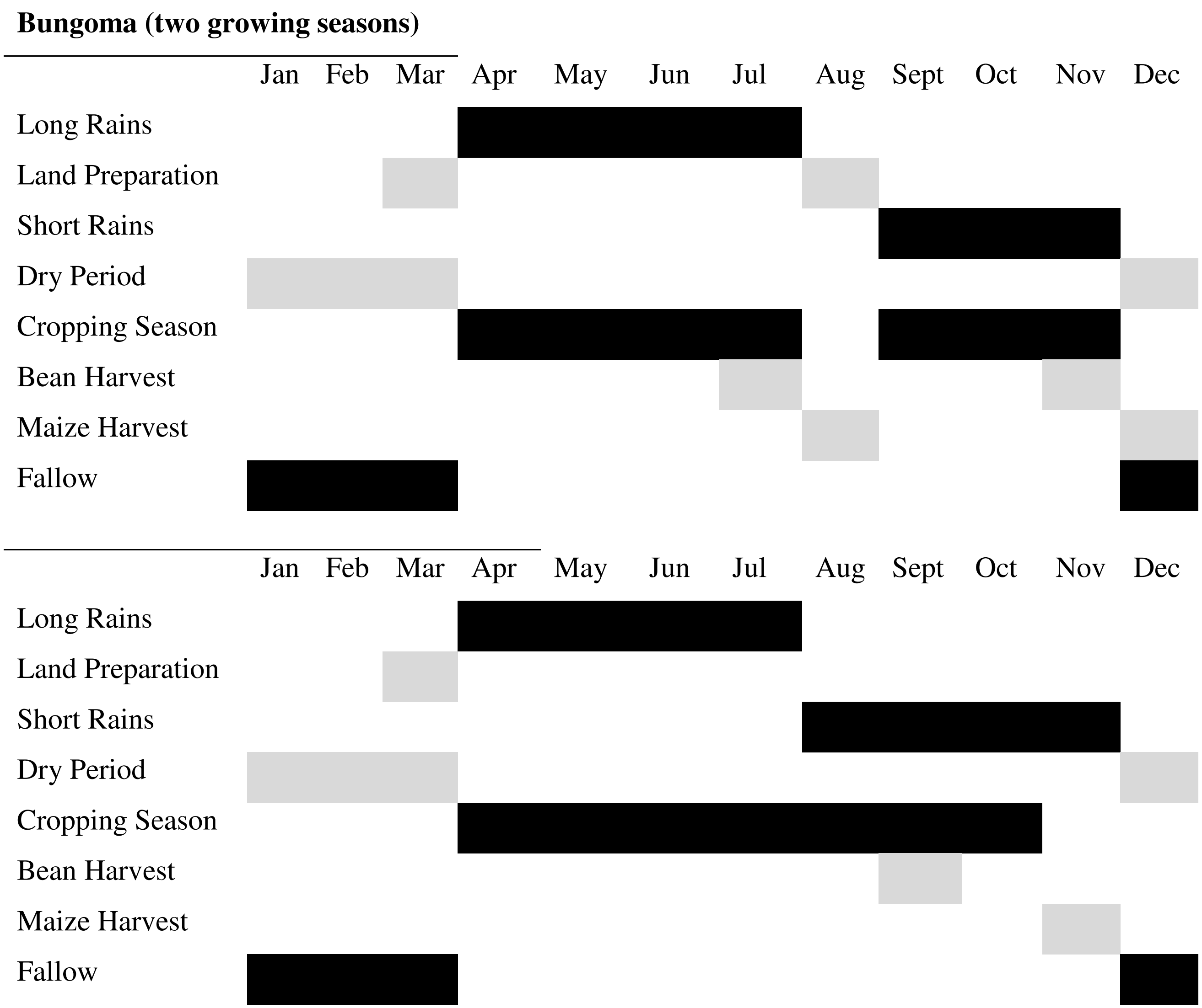

Fig. 1 Diagram representing timeframe of cropping seasons and associated management practices for Bungoma and Trans-Nzoia sites

Planting for LR season in Bungoma and for the entire year in Trans-Nzoiawas done in mid-April and for SR season in Bungoma in mid-September. Maize was planted at 53,500 plants per hectare and spaced 75cm x30 cm. Beans were planted at 89,000 plants per hectare in between maize rows and spaced at 15 cm within rows. More information on plant parameters is provided in Table 2. Weeding was done three times during each growing season by deep tillage with a hand hoe.Phosphorous (P)at a rate of 60kg Pha^{-1} asdia-ammonium phosphate (DAP, 18 % N and 46% P_2O_5)was appliedat planting andN at a rate of 60kg N ha^{-1}as calcium ammonium nitrate (CAN, 27%N) was applied as top dress to maize when maize had six leaves and was 30-45 cm tall.

2.2 Field Sampling

Soil and gas sampling was done for three years, three times per year during periods that corresponded with LR, SR and FP seasonsin both Bungoma and Trans-Nzoia. Four randomly established ten x five meterplots were laid out within fields under typical farmers cropping practices. In each plot, two sub-plots within the vicinity of maize plants and two sub-plots within the vicinity of bean plants were established. Within each sub-plot, polyvinyl chloride (PVC) rings (10 cm high and 25 cm diameter) were installed at each point (four per plot, 16 per study site). These rings served as bases for chamber tops installed periodically for GHG sampling. Chamber tops were 10 cm high and 25 cm in diameter and were made of PVC coated with thin-walled aluminum material following [17-18]. Tops were fitted with silicone septa that served as a port for gas sampling.

Soil (0-10 cm) samples were collected 20 cm from each chamber. Soil was homogenized and a sub-sample oven dried at 105°C for 48 hours to calculate gravimetric water content at the time of sampling [19]. The remainder of each soil sample was air-dried, sieved through a 2-mm sieve, packed and shipped to USA for further analyses. Upon arrival at the laboratory, soil was pre-incubated for 14 days in dark aerobic conditions, at 23% soil moisture content and temperature maintained at 30°C [20]. At the end of the 14-day period, 5 g of moist soil was oven dried at 102°C for 48 hours to calculate gravimetric water content as described above. Ammonium-N (NH_4) and nitrate-N (NO_3) concentrations were determined by extracting 10 g of soil with 50 ml of a 2.0 *M* potassium chloride (KCl) using colorimetric methods of Weatherburn[21] and Doane and Howarth [22] on a microplate spectrophotometer (BioTek, Inc., Winooski, VT). Potentially mineralizable nitrogen (PMN) was determined using 14-day anaerobic incubation [23-24]. Specifically, 5-g samples of pre-incubated soil were placed in 50 ml plastic centrifuge tubes with 12.5 ml of deionized water. Tube headspaces were filled with dinitrogen (N_2) gas to replace atmospheric air, and tubes were sealed with plastic caps. All samples were incubated in the dark at room temperature for 14 days [25]. At the end of the 14-day period samples were extracted using 12.5 ml of a 4.0 mol L^{-1}KCl and extracts analyzed for NH_4following the method described earlier. PMN was calculated as the difference between initial and post anaerobic incubation concentrations.

Additional 0-15 cm soil samples were collected at the beginning and end of each experimental year for determination of soil pH, total P, total C, total N and available P at the Department of Soil Science, University of Eldoret in Kenya using methods described by Okalebo et al. [26]. Soil bulk density was determined using the volumetric core method [27]. Bulk density estimates were used to convert gravimetric soil water content to water filled pore space (WFPS).

Gas measurements were initiated by deploying chambertops on the previously installed PVC base rings and immediately sealed with rubber gaskets. Gas samples were drawn from chamber headspace using 60-ml plastic syringes. Samples were drawn immediately after each chamber was sealed and then at 15 and 30 minutes. For each sample, a30-ml aliquot of gas was injected into a previously evacuated 12-ml Labco® glass vial sealed with butyl rubber septa. Samples were shipped to USA within two weeks of sampling. Pressurized gas in vials was analyzed for CO_2, CH_4 and N_2O concentrations using gas chromatography (Varian 38001 equipped with automatic injector, thermal conductivity, flame ionization and electron capture detectors to measure CO_2, CH_4 and N_2O, respectively). Ten samples containing internal lab standards that travelled to research sites were also analyzed. Gas fluxes were estimated from the rate of change of gas concentrations in chamber headspaces over the 30-minute time periods using Fick's Gas Law [28-29]. Air and soil temperature were recorded at the beginning and end of each sampling and used to calculate GHG fluxes.

Maize height was assessed on five randomly selected plants using a measuring tape stretched between the plant base at soil surface and the arch of the uppermost fully developed leaf. Maize and bean yields were determinedat crop maturity by hand harvesting grain from a three-meter distance in the middle row. Grain was air dried to approximately 12% moisture content.

2.3 DataAnalysis

Data was analyzed using split plot in time and completely randomized design using R [30]. Effects of site, season and site x season interaction were assessed using site as a fixed term, time of sampling as a repeated measurement and replicated plots as random terms in the PROC MIXED statistical model. For site and season comparisons, data were based on weighted values derived from individual crop planting densities. The effect of individual crops was assessed using site as a fixed term, time of sampling as a repeated measurement and crop and replicated plots as random terms in the PROC MIXED statistical model. Data was tested for normality using the Shapiro-Wilktest and log-transformed to assure normal distribution of data for further statistical analyses. Mean separations were conducted using the Fisher's protected Least Significance Difference (LSD) procedures. Treatment effects were considered significant when probabilityof a greater F values were equal to or lower than 0.05, unless otherwise stated. Pearson correlations and linear regressions analyses were developed to test the relationships amongWFPS, PMN, NH_4, $NO_3$and GHG fluxes.

3. RESULTS AND DISCUSSION

3.1 Weather,Crop Performance and Soil Parameters

Air temperatures in Bungoma during the study period averaged 21ºC and were two degrees higher than those in Trans-Nzoia (Fig. 2). Bungoma also received a cumulative annual rainfall of 1305 mm, which was 250 mm less than Trans-Nzoia. Seasonal distribution ofrainfall showed moreintense rainfall events during LR and more prolongedperiods of no rainfall during SR in Bungoma.

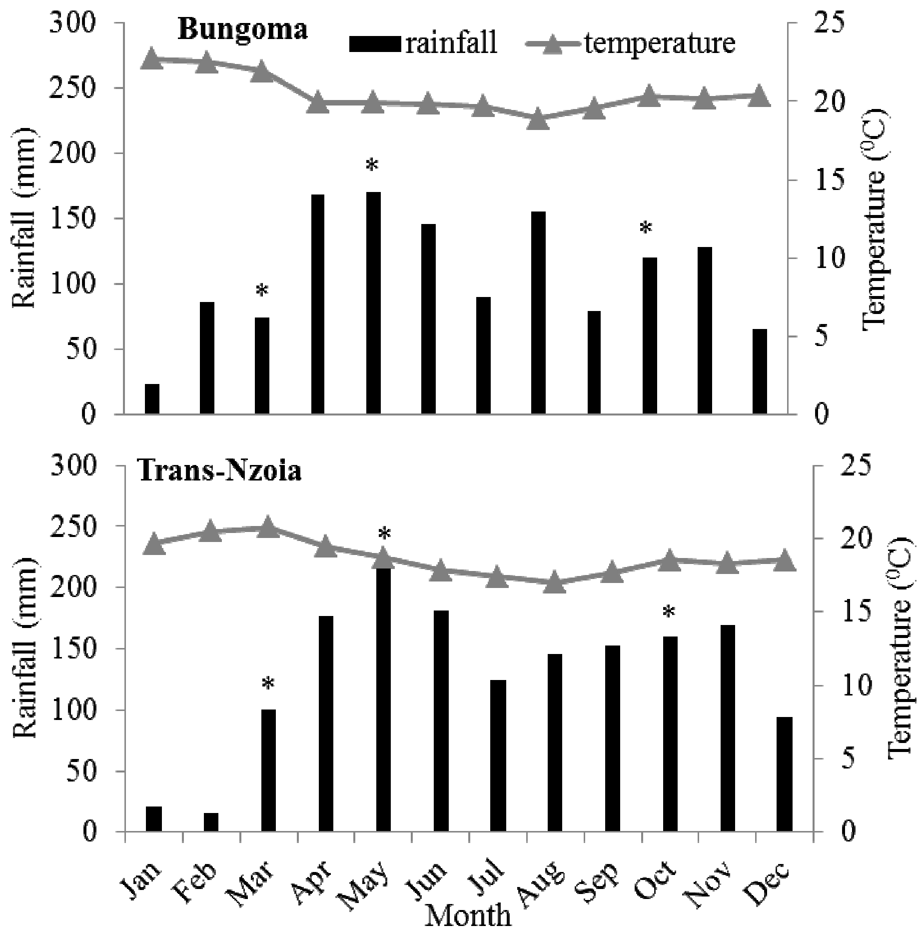

Fig.2 Three-year average monthly cumulative rainfall (mm) and air temperatures (^oC) during Long Rains (LR), Short Rains (SR) and Fallow Period (FP). Asterisks indicate sampling periods.

Soils in Bungoma had 2.04 g kg^{-1} of total C and 0.2 g kg^{-1} of total N which amounted to 30% less than soils in Trans-Nzoia (Table 2). Both sites had low but comparable total P contents, but soils in Bungoma had 7.7 mg $kg^{-1}$of available P which amounted to 50% less than soils in Trans-Nzoia. Soil pH was comparable between the locations and averaged 5.3.

Table 2 Soil (0-15 cm) chemical properties averaged across two years. Values that follow "±" are standard errors of a mean. Lower case letters indicate significant differences between sites at *$P \leq 0.05$.*

Soil Properties	Bungoma	Trans-Nzoia
pH	5.2 ± 0.1 *ns*	5.3 ± 0.1 *ns*
Total C (g kg^{-1})	2.04 ± 0.5 *b*	3.04± 0.1 *a*
Total N (g kg^{-1})	0.20 ± 0.05 *b*	0.30 ± 0.03 *a*
Total P (mg kg^{-1})	30.0 ± 10 *ns*	50.0 ± 10 *ns*
Available P (mg kg^{-1})	7.1 ± 1.5 *b*	13.3 ± 2.0 *a*

Soil WFPS was significantly greater across all sampling periods in Trans-Nzoia compared with Bungoma (Fig.3). Interestingly, there were no differences in WFPS between sampling events in Bungoma and the values ranged between 30.0% during FP and 37.0% during SR. In Trans-Nzoia, the highest soil WFPS of 49% was reported during LR and the lowest WFPS of 39% was observed in FP with intermediate values reported for SR.

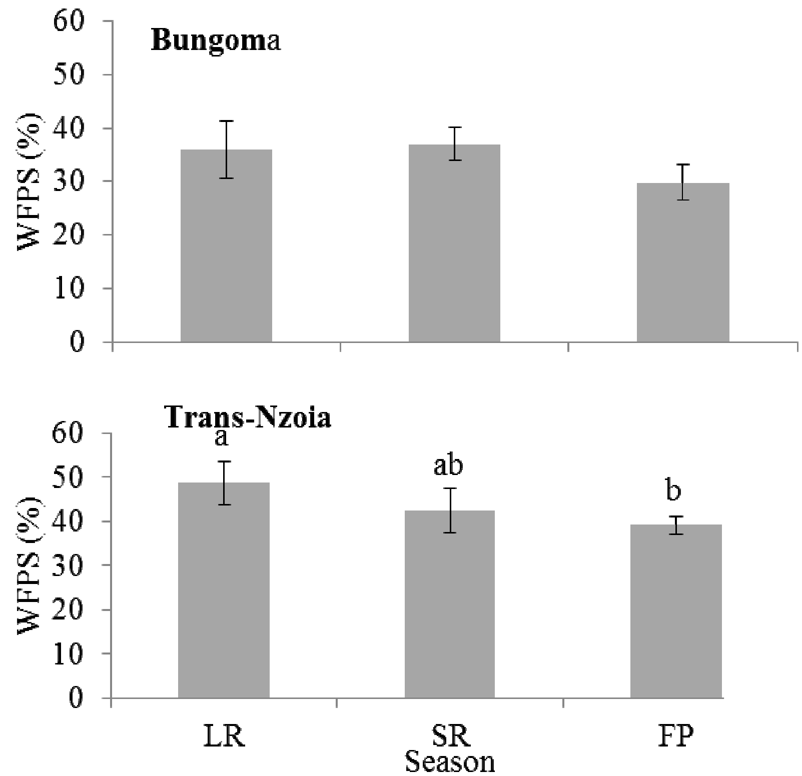

Fig. 3 Water filled pore space (WFPS %) during Long rains (LR), Short Rains (SR) and Fallow Period (FP) averaged across the three years. Bars with same letters within a location are not significantly different at $P \leq 0.05$.

Maizeplants at V-6 werebetween 40% to 50% shorter in Bungoma compared with Trans-Nzoia(Table 3). Maize yields in Bungoma totaled 1.4Mg ha^{-1}per yearfrom both seasons, which amounted to 40% loweroverall yields ported forTrans-Nzoia from one long growing season. Bean yields in Bungoma totaled 0.23Mg ha^{-1}during LRand, no bean yields werepoor crop establishment during SRin all years of the experiment. This amounted to 66% lower annual yieldsin Bungoma compared to Trans-Nzoia.

Table 3 Maize and bean growth parameters averaged for two seasons. Values that follow "±" are standard errors of a mean. Lower case letters indicate significant differences between sites at $P \leq 0.05$.

	Bungoma	Trans-Nzoia
Long Rains		
Maize height at V-6 (cm)	70.5 ±10.7b	126.1 ± 20.6a
Maize spacing (m^{-2})	0.23	0.23
Maize yield (Mg ha^{-1})	1.10±0.4b	2.00 ± 0.1a
Bean spacing (m^{-2})	0.11	0.11
Bean yield (Mg ha^{-1})	0.20 ± 0.1b	0.70 ± 0.1a
Short Rains		
Maize height at V-6 (cm)	68.8 ± 17.1	-
Maize spacing (m^{-2})	0.23	-
Maize yield (Mg ha^{-1})	0.30 ± 0.1	-
Bean spacing (m^{-2})	0.11	-
Bean yield (Mg ha^{-1})	-	-

3.2.Soil Nitrogen

Overall, soil PMN concentrations were up to four times greater in Bungoma than in Trans-Nzoia (Fig. 4a).In Bungoma, PMN values during SR and FP amounted to 9.1 and 6.9 mg kg^{-1}, respectively and were almost three times greater compared with values reported for LR. No differences in PMN between seasons were observed in Trans-Nzoia with greater but non-significant soil total N mineralization during SR and FP compared with LR.Crop species effect had a significant seasonal impact on soil PMN in Trans-Nzoiaonly (Fig. 5a). Up to four times more PMN was observed in soil associated with maize plants during LR comparedwith 1.0 mg kg^{-1} of PMN in soils associated with bean plants (Fig.5a).

Soil NH_4 concentrations were also up to four times greater in Bungoma than in Trans-Nzoia (Fig.4b).The highest NH_4in Bungoma of 18.5 g kg^{-1} was observed in SR which amounted to anywhere between nine to five times the levels reported for LR and FP, respectively.In Trans-Nzoia, $NH_4$of only 2.8 g kg^{-1} was also significantly higher in SR and the values were only two times greatest compared with FPand LR (Fig.4b).

In comparison, soil $NO_3$was higher in Trans-Nzoia compared with Bungoma (Fig. 4c). In Trans-Nzoia, the highest NO_3 of 32.5 g kg^{-1} was observed in SR and the values in LR and FP were significantly lower and ranged between 19.7 g $kg^{-1}$and 23.7 g kg^{-1}. In Bungoma, NO_3were comparable between LR and SR and ranged between 25.6 g kg^{-1} and 26.9 g kg^{-1} which was about 40% more compared with FP.

Both locations demonstrated the highest N_2O fluxes during SR and the lowest fluxes during FP with much greater N_2O fluxes in Bungoma (Fig. 4d). In Bungoma, the highest flux of 70.6 μg m^{-2} h^{-1} was almost twice as high compared with N_2O flux during SR in Trans-Nzoia. Fluxes during LR ranged between 25.8 μg m^{-2} h^{-1}in Bungoma and 19.0 μg m^{-2} h^{-1} in Trans-Nzoia and between 6.2 μg m^{-2} h^{-1} and 12.0 μg m^{-2} h^{-1}during FP. The magnitude of N_2Ofluxes depended on soil associations with specific crops as demonstrated by a significant season x crop interactions at both Bungoma and Trans-Nzoia. Maximum N_2O of 120.8 μg m^{-2} h^{-1} was reported in soils associated with beans during SR in Bungoma,which was twice as much compared with soils associated with maize plants (Fig 5b). In comparison, maximum N_2O of 26.5 μg m^{-2} h^{-1} was reported for soils associated with bean plants during LR in Trans-Nzoia which was almost three times as high compared with soils associated with maize.

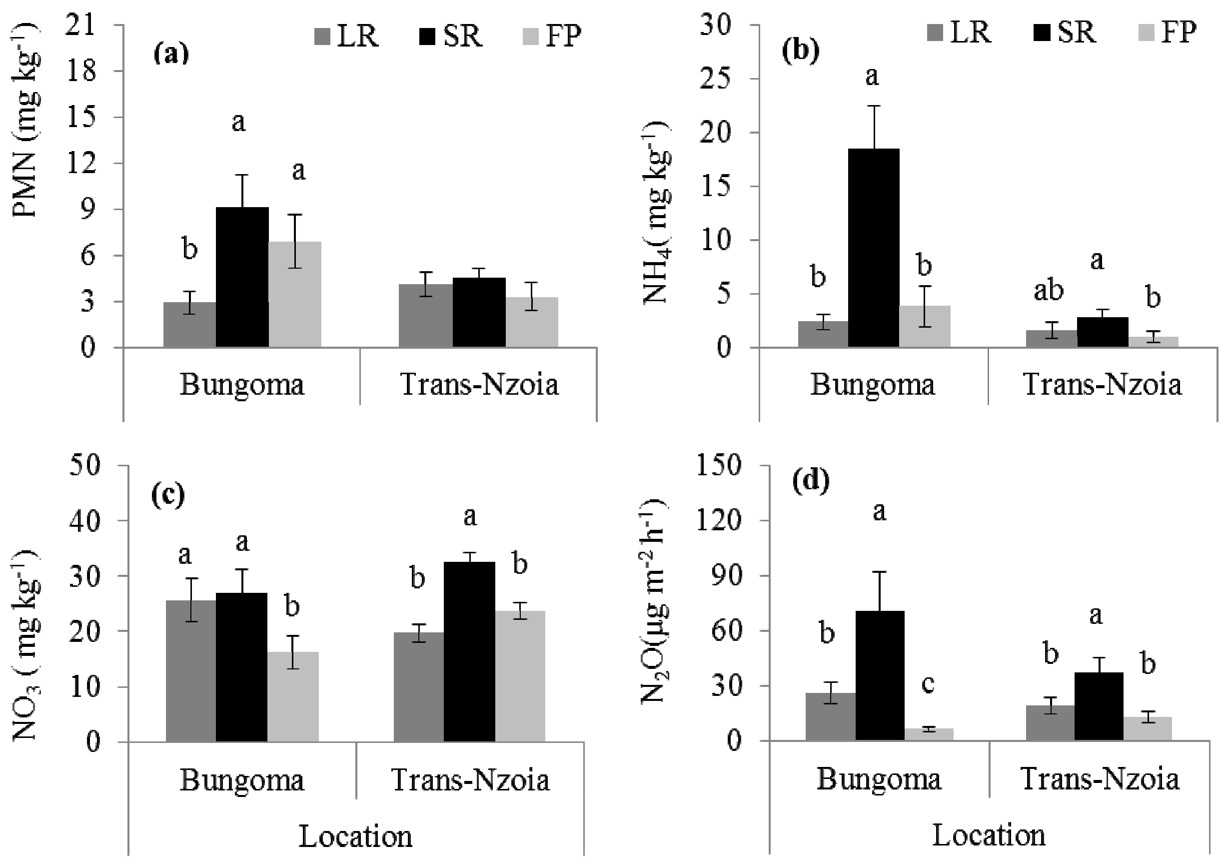

Fig. 4 (a) Soil potentially mineralizable nitrogen (PMN, (b) ammonium (NH_4),(c) nitrate (NO_3) concentrations and (d) nitrous oxide (N_2O) fluxes for Long Rains (LR), Short Rains (SR) and Fallow Period (FP) for Bungoma and Trans-Nzoia locations. Lower case letters indicate least significant differences at $P \leq 0.05$.

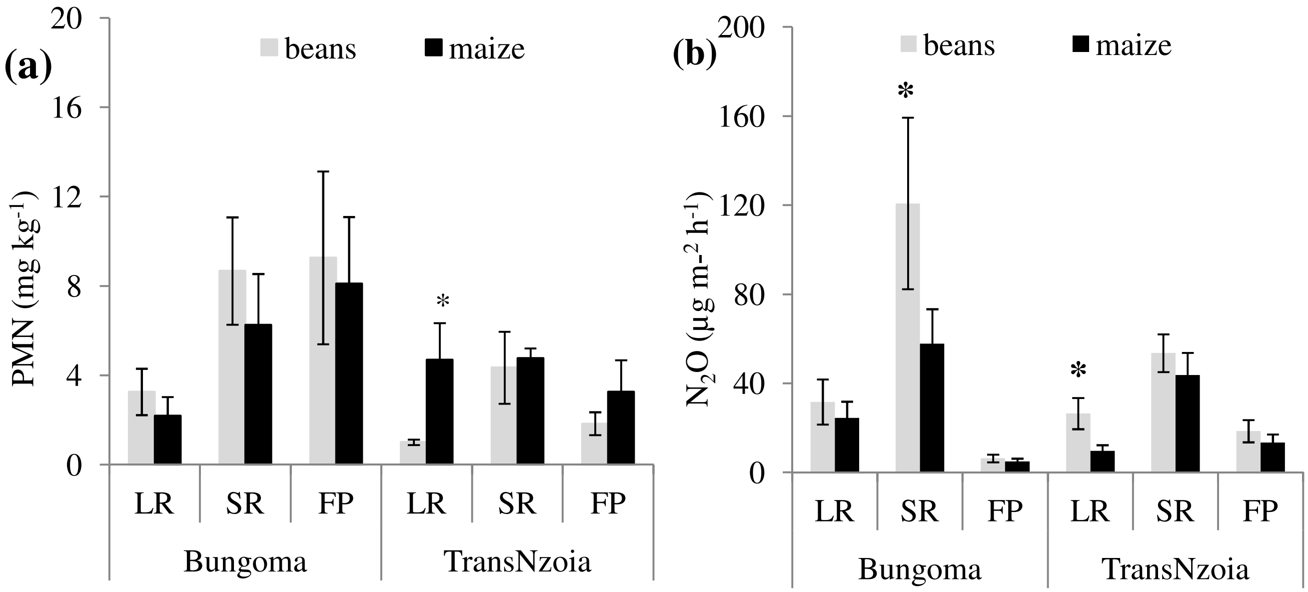

Fig.5 (a) Soil Potentially Mineralizable Nitrogen (PMN) and (b) nitrous oxide fluxes from soils associated with different crops (beans and maize) during Long Rains (LR), Short Rains (SR) and Fallow Period (FP) at Bungoma and high Trans-Nzoia locations averaged across the three years. Asterisks indicate a significant difference between crops at $P \leq 0.05$ within each location.

3.3 Soil Carbon

Soil CO_2 fluxes were the highest during SR and the lowest during FP in both locations with values in Bungoma much higher compared with Trans-Nzoia(Fig. 6a). The highest CO_2 fluxes of 116.3 mg m^{-2} h^{-1} during SR in Bungoma and the highest flux of 82.3 mg m^{-2} h^{-1} during SR in Trans-Nzoia were approximately 1.5 times higher that during LR. During FP, CO_2 fluxes declined to significantly lowest levels at both locations. CO_2 fluxes also depended on soil associations with specific crops as demonstrated by a significant season x crop interactions (Fig. 7a). In Bungoma, CO_2 fluxes from soils associated with maize plants were 45% greater compared with soils associated with beans in general and specifically, 24%, 75% and 34%

greater during SR, LR and FP, respectively. In Trans-Nzoia, CO_2 fluxes from soils associated with beans were comparable to those associated with maize except for FP, when they were 19% greater from soils associated with beans than from those associated with maize (Fig. 7a).

Soil CH_4 fluxes were the least negative during FP, intermediate during LR and the most negative during SR at both sites and the values were much lower in Bungoma than Trans-Nzoia (Fig. 6b). CH_4 fluxes depended on soil associations with specific crops as demonstrated by a significant season x crop interaction. Soils associated with beans demonstrated over 50% more negative fluxes than soils associated with maize except for CH_4 fluxesduring FP in Trans-Nzoia, where the reverse pattern was observed (Figure 7b). In Bungoma, CH_4 fluxes associated with beans amounted to 211%, 38% and 62% greater CH_4 assimilation compared with soils associated with maize during FP, LR and SR, respectively. In Trans-Nzoia, CH_4 fluxesfromsoils associated with beans and maize plants were comparable during FP (Figure 7b). During LR and SR, CH_4 fluxes from soils associated with beans were on average, 100% and 156% more negative than from soils associated with maize, respectively.

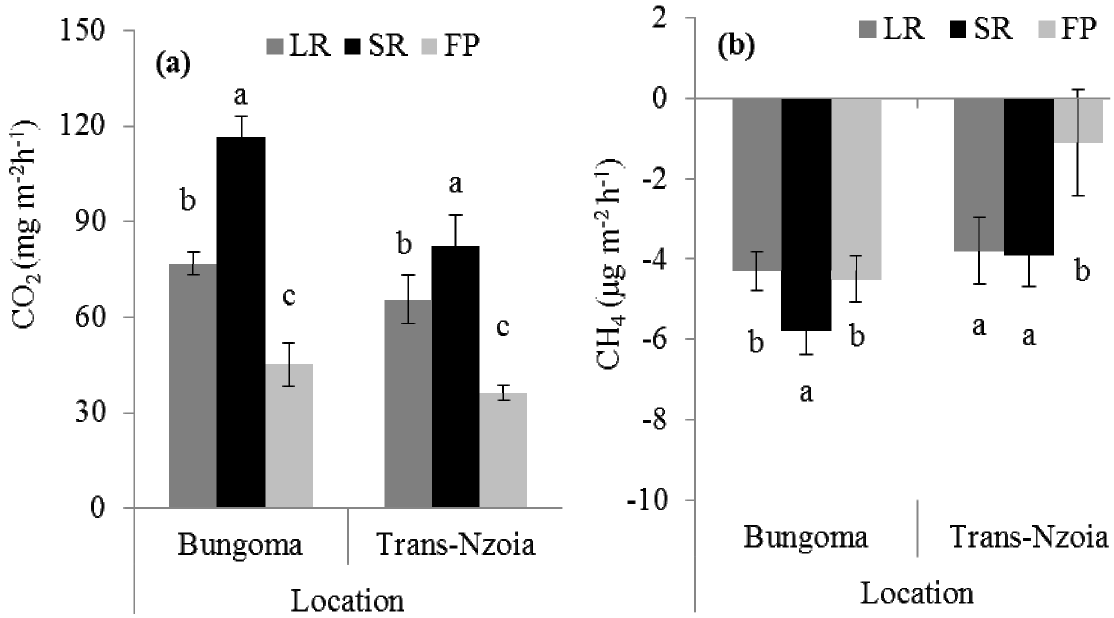

Fig. 6 (a) carbon dioxide (CO_2) and (b) methane (CH_4) fluxes during Short Rains (SR), Fallow Period (FP) and Long Rains (LR) averaged across the three years Bungoma and Trans-Nzoia locations. Lower case letters indicate least significant differences at *$P \leq 0.05$*.

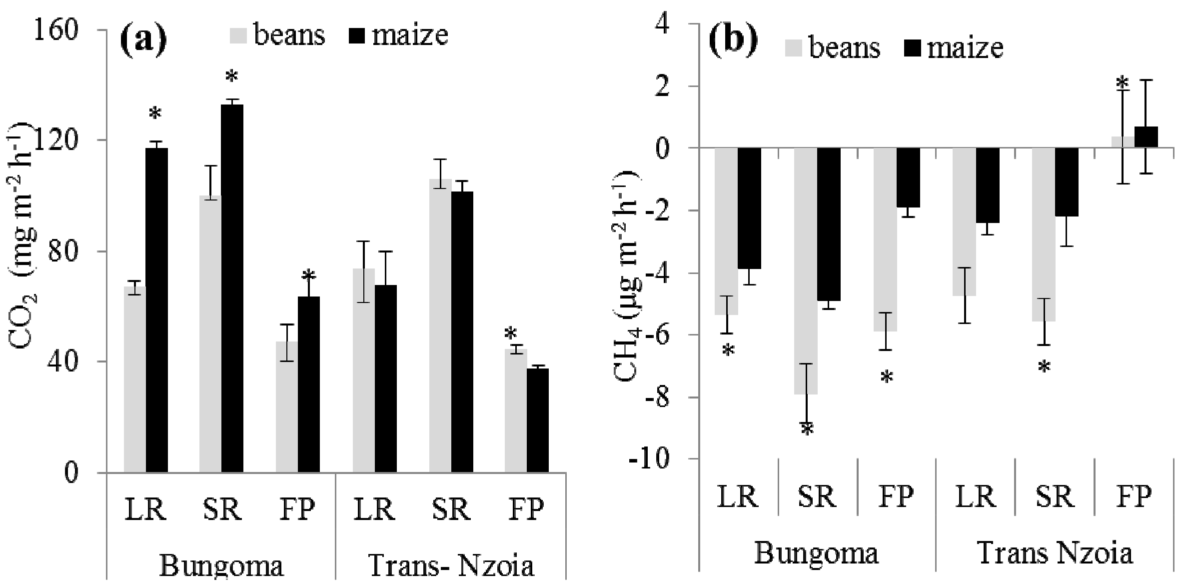

Fig.7 (a) Carbon dioxide (CO_2) and (b) methane (CH_4) from soils associated with different crops (beans and maize) during Long Rains (LR), Short Rains (SR) and Fallow Period (FP) at Bungoma and high Trans-Nzoia locations averaged across the three years. Asterisks indicate a significant difference between crops at $P \leq 0.05$ within each location.

3.4 Relationship Between C and N Mineralization

Pearson correlations showed positive relationship between N_2O and WFPS during LR and SR at both locations (Table 4). N_2O was positively correlated with CO_2 in Trans-Nzoia but negatively correlated with CO_2 in Bungoma during SR only. CO_2 was also positively correlated with WFPS during SR in Bungoma only. PMN was positively correlated with N2O during SR in Bungoma only and negatively correlated with N_2O during LR in Trans-Nzoia. NH_4 was negatively correlated with NO_3 in both locations during LR only.

Regression analyses demonstrated that 77% to 80% of N_2O fluxes can be predicted based on CO_2 fluxes during SR only in both locations and 43% during LR in Trans-Nzoia (Table 5). The slope values however,demonstrated differential patterns as the regression slope for Bungoma had a negative value while for Trans-Nzoia had a positive value. Furthermore, regression analyses demonstrated that between 61% and 65% of N_2O flux can be predicted based on soil WFPS for both cropping seasons in Bungoma and for SR in Trans-Nzoia (Table 5). Only 30% of N_2O flux during LR in Trans-Nzoia can be predicted based on soil WFPS. The regression slope for the N_2O fluxes per unit WFPS for LR was comparable between both locations and ranged between 1.74 and 1.46. The slope of regression during SR however, was 5.68 for Bungoma, which was approximately 3.5 times greater compared with the slope calculated for Trans-Nzoia. Between 35% and 38% of N_2O flux in Bungoma during SR can be predicted based on incubated soil NH_4 and PMN concentrations and 41% of N_2O flux in Trans-Nzoia during SR can be predicted based on incubated soil NO_3 concentrations (Table 5).

4. DISCUSSION

Soil incubation assays to determine potentially mineralizable N are robust in assessing the magnitude of N mineralization under controlled enclosed conditions. Therefore, direct field N_2O flux measurements and laboratory N incubation assays suggest that soil water content played an important role in support of microbial processes contributing to N mineralization across all seasons and all sites. Our results indicate that growing crops during two growing seasons resulted in very high rates of soil N mineralization as demonstrated by high PMN and N_2O fluxes. Since the NH_4 and NO_3 concentrations appeared to be high compared with studies performed in field-conditions of fertilized maize tillage treatments [31], a significant portion of inorganic N was likely lost to NO_3 leaching, N_2O production and not plant uptake as demonstrated by low overall yields. In general, the magnitude of soil N mineralization indicated by N_2O fluxes were comparable to those reported from maize production using comparable rates of inorganic N fertilizer in SSA [32] and in South America [33]. The magnitude of N_2O fluxes in our study however, was much greater when compared with fluxes from loamy soils with high SOM [34-35].

Table 4 Pearson's correlations between percent water filled pore space (WFPS), greenhouse gas fluxes (CO_2, CH_4 and N_2O) and soil nitrogen mineralization (PMN, NO_3 and NH_4) measured during long rains (LR) and short rains (SR) seasons at low elevation (Bungoma) and high elevation (Trans-Nzoia) sites.

		LR						**SR**					
		WFPS	**CO_2**	**CH_4**	**N_2O**	**PMN**	**NO_3**	**WFPS**	**CO_2**	**CH_4**	**N_2O**	**PMN**	**NO_3**
Bungoma	**WFPS**	1						1					
	CO_2	0.32	1					-0.49	1				
	CH_4	-0.23	-0.44	1				-0.27	**-0.53**†	1			
	N_2O	**0.75****	0.11	0.03	1			**0.81****	**-0.87****	0.14	1		
	PMN	-0.46	0.22	0.16	0.37	1		0.46	-0.33	-0.1	**0.53**†	1	
	NO_3	-0.19	0.14	0.3	0.35	0.19	1	-0.33	0.27	0.1	-0.39	-0.45	1
	NH_4	0.02	-0.03	-0.07	-0.11	-0.1	**-0.89****	**0.58**	-0.41	-0.1	**0.63***	0.38	-0.08
Trans-Nzoia	**WFPS**	1						1					
	CO_2	-0.13	1					**0.73****	1				
	CH_4	0.21	-0.47	1				-0.1	-0.33	1			
	N_2O	**0.63***	**0.66****	0.04	1			**0.79****	**0.89****	-0.41	1		
	PMN	0.09	**-0.57**†	0.35	**-0.58**†	1		0.1	-0.33	0.03	-0.11	1	
	NO_3	0.26	-0.33	0.49	-0.22	-0.11	1	**-0.66****	**-0.83****	0.27	0.21	0.47	1
	NH_4	**-0.51**†	-0.1	-0.1	-0.23	0.18	**-0.51**†	-0.30	-0.44	0.13	-0.17	-0.16	0.21

Table 5 Regression equations, regression R square value (Rsq) and P values of the relationship between nitrous oxide (N_2O) fluxes and percent soil water-filled pore space (WFPS), carbon dioxide (CO_2), soil potentially mineralizable nitrogen (PMN), ammonium (NH_4) and nitrate (NO_3) concentrations for long rains (LR) and short rains (SR) seasons at low elevation (Bungoma) and high elevation (Trans-Nzoia) sites.

	LR			**SR**		
Location	**Equation**	**Rsq**	**P value**	**Equation**	**Rsq**	**P value**
Bungoma						
WFPS	y = 1.74x - 53.71	0.61**	*≤ 0.01*	y = 5.68x - 98.93	0.65**	*≤ 0.01*
CO_2			*ns†*	y = -3.1x + 451.50	0.77**	*≤0.01*
PMN			*ns*	y = 9.59x + 18.57	0.35*	*≤ 0.05*
NO_3			*ns*			*ns*
NH_4			*ns*	y = 4.90x + 28.45	0.38*	*≤ 0.01*
Trans-Nzoia						
WFPS	y = 1.46x + 105.00	0.30*	*≤ 0.05*	y = 1.65 x - 38.39	0.61**	*≤ 0.01*
CO_2	y = 0.36x + 43.80	0.43*	*≤ 0.05*	y = 1.48x - 105.30	0.80**	*≤0.01*
PMN			*ns*			*ns*
NO_3			*ns*	y = 0.66x + 6.05	0.41**	*≤0.01*
NH_4			*ns*			*ns*

Soil disturbance associated with planting the second crop played an important role in accelerating soil N mineralization during SR in Bungoma as demonstrated by the highest rates of PMN, NH_4 and N_2O fluxes. Significant relationships between N_2O fluxes and soil PMN and NH_4 concentrations supported the notion of high rates of seasonal nitrification.Not only were the overall soil N mineralization and N_2O fluxes greatest during SR in Bungoma, but also, contrary to our expectations, N_2O fluxes were the greatest from soils associated with bean plants, further demonstrating limited N retention and high Nturnover of N-rich bean residues also proposed by Jeuffroy et al.[36]. However, elevated N_2O fluxes from soils associated with beans could also be attributed to seasonal weeding tillage performed in maize inter-rows that can sever bean plant roots and root nodules [37].

Typical farming practicesalso resulted in a greater overall C mineralization compared with values reported for similar but unmanaged soils in SSA [38-40]. Periodic CO_2 fluxes during LR and SR were greater than fluxes from similarly managed soils with higher total C content under maize-soybean production [34-35; 41-42]. Though, sporadic rainfall events are known to trigger C mineralization and immediate CO_2 pulses [11], our data collection was always completed before the afternoon rain showers and the CO_2 fluxes did not correlate with WFPS except for during SR in Trans-Nzoia. The highest CO_2 flux was observed during SR in Bungoma when soil WFPS was comparable to FP and the location experienced below average cumulative rainfall during the study period. Therefore the highest CO_2 flux during SR in Bungoma was likely caused by additional tillage disturbance for land preparation and weeding of the second maize bean crop, which likely accelerated decomposition of fresh plant residues left behind after LR crop harvest. This was also observed by Ellert and Janzen [43]. Additional tillage operations and new crop production during the second growing season limited soil ability to sequester newly deposited plant-derived organic material and could contribute to SOM depletion of already much lower C and N soils when compared with Trans-Nzoia. Employing soil conservation practices such as reduced tillage for both locations and, in case of Bungoma, letting the land rest during SR can help regain some of the SOM over time. Mapanda et al.[32] demonstrated that fallowing for at least 10 years and amending maize with adequate amounts of N fertilizer lowered CO_2 fluxes and improved SOM and maize yields in Zimbabwe.

Most agricultural soils worldwide are effective CH_4 sinks except for submerged agricultural soils where the anaerobic environment stimulates CH_4 production [44]. Soils in this study appeared to be weak sinks or even mild sources of CH_4 fluxes. The flux values obtained in this study were, however, less negative compared with the previous study by Mapanda et al.[32] from typical maize production under different levels of N fertilizer application in Zimbabwe. Low soil ability to act as a CH_4 sink in our study could be due to the negative effects of tillage disturbance on SOM and possible destruction of microsites reducingthe populations of methanotrophic bacteria [45].

5. CONCLUSIONS

Results from this study supported the overall hypothesis of greater SOM mineralization and lower yields in regions where crops were grown during two seasons per year compared with one long growing season. High SOM mineralization with low plant residue returns and low overall yields in this region suggest declining soil fertility and limited annual SOM replenishment. Continuing typical crop production in this region may ultimately become more challenging and unsustainable in the long-term. Smallholder farmers in Bungoma are however, in economic need to grow crops during two growing seasons. Therefore, the alternative of fallowing the land during SR may face limited success of adoption. Other alternatives may include government supported incentives. These may include abstaining from staple crop production and instead, establishment of N fixing edible cover crops that can be introduced as a relay after LR bean harvest. Moreover, since the incidence of crop failure during SR in Bungoma is likely to become more frequent, focusing efforts toward one-season crop production during LRmay also be of a value to farmers. In general, both locations could greatly benefit from crop residue retention and transitioning to soil management systems that rely on less deep and less frequent tillage operations such as no-till.

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