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ORIGINAL ARTICLE

Nitrous oxide (N_2O) emissions in response to increasing fertilizer addition in maize (*Zea mays* L.) agriculture in western Kenya

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Abstract National and regional efforts are underway to increase fertilizer use in sub-Saharan Africa, where attaining food security is a perennial challenge and mean fertilizer use in many countries is <10 % of nationally recommended rates. Increases in nitrogen (N) inputs will likely cause increased emissions of the greenhouse gas nitrous oxide (N_2O). We established experimental plots with different rates of N applied to maize (*Zea mays*) in a field with a history of nutrient additions in western Kenya and measured N_2O fluxes. Fertilizer was applied by hand at 0, 50, 75, 100, and 200 kg N ha^{-1} in a split application on March 22 and April 20, 2010. Gas sampling was conducted daily during the week following applications, and was otherwise collected weekly or biweekly until June 29, 2010. Cumulative fluxes were highest from the 200 kg N ha^{-1} treatment, with emissions of 810 g N_2O–N ha^{-1}; fluxes from other treatments ranged from 620 to 710 g N_2O–N ha^{-1}, but with no significant differences among treatments. Emissions of N_2O during the 99-day measurement period represented <0.1 % of added fertilizer N for all treatments. Though limited to a single year, these results provide further evidence that African agricultural systems may have N_2O emission factors substantially lower than the global mean.

Keywords Nitrogen · Africa · Greenhouse gas · Agricultural intensification · Carbon dioxide · Methane

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Introduction

Agricultural systems are responsible for 80 % of anthropogenic emissions of nitrous oxide (N_2O), a powerful greenhouse gas that is also the leading cause of stratospheric ozone depletion (Robertson and Vitousek 2009; Ravishankara et al. 2009). Nitrous oxide can be produced as a byproduct during the microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), and is an intermediate in the microbial reduction of NO_3^- to atmospheric N_2. It can also be produced in other processes such as dissimilatory nitrate reduction to ammonium and co-denitrification. The addition of fertilizer tends to increase the rates of

these transformations, and of trace gas N emissions as well, sometimes by an order of magnitude or more (Firestone and Davidson 1989; Predotova et al. 2010). In 2007, 12.6 % of global cultivated land was in sub-Saharan Africa (SSA; Faurès and Santini 2008), but the region is responsible for only 6 % of global anthropogenic N_2O emissions (Hickman et al. 2011), largely because rates of fertilizer use in the region are extremely low. For maize—the recipient of most fertilizer in SSA (FAO 2006)—nitrogen (N) inputs are low; for example, in Western Kenya an average of 7 kg N ha^{-1} $year^{-1}$ is used, producing yields of 2.0 tons ha^{-1} $year^{-1}$ (Vitousek et al. 2009). In many other countries in SSA, average fertilizer use is <1 kg fertilizer ha^{-1} $year^{-1}$ (Peoples et al. 1995). In contrast, fertilizer applications are an order of magnitude or more higher in wheat-maize double cropping system in North China(588 kg N ha^{-1} $year^{-1}$), and in a tile-drained maize-soybean rotation in Illinois, USA (155 kg N ha^{-1} $year^{-1}$) resulting in respective yields of 8.5 and 8.2 tons ha^{-1} $year^{-1}$ per crop (Vitousek et al. 2009).

Increased use of inorganic fertilizer is seen as essential for increasing food security and improving soil fertility in SSA (Vanlauwe and Giller 2006). Maize is the primary staple crop in Kenya, where it is grown on 1.4 million ha, predominantly by smallholder farmers (De Groote et al. 2005). But largely because fertilizer use is low among smallholders, mean annual production was only 1.7 tons ha^{-1} from 2000 to 2005, meeting about 80 % of Kenya's maize consumption and resulting in an increasing need for maize imports (De Groote et al. 2005). The Alliance for a Green Revolution in Africa (AGRA) is working to increase fertilizer use six-fold across the continent by 2015, to an average of 50 kg ha^{-1} $year^{-1}$ (AGRA 2009). While many measurements have been made of crop responses to increasing fertilizer additions in SSA, data on soil trace gas emissions are sparse. To date, field measurements of N_2O emissions from soils treated with mineral fertilizer in SSA have been published only for Kenya (Baggs et al. 2006), Zimbabwe (Mapanda et al. 2010, 2011, 2012), Burkina Faso (Brümmer et al. 2008), Madagascar (Chapuis-Lardy et al. 2009), and Mali (Dick et al. 2008) and for fertilization rates of 23 (Dick et al. 2008), 52.5 (Brümmer et al. 2008), 56 (Chapuis-Lardy et al. 2009), 60 (Mapanda et al. 2011), 100 (Baggs et al. 2006),120 (Mapanda et al. 2010, 2011, 2012), and 140 kg N ha^{-1} (Brümmer et al. 2008), and only the studies in Zimbabwe, Burkina Faso, and Mali included more than a single rate of mineral fertilizer application.

The simple narrative of low nutrient inputs, negative nutrient balances, and fertility decline in SSA is complicated by substantial heterogeneity in soil nutrient balances at a variety of scales. In the first place, nutrient balances are not universally negative in SSA, with 15 % of published studies finding positive balances for N (Cobo et al. 2010). Some of this heterogeneity plays out across farms: more than 75 % of the time, wealthier farmers' fields exhibit higher N balances than poorer farmers' fields in the same cropping system (Cobo et al. 2010). But this heterogeneity also occurs within individual farms, with a gradient of decreasing N balances extending from relatively high N balances in fields near the homestead ("infields" where farmers may be more likely to allocate resources) to lower N balances in fields further away ("outfields;" Tittonell et al. 2007). N balances in published studies were higher in infields than outfields nearly 90 % of the time (Cobo et al. 2010). In addition, the nutrient status and N balance of agricultural soils in SSA is likely to change as an African Green Revolution takes hold and nutrient inputs increase. It is important to understand how N_2O fluxes respond to fertilizer inputs in soils with different management and fertility status in order to better constrain the potential magnitude of fluxes in the future.

We conducted a field experiment on a well-managed site on a research station in Western Kenya to evaluate how N_2O emissions respond to inorganic fertilization in a relatively fertile African agricultural system.

Materials and methods

Site information

An experimental maize field was established at the Maseno Veterinary Farm and Agricultural Training Center in Maseno, Kenya in early 2010. The site has been used for livestock production since the Center was established in 1927. Food crops are typically sown in March and September for the long and short rainy seasons, respectively, with the majority of annual food production occurring during the first rainy season of the year. Mean annual rainfall is 1,750 mm.

The field was located at 0°0′ North and 34°35′ East, at an altitude between 1,500 and 1,600 m above sea level. Soils are derived from a Nyanzan basalt, with 26 % sand, 21 % silt, 53 % clay, 2.09 % C, 0.21 % N, and a pH of 4.6–5 in the top 20 cm. Soils are well-drained, and soil depth in the area is typically 1.2 m or more.

An area measuring 100 m × 20 m was ploughed and harrowed by hand in February and March 2010, during which several precipitation events occurred. For the 16 years prior to the establishment of the experiment, napier grass (*Pennisetum purpureum*) was grown in the plots and adjacent field for cattle forage. Manure collected from paddocks had been discarded along the edge of the field.

Experimental design

Five levels of fertilizer additions were used: 0, 50, 75, 100, and 200 kg N ha^{-1}. Treatments were applied in a randomized complete block design, consisting of 4 blocks with 5 plots each. Each plot was 5.25 m × 3 m. Rows were spaced at 0.75 m intervals, and plants were seeded by hand at 0.30 m intervals within rows following regional recommendations, for 7 rows of 10 plants per plot, and a plant population of 44,444 plants ha^{-1}. Two additional rows were planted at the edge of each plot to be harvested in April for the estimation of plant volume (see below). A hybrid maize variety, DK 8031, was used in all plots. At planting, two seeds were placed in each seeding hole, and plants were thinned to one plant per seeding hole within 2 weeks of emergence.

As recommended by regional extension services, 1/3 of the fertilizer N was applied as diammonium phosphate (DAP, 18 % N) at planting on March 22, and the remaining 2/3 was applied as urea (46 % N) on April 20. Fertilizer applications were pre-weighed and applied by hand. The DAP was placed within 5 cm of the seed in a seeding hole roughly 5 cm deep; urea was applied as topdressing on either side of the stem of each plant (within about 5 cm), and incorporated 2 cm below the soil surface. The field was weeded twice by hand: once during the week before the topdressing application, and again several weeks later.

The 18 maize plants in the center of each plot were harvested by hand on August 9. The fresh weight of all stalks and cobs was measured within 24 h of harvest, and subsets were measured for wet to dry weight conversions. Grain subsamples were also dried to estimate wet to dry weight conversions; all plant samples were dried at 60 °C. Additional subsamples of plant biomass and grain were dried and analyzed for C and N content using a FLASHEA 1112 elemental analyzer (CE Instruments, Hindley Green, UK).

Trace gas measurements

Gas samples were collected for the estimation of N_2O, carbon dioxide (CO_2), and methane (CH_4) emissions from March 18 to June 29 using a static chamber approach (Holland et al. 1999); samples were collected daily for 7 days following each fertilizer application and then weekly or biweekly for the duration of the measurement period. CO_2 fluxes were also measured dynamically on selected dates using a LI-COR LI-7000 (LI-COR Biotechnology, Lincoln, NE). Because basal fertilizer was applied exclusively in the seeding hole and topdressing fertilizer was applied within about 5 cm of the maize stem, a stratified random sampling strategy was employed to more effectively capture fluxes from the fertilizer applications. During the week before planting, a beveled PVC ring (25.5 cm diameter) was centered over the position where a seeding hole would be made and inserted several centimeters into the soil in each plot until fixed firmly in the soil, resulting in chamber heights that ranged from 8 to 12 cm when fitted with a cover. These rings remained in place during all pre-topdressing measurements, until plants grew too large for the chambers. Prior to the topdressing application, each ring was removed and moved into a position between two maize plants within a row, so that opposite edges of the ring were within 1–5 cm of a maize stem, and covering the area where the topdressing application is applied. Half of the topdressing application for each of these two plants was placed inside the ring and adjacent to each plant, so that the chamber ring covered soil receiving the equivalent of a full topdressing fertilizer application for a single plant. The chambers were kept in this position for the remainder of the experiment.

Prior to planting, one additional chamber was inserted over soil between maize rows in a randomly selected plot within each block (a total of four chambers) to provide data for estimations of fluxes from areas not receiving fertilizer and to calculate

seasonal fluxes at the field scale. These chambers were not moved during the experiment. Data from these additional 'between row' chambers are necessary to estimate field-scale fluxes, particularly when fertilizer is banded or hand-applied in close proximity to seedlings (e.g., Adviento-Borbe et al. 2007; Ma et al. 2010). These data were not included in the statistical analysis of the fertilizer treatments, since the fluxes are from soils where fertilizer was not added.

At sampling, a molded PVC chamber top fitted with a vent and a septum was placed over each ring and made gas-tight. Polypropylene syringes were used to collect 12 ml gas from each chamber at 0, 10, 20, and 30 min following placement of the chamber lid and transferred to evacuated 9 ml glass vials (Teledyne Tekmar, Mason, OH). Sample vials were stored at room temperature until they were taken to the Cary Institute of Ecosystem Studies in Millbrook, NY; USA for analysis. All samples were analyzed for N_2O and CO_2 by gas chromatography using a Shimadzu GC-14 gas chromatograph (Shimadzu Scientific Instruments, Columbia, MD; USA) fitted with electron capture and thermal conductivity detectors. A subset of samples was also analyzed for CH_4 using a Shimadzu GC-8a GC fitted with a flame ionization detector. Concentrations were corrected for leakage and consumption of gas by septa between sampling and analysis based on changes in concentrations of vials that were prepared and handled identically to the sample vials, but were injected with 10 ml of standard gas (1.0 ppm N_2O in N_2, Scott Specialty Gases, Breda, Netherlands).

Fluxes were calculated according to the following equation:

$$F_{N_2O} = b \times V_{Ch} \times MW_{N_2O-N} \times 60 \times 10^3/R \times t \times A_{Ch}$$

where $F_{N_2O} = N_2O$ flux rate [ng N_2O–N cm^{-2} h^{-1}], b = mixing ratio change (ppmv min^{-1}), V_{Ch} = chamber volume (l), p = pressure (atm), MW_{N_2O-N} = molecular weight of N_2O–N (28.0134 g mol^{-1}), R = gas constant [0.08206 (L atm)/(K mol)], T = temperature (°K), and A_{ch} = chamber base area (cm^2). A similar approach was taken for CO_2 and CH_4 calculations. A correction to account for the air displaced by maize seedlings within the chamber was made for the April 6 and 13 samplings. The volume displaced by plants was estimated by the average volume of water displaced by five plants harvested from the edge of the plot, and the chamber volume was adjusted accordingly in flux calculations.

Gas samples were collected with varying frequencies. Following the basal fertilizer application on March 22nd, samples were collected daily for 7 days, and then weekly until topdressing. Samples were also collected daily for 7 days following topdressing application on April 13, and then weekly until May 29; additional gas samples were collected on June 15 and 29. In total, gas sampling was conducted on 23 days during maize growth. Dynamic measurements of CO_2 emissions were also made during the first 2 weeks after planting (March 27–29, April 6), and again after topdressing (May 8).

Soil measurements

Soil samples were collected from each plot to 20 cm depth before planting for characterization. Soils were dried at 60° C, and major rocks and roots removed. Subsamples were analyzed for particle size using the hydrometer method and for total C and N using a FLASHEA 1112 elemental analyzer (CE Instruments, Hindley Green, UK).

Estimates of daily and seasonal N_2O emission rates, emission factors, and field-scale emissions

Mean daily emission rates, estimated from the chamber measurements of emissions, assumed no diurnal variation in emissions. This assumption may result in an inaccurate estimate of the mean daily flux, though diurnal variation in N_2O fluxes is not always observed in tropical agroecosystems (Le Roux et al. 1995; Crill et al. 2000). Cumulative emissions were estimated by integration of the area under the curve described by linear interpolations of these daily mean N_2O rates, extending for 99 days from March 23, 2010 through June 29, 2010, the final sampling date. Emissions measured from one plot in the 0 kg ha^{-1} treatment and one plot in the 50 kg N ha^{-1} treatment exhibited unusually high CO_2 emission rates, suggesting that emissions may have been influenced by fresh manure in the soil, but were included in all estimates and statistical analyses.

Estimates of field-scale emissions were calculated using a weighted average of cumulative fluxes from chambers covering fertilizer applications and

chambers placed between rows. The proportion of the field allocated to fertilizer-induced emissions (0.227) is equal to the proportion of the field area described by a 12.75 cm radius extending from each maize stem (the radius of the chambers used). We assumed that chambers covering fertilizer applications captured all fertilizer-related emissions. As such, these estimates may under-estimate field-scale emissions if a broader area of soil was affected by the added N.

Estimates of the percentage of fertilizer N lost as N_2O were calculated by dividing the difference between field-scale cumulative emissions from chambers receiving the 0 kg N ha^{-1} fertilizer treatment and field-scale cumulative emissions for a given treatment by the amount of fertilizer N added in that treatment. An alternative set of estimates was also calculated for each treatment using cumulative fluxes from chambers placed between rows in place of the cumulative fluxes from the control chambers. These alternative estimates were calculated because fluxes from the 0 kg N ha^{-1} treatment were higher than from many fertilized treatments, perhaps a result of manure in some fields and elevated N and C availability in those plots, and may lead to artificially low estimates of the percentage of fertilizer N lost as N_2O. Together, these estimates may bracket the range of the amount of N lost from these soils as N_2O.

Statistical analysis

Two separate statistical analyses of gas fluxes were conducted to account for the switch in chamber positions between the basal and topdressing applications, as the change in chamber position also changed the experimental unit being sampled. We conducted one mixed model ANOVA of the mean daily emission response following the basal application and a second mixed model ANOVA for the topdressing application through the end of the measurement period. The daily flux derived from cumulative estimates was used as the response variable. Treatment was considered a fixed effect, and block as a random effect in the analyses. N_2O fluxes were square root transformed and CO_2 emissions were inverse transformed to meet the assumptions of ANOVA. All analyses were conducted using the R programming language.

Results

N_2O fluxes

Pulses of N_2O were observed following each fertilizer application. Fluxes were highest during the month following topdressing, increasing from roughly 10 g N_2O–N ha^{-1} day^{-1} for the 0 through 100 kg N ha^{-1} treatments to 29.4 (9.7 SE) g N_2O–N ha^{-1} day^{-1} in the 200 kg N ha^{-1} treatment (Fig. 1).

No treatment effects for were found for the fluxes following basal fertilizer applications ($P = 0.54$) or for the fluxes from topdressing to the end of the measurement period ($P = 0.14$). Fluxes did not seem to respond to the topdressing fertilizer applications until a 44 mm rain event on April 25, at which time apparent differences emerged between the 200 kg N ha^{-1} treatment and all the other treatments (25.9 ($\pm$ 6.64 SE) ng N_2O–N cm^{-2} h^{-1} for the 200 kg N ha^{-1} treatment compared to about 9 ng N_2O–N cm^{-2} h^{-1} for all others; Fig. 1).

Cumulative and field-scale N_2O emissions

Measured fluxes of N_2O varied by over an order of magnitude over the course of the growing season (Fig. 1). Cumulative N_2O emissions at the field-scale ranged from 620 to 810 g N_2O–N ha^{-1} (Table 1). Roughly 60 % of N_2O emissions from the 200 kg N ha^{-1} chambers were emitted during the 3 weeks following the topdressing application. Emissions for all except the 0 kg ha^{-1} treatment tapered off during the last 6 weeks of measurements. During May and June, N_2O emissions from the 0 kg N ha^{-1} treatment were sometimes an order of magnitude higher than in the 50 kg N ha^{-1} treatment (Fig. 1). These high emissions lead to comparably high estimates for the interpolated dates, and relatively large cumulative N_2O emissions from the 0 kg N ha^{-1} plots. Annual emissions from unfertilized soils would be roughly 1 kg N_2O–N ha^{-1} assuming that emissions during the short rainy season are of the same magnitude as those measured during the long rainy season, and that emissions are effectively zero during the dry seasons, and would reach 2.2–2.6 kg N_2O–N ha^{-1} if the emissions observed here are representative of the entire year.

Emissions from the between-row chambers were lower and had a narrower range of emissions than

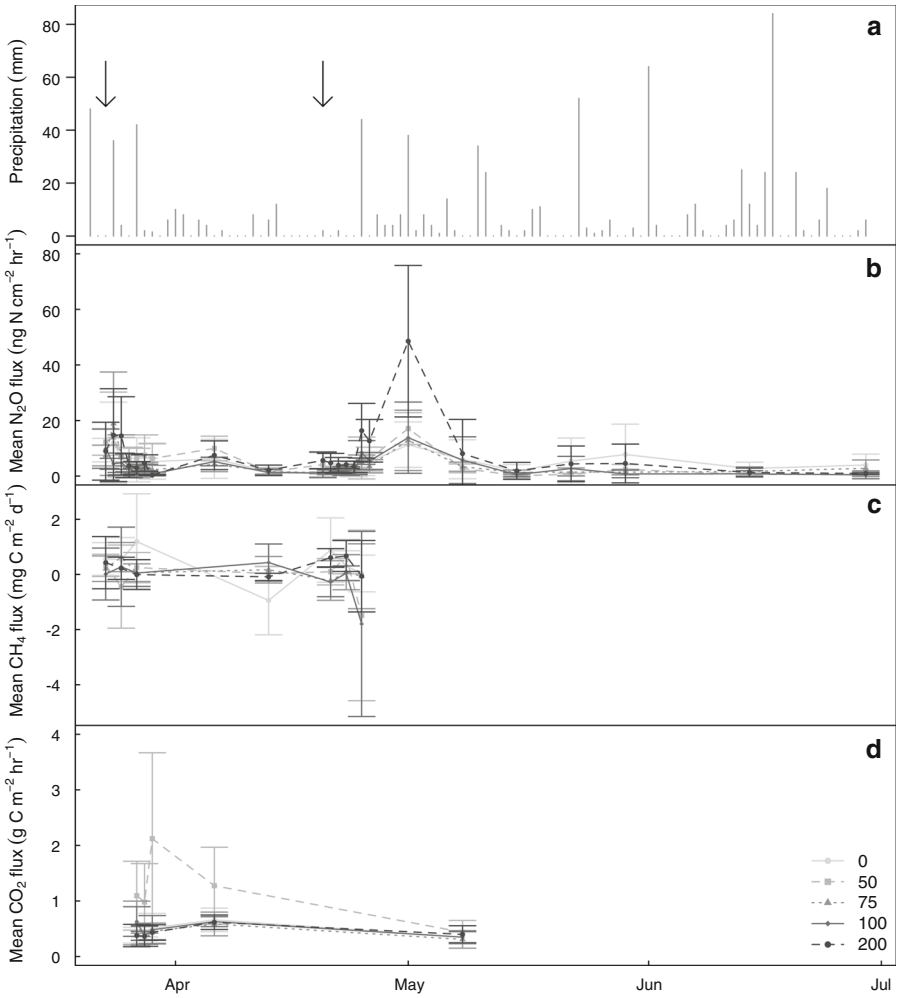

Fig. 1 **a** Precipitation and **b** N_2O, **c** CH_4, and **d** CO_2 fluxes for each treatment, measured in Maseno in 2010. *Arrows* indicate dates of fertilizer application. *Error bars* represent the standard error of the treatment means. Fluxes of N_2O and CH_4 are based on static thirty-minute measurements made using gas chromatography; CO_2 fluxes are based dynamic on 5-min measurements using infrared gas analysis. Mean CH_4 emission rates were not significantly different from zero

emissions from the control plot chambers (1.59–5.03 ng N_2O–N cm^{-2} h^{-1} over the entire measurement period for between-row chambers vs. −0.16 to 27.45 ng N_2O–N cm^{-2} h^{-1} from control plots; Table 1). Consequently, estimates of the amount of fertilizer N lost as N_2O using the between-row measurements were larger than the estimates using measurements from measurements from the control plots, but in both cases, <0.1 % of fertilizer N was lost as N_2O (Table 1).

Although measurements in this experiment did not extend through the end of the year, by the end of the sampling period emission rates from the 50, 100, and 200 kg N ha^{-1} treatments were lower than the control and had dropped to rates comparable to levels from dry soils before planting and fertilization (0.23, 0.25, and 0.51 ng cm^{-2} h^{-1}, for 50, 100, and 200 kg N ha^{-1} respectively at the end of the sampling period, compared to 0.30 ng cm^{-2} h^{-1} (0.72 g ha^{-1} day^{-1}) before planting), and did not differ significantly from 0 ($P = 0.07$).

CO_2 and CH_4 emissions

There was no difference in CO_2 or CH_4 emission rates in response to different rates of fertilizer applications ($P = 0.10$ and $P = 0.99$, respectively; Fig. 1).

Table 1 Estimates of fertilizer N lost as N_2O, mean cumulative emissions from within-row chambers, and mean field-scale emissions over the 99-day measurement period

Fertilizer treatment (kg N ha^{-1})	Fertilizer N lost as N_2O (%)	Fertilizer N lost as N_2O, alternative estimates (%)	Mean cumulative emissions from within-row chambers (g N_2O-N ha^{-1})	Mean cumulative field-scale emissions (g N_2O-N ha^{-1})
0	N/A	N/A	980	710
50	−0.08	0.07	800	670
75	−0.11	−0.007	624	630
100	−0.09	−0.015	580	620
200	0.05	0.088	1,390	810
Between-row	N/A	N/A	635	N/A

The alternate estimates of fertilizer N lost as N_2O are based on cumulative field-scale emissions, using between-row chambers as a baseline to calculate the percentage of fertilizer N lost as N_2O. Field-scale emissions are weighted averages of the chambers used for the observed rates and between-row chambers; all cumulative emissions were calculated using linear interpolation between measurement dates

Table 2 Summary of harvested grain and stover biomass and N content

Treatment (kg N ha^{-1})	Grain wt (kg ha^{-1})	Stover wt (kg ha^{-1})	Grain N (%)	Stover N (%)
0	4,780	9,942	1.385	1.036
50	3,970	10,625	1.485	1.087
75	4,610	12,082	1.612	1.184
100	4,563	11,171	1.605	1.209
200	4,496	10,370	1.745	1.288

Estimates of stover and grain weight ha^{-1} are based on extrapolations for values on a per plant basis at a planting density of 44,444 plants ha^{-1}

Emissions of CO_2 and N_2O were correlated across dates ($P < 0.01$, $r = 0.48$), and the relationship was stronger for dates on which CO_2 emissions were measured using the LI-7000 ($P < 0.001$, $r = 0.66$). Cumulative CO_2 emissions based on the LI-COR measurements over the 41-day period when LI-COR measurements were made ranged from 4,300 to 5,200 kg CO_2 ha^{-1}, except for the 50 kg N ha^{-1} treatment, which had cumulative CO_2 of 10,400 kg CO_2 ha^{-1}. Mean CH_4 emissions were not significantly different from zero.

Maize yields

There was no response of crop yield or total biomass to fertilizer additions; grain yield ranged from 3,970 kg ha^{-1} to 4,780 kg ha^{-1} dry weight ($P = 0.15$; Table 2). Although there were no differences in grain yield, variation in the percentage of N within grain was almost entirely explained by differences in fertilizer treatment ($P = 0.01$, adjusted $R^2 = 0.89$, Table 2). Mean stover N concentrations also increased linearly from 1.04 to 1.29 % (adjusted $R^2 = 0.76$ in a regression including block and fertilizer treatment; Table 2). Assuming the measured values are representative of all harvested grain and stover, total aboveground plant N exceeded N inputs for each treatment other than the control.

Discussion

The few existing studies of N_2O emissions from inorganic fertilizer additions in SSA hint at the possibility that the emissions that accompany agricultural intensification in the region may be lower than might generally be expected. In this study, fertilizer-induced emissions were indeed low compared to emissions from agricultural systems receiving similar rates of N inputs in other parts of the world. Emissions from soils receiving comparable rates of fertilizer input in studies in Michigan were typically 2–3 times higher than those observed in this study (McSwiney and Robertson 2005; Hoben et al. 2010). The percentage of fertilizer N lost as N_2O was also smaller in this study than in some other tropical systems: for example, N_2O emissions in a recently cleared forest plot planted with maize-legume rotations receiving a split application of 100 kg N ha^{-1} in Peru emitted an average of 1.53 % of N inputs as N_2O (Palm et al.

2002), and an average of 2.3 % from a maize "chop and mulch" system in Brazil (Davidson et al. 2008). The low fluxes may be due in part to the slightly acidic soils of the site; broadly, denitrification tends to decrease with increasing acidity (e.g., Cuhel et al. 2010). In addition, in this study, fertilizer was applied using both a split application and "micro-dosing" technique, which can be expected to result in lower fertilizer losses in the form of N_2O than would result from a uniform broadcast application since fertilizer timing and placement is matched more closely to plant demand (Adviento-Borbe et al. 2007). With the maize plants taking up more N than was added in fertilizer across all treatments, plant uptake of added fertilizer may play a part in explaining the relatively small losses of fertilizer N as N_2O (Table 2). Negative N balances exist in 85 % of smallholder agriculture in SSA (Cobo et al. 2010), and can be observed even under relatively high rates of N input have been observed in multiple sites in SSA (Nziguheba 2013).

N_2O emissions from agroecosystems in the region also tend to be low in the absence of N inputs. While a global mean of 1 kg N_2O–N ha^{-1} has been reported from unfertilized cropped soils (Van Groenigen et al. 2010), N_2O emissions from unfertilized agricultural soils in SSA are only about half that amount, with a mean of 670 g N_2O–N ha^{-1} $year^{-1}$ and a median of 450 g N_2O–N ha^{-1} $year^{-1}$ (Chikowo et al. 2004; Millar et al. 2004; Baggs et al. 2006; Brümmer et al. 2008; Dick et al. 2008; Mapanda et al. 2011, 2012). These averages from SSA are based on a small sample size of only nine sites, including four relatively close to one another in Zimbabwe (Mapanda et al. 2011, 2012), and two within the same village in Kenya (Millar et al. 2004; Baggs et al. 2006). At roughly 1–2.6 kg N_2O–N ha^{-1} $year^{-1}$, the background fluxes observed in both the control plots and in the inter-row chambers in this study are considerably higher than the averages for unfertilized soils in published field studies in SSA, suggesting that it may be important to consider the heterogeneity in soil fertility in African farming systems when estimating agricultural N_2O emissions in SSA.

Emission factors from studies in sub-Saharan Africa—whether using mineral or organic forms of N as inputs are almost all below 1 % (Chikowo et al. 2004; Kimetu et al. 2006; Baggs et al. 2006; Brümmer et al. 2008; Dick et al. 2008; Chapuis-Lardy et al. 2009; Mapanda et al. 2010, 2011, 2012), except when fertilization rates exceeded 200 kg N ha^{-1} (Millar et al. 2004; Baggs et al. 2006; Predotova et al. 2010; Lompo et al. 2012), though three are two exceptions where emission factors above 1 % can be found at fertilization rates below 200 kg N ha^{-1} (Millar et al. 2004; Dick et al. 2008). These low emission factors are also found in lab incubations (Millar et al. 2004; Millar and Baggs 2005; Gentile et al. 2008), though it should be emphasized that few field studies included measurements across an entire year, and the lab studies are of short duration. Similar results were observed here, with <0.1 % of added fertilizer lost as N_2O during the 99-day measurement period in all treatments (Table 1).

Pulses of microbial activity and trace gas fluxes typically occur with the onset of the rainy season in seasonally dry environments (Davidson 1992). The basal N_2O pulse—which was of a similar magnitude for the control and all but the 100 kg N ha^{-1} treatment—occurred during a week of rain events (134 mm total) following a 9-day dry period at the onset of the rainy season. This correspondence suggests that precipitation may have been a more important driver of fluxes than the basal fertilizer application, especially as N input rate had no effect on N_2O emissions following the basal fertilization event ($P = 0.54$, Fig. 1).

Although the mixed model ANOVA of N_2O emissions following the second fertilizer application did not find a significant effect of fertilization rate on emissions ($P = 0.14$), it seems possible that the large variability in fluxes in general and the high fluxes from the control plots in particular may be swamping an increase in emissions with the 200 kg N ha^{-1} treatment. Such an increase would be consistent with a meta-analysis that found a threshold at fertilizer inputs of roughly 200 kg N ha^{-1}, above which emissions more than doubled (Van Groenigen et al. 2010). It appears that any possible (but not significant) increase in emissions at 200 kg N ha^{-1} observed in this study may be attributed in part to N availability in excess of biological demand during the 2 weeks following fertilizer application, when emissions were highest.

Though grain N increased with fertilization rate ($P = 0.01$, $R^2 = 0.89$), the lack of a yield response in these soils was surprising, and suggests that N availability in these soils may generally be sufficient for plant productivity and that productivity may be limited by nutrients other than N or P. The similar

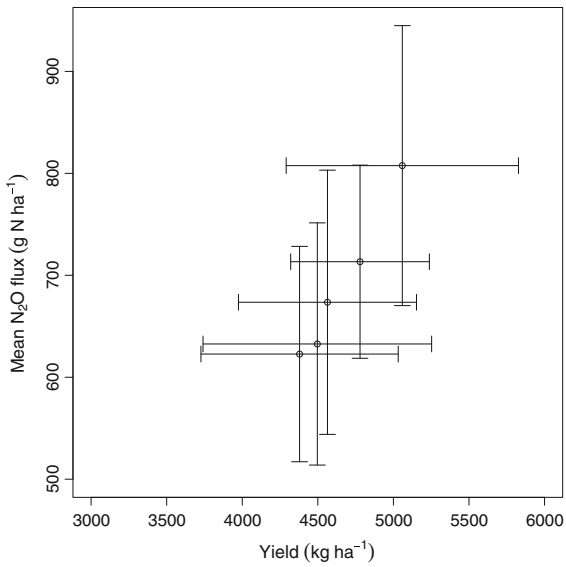

Fig. 2 Cumulative field-scale fertilizer-induced N_2O flux in relation to mean yield for each N input rate in 2011 and 2012. Cumulative fluxes were calculated using linear interpolation between measurement dates. *Error bars* represent the standard error of the treatment means

levels of total N in harvested biomass from the 100 and 200 kg N ha^{-1} treatments (208 and 212 kg N ha^{-1}, respectively) suggests that plant demand could largely be met by the 100 kg N ha^{-1} application rate at this site, further suggesting that it is possible that the doubling of N inputs from 100 to 200 kg N ha^{-1} may result in greater losses of N to the environment. Average grain yields in the experimental plots compared favorably to the mean of 3.2 kg ha^{-1} for farmers in villages in and around Sauri growing hybrid maize using similar management and N addition rates predominantly in the range of 40 to 100 kg N ha^{-1} (Generose Nziguheba, personal communication).

While absolute N_2O emissions may increase with increasing fertilizer use, if accompanied by a larger relative increase in food production, the overall efficiency of food production relative to N_2O production increases, suggesting that food production may be managed for high yields while limiting increases in associated N_2O emissions (Mosier et al. 2006; Van Groenigen et al. 2010). In this study, the efficiency of food production per unit N_2O emitted followed the pattern of overall emissions because there was no yield response to fertilizer additions in this relatively fertile soil and limited effect of fertilizer input on N_2O flux (Fig. 2).

The history of manure deposition in the site and the recent conversion to maize make the results of this study more typical of smallholder farmers who are wealthy in the context of agriculture within SSA–smallholders who own livestock, and who use manure consistently in crop production. The mean total C and N in the top 20 cm of soil in this site were about 50 % higher than in the top 20 cm of soil from maize fields from 16 neighboring villages (Sean Smukler, personal communication). The history of manure deposition in the site also introduces potential heterogeneity in soil C, N, and N_2O fluxes, which can—and likely did—affect our ability to evaluate the effects of differences in N inputs independent of heterogeneity in soils. But these results provide some insight into how changes in N input types and amounts may affect emissions from smallholder systems in Kenya and other parts of SSA, where crop production and livestock production take place within a single, complex landscape.

The highly heterogeneous landscape and short duration of measurements are limitations of this study. However, the results add to evidence in the literature suggesting that N_2O emissions from agriculture in SSA may be considerably <1 % of added fertilizer across a range of application rates, including at rates in excess of those advocated by the AGRA, and in excess of recommended rates for maize in different parts of SSA (Nziguheba et al. 2010). When detailed data are not available in compiling national greenhouse gas emission inventories, the IPCC uses a default emission factor of 1 % for direct emissions (Bouwman 1996; Mosier et al. 1998), and the lack of detailed data in SSA means that national greenhouse gas emission inventories in SSA rely on the IPCC default. The field data published here and elsewhere suggest that the use of this IPCC default in SSA may result in consistent over-estimation of N_2O emissions from agriculture in the region, but given the general paucity of data, additional studies examining N_2O responses to different management practices and N addition rates in SSA will be essential for understanding the effects of increasing fertilizer use on the radiative balance of the atmosphere.

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