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Livelihood and climate trade-offs in Kenyan peri-urban vegetable production

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ABSTRACT

Trade-offs between livelihood and environmental outcomes due to agricultural intensification in sub-Saharan Africa are uncertain. The present study measured yield, economic performance and nitrous oxide (N_2O) emissions in African indigenous vegetable (AIV) production to investigate the optimal nutrient management strategies. In order to achieve this, an on-farm experiment with four treatments – (1) 40 kg N/ha diammonium phosphate (DAP), (2) 10 t/ha cattle manure, (3) 20 kg N/ha DAP and 5 t/ha cattle manure and (4) a no-N input control – was performed for two seasons. Yields and N_2O emissions were directly measured with subsampling and static chambers/gas chromatography, respectively. Economic outcomes were estimated from semi-structured interviews (N = 12). Trade-offs were quantified by calculating N_2O emissions intensity (N_2OI) and N_2O emissions economic intensity (N_2OEI). The results indicate that, DAP alone resulted at least 14% greater yields, gross margin and returns to labour in absolute terms but had the highest emissions ($p = 0.003$). Productivity-climate trade-offs, expressed as N_2OI, were statistically similar for DAP and mixed treatments. However, N_2OEI was minimized under mixed management ($p = 0.0004$) while maintaining productivity and gross margins. We therefore conclude that soil fertility management strategies that mix inorganic and organic source present a pathway to sustainable intensification in AIV production. Future studies of GHG emissions in crop production need to consider not only productivity but economic performance when considering trade-offs.

1. Introduction

Africa accounts for 16.4% of the world's N_2O emissions, of which 42% (excluding grassland and savannah burning) results from agriculture (Hickman et al., 2011). Agriculture generates N_2O emissions due to chemical fertiliser and animal manure use (Syakila and Kroeze, 2011). N_2O is released when N in the fertiliser materials is converted to N_2O gas through two microbial-mediated processes: nitrification and denitrification. Nitrification is the oxidation of ammonia to nitrate and denitrification is the reduction of nitrate and nitrite to dinitrogen gas (Mosier et al., 1998; Robertson and Groffman, 2007). The amount of N_2O produced during nitrification and denitrification depends on management and environmental factors, including the amount of N in the fertilising material, soil temperature, soil moisture/precipitation, soil physical properties, pH, available soil carbon and tillage practice (Shcherbak et al., 2014; Kim et al., 2016).

However, the climate impacts of fertiliser use need to be considered in relation to its benefits to society. This is particularly important in Africa, where agriculture supports both livelihoods and economies. The livelihoods of two thirds of the population come from agriculture (IFDC, 2006) and on average it contributes 25% of gross domestic product (Africa Agriculture Status Report, 2016). Furthermore, the importance of fertiliser in African agricultural production is predicted to increase. Population trends and dietary patterns due to urbanisation and affluence are expected to increase food demand, driving agricultural intensification and additional fertiliser use (Tilman and Clark, 2014). Intensification of nutrient use may stimulate higher N_2O emissions by comparison with current levels. It is essential to have an improved understanding of the potential trade-offs between the N_2O emissions and productivity of farming systems in the development of environmentally friendly farm management strategies that also meet livelihood needs.

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The extent of livelihood and environmental trade-offs from fertiliser use is uncertain, especially in farming systems in sub-Saharan Africa (SSA). Only a few studies have investigated N_2O emissions from African soils. These studies report N_2O emissions per unit land area and range from -0.1 to 113 kg N_2O-N ha^{-1} yr^{-1}. For instance, Dick et al. (2008) measured N_2O emissions from a cereal/legume rotation growing in alfisol soils in Mali and found N_2O emission levels of 0.6–1.5 kg N_2O-N ha^{-1} yr^{-1}. This was on average 20% lower than N_2O emissions from ten fields in humic nitisol soils with vegetables, pasture, tea, maize, cassava and forage feed on smallholder farms in east Africa (Rosenstock et al., 2016). However, N_2O emissions from intensive urban vegetable gardens tend to be high and are the sources of the high cumulative N_2O fluxes reported in African soils, *i.e.* 34–113.4 kg N_2O-N ha^{-1} yr^{-1} (Predotova et al., 2010; Lompo et al., 2012).

Of those studies that have been produced *in situ* measurements of emissions in SSA, few accompany measurements of emissions with yield data of which all are from soils treated with chemical N (Nyamadzawo et al., 2014a; Hickman et al., 2014; Hickman et al., 2015; Pelster et al., 2017). The results from some of these studies indicate greater N_2OI, calculated by expressing N_2O emission as a function of yield, from soils treated with no or high N inputs. For example, Nyamadzawo et al. (2014a) reported a 94% reduction in N_2OI of rape (*Brassicas napus*) in Zimbabwe from soils amended with 65 kg N ha^{-1} compared to adjacent plots treated with no N and N fertilisation at 240 kg N ha^{-1}. N fertilisation at 75 and 100 kg N ha^{-1} reduced N_2OI of maize yield in Kenya by 7% and 28.6% when compared to no N and N fertiliser application at 200 kg N ha^{-1} respectively, although there was no response to fertiliser addition in crop yields (Hickman et al., 2014). In general, these studies demonstrate that moderate nutrient intensification increases crop yields without necessarily increasing N_2O emissions, as was suggested by Shcherbak et al. (2014) based on a global meta-analysis. However, the underlying dataset only contained one study from Africa indicating that despite increased attention being paid to N_2O and yield trade-offs globally (van Groenigen et al., 2010; Linquist et al., 2012), our understanding of the extent of livelihood and climate trade-offs due to soil fertility management in SSA is limited.

The shift in focus to include productivity with climate objectives is promising. However, productivity is only a small part of what drives on-farm decision-making. Farmers, especially those that are market-oriented such as African indigenous vegetable (AIV) producers in peri-urban systems, typically make production decisions based on economics (Okello et al., 2014). No previous studies in SSA or elsewhere globally have investigated the trade-offs between economics and GHGs due to farm management practices in the same way as N_2OI. This is problematic because productivity and economic viability do not always follow the same pattern, *e.g.* yields might increase but net revenues fall due to increased costs of production (Pimentel et al., 2005). Therefore it is imperative to examine trade-offs not only between productivity and emissions, but between the economic viability of farming systems and emissions.

The present study investigated productivity and economic and climate trade-offs in soil fertility management strategies in smallholder AIV production in Kiambu county, Kenya. The importance of vegetables, particularly AIVs, has increased in Kenya due to their contribution to food security, human nutrition and income diversification for smallholder farmers (Ngugi et al., 2007; Abukutsa-Onyango et al., 2010). AIVs in Kenya are characterised by multiple planting and harvesting cycles throughout the year, diverse production systems depending on their location (urban, peri-urban or rural), use of either organic, inorganic or a mix of N inputs, and their degree of market integration (Shackleton et al., 2009). Therefore, the importance of AIVs to Kenya's food security and their intensive production practices make them a good model system for studying economic and climate trade-offs in soil fertility management strategies. Kiambu was chosen because it is a centre of peri-urban AIV production. We hypothesised that current N fertilisation strategies commonly used in smallholder AIV production do not generate significantly different N_2O emission profiles and thus can be optimised to meet yield, economic outcome and environmental goals.

2. Materials and methods

2.1. Study site

An on-farm experiment was established in Wangige, Kiambu county, Kenya (1°13′12.672″ N, 36°41′54.936″E, altitude: 1940 m) on a site that is representative of peri-urban smallholder AIV production in the area. The site has been under smallholder AIV cultivation for the past six years. During that period, vegetables have been grown during the two rainy seasons each year. The ‘long rains' are from mid-March to mid-June while the ‘short rains' fall from October to mid-December. The region receives a mean annual rainfall of about 950 mm and has an average monthly maximum and a minimum temperature of 23.8 °C and 12.6 °C respectively. The soils are broadly classified as Humic Nitisols (Kimetu et al., 2006).

2.2. Experimental design and treatments

The experiment spanned two growing seasons: short rains in 2015 (season I) and long rains in 2016 (season II). The experiment was completely randomised with three replicates of four treatments. The treatments were a no-input control and three nitrogen sources: (1) diammonium phosphate (DAP, 18:46:0) at a rate of 40 kg N ha^{-1}, (2) manure at a rate of 10 t fresh cattle manure ha^{-1} (29.5 kg N ha^{-1}), and (3) a mixture of DAP and manure applied at 34.7 kg N ha^{-1} (20 kg N from DAP and 14.7 kg N derived from 5 t of fresh cattle manure ha^{-1}) for each season. The treatments were applied once at the beginning of each rainy season (20/10/15-season I and 9/4/16-season II) at the same time as fertilisation was being undertaken by other farmers in the area. The selected treatments and application rates represented soil fertility strategies commonly practised by smallholder AIV farmers in Kiambu (HORTINLEA household survey, 2014). Each plot measured 9 m^2 (3 m × 3 m) with a 1-m buffer. African nightshade (*Solanum scabrum*) seeds were incorporated 15 cm apart in rows with 40 cm between the rows. Plot management was in line with local practice and is summarised in Table 1.

2.3. Productivity

Vegetables in N-treated plots were harvested twice in season I and

Table 1
Agronomic practices for African nightshade vegetable production during both growing seasons.

Season	Land preparation	Planting/fertiliser application	Thinning	Weed/pest management	Harvesting
1	12/9/15-1st ploughing by hand, 19/10/15-2nd ploughing (making soils fine for planting)	20/10/15-Sowing seeds and fertiliser application by hand	11/11/15-Thinning	17-18/11/15-Weeding by hand, 19/11/15-application of pesticide	26/11/15-1st harvesting, 19/12/15-2nd harvesting
2	26/3/16-Ploughing by hand	9/4/16-Sowing seeds and fertiliser application by hand	23/4/16-Thinning and gapping	30/4/16- Weeding by hand, 3/5/16-application of pesticide	13/5/16-1st harvesting, 11/06/16-2nd harvesting, 23 July-3rd last harvest

three times in season II (Table 1) and the control plots were harvested once in season I and twice in season II. This is because vegetables in control plots grew at a slower rate compared to other plots. Therefore, by the time of the harvest, vegetables had not developed more than three branches which were needed to carry out the first harvest. Consequently, by harvesting vegetables once (season I) and twice (season II) from control had no significant effect on the total yields. The harvesting procedure matched farmer's common practice. Fresh edible leaves and young stems were cut manually from each vegetable plant with more than three branches, leaving a basal stem to regrow. The same harvesting procedure was followed at each harvesting except during the final harvest of each season where all the above ground biomass was removed by cutting all the vegetables at the soil surface. Fresh yields from each subplot were weighed once in the field at each harvesting using a portable digital weighing scale (Vigo brand). Seasonal vegetable yields were determined for each treatment by totalling the weight of all the fresh vegetables harvested in each season. The total vegetable yield for each plot was obtained by summing seasonal yields from both seasons. The fresh weight of freshly harvested vegetables was used to determine vegetable yields because AIVs are usually sold in the market with prices and returns based on fresh weights.

2.4. N_2O fluxes

Gas samples were collected between 10 am and 1 pm throughout the experimental period. Gas sampling occurred one to three times per week depending on soil management and the expected flux. Samples were collected using vented static chambers (Parkin and Venterea, 2010). Each chamber comprised a lid (27 × 37.2 × 12.5 cm) and a base (27 × 37.2 × 10 cm) clipped together tightly using metallic clamps to avoid gas leakage. Chamber bases were inserted 5–7 cm into the soil one week before the first sampling. The chambers remained in place throughout the season. They were fitted with 50 cm vents (2.5 cm in diameter), gas sampling ports and thermometers to measure internal temperatures, as also described in previous studies (Rosenstock et al., 2016; Tully et al., 2017). Vegetation was not allowed to grow inside the chamber bases. Weeds and other plants growing in the chamber bases were cut to soil height before measurements were taken.

The chambers were closed for 30 min during each sampling event and gases taken at 10-minute intervals from each chamber using the gas pooling method (Arias-Navarro et al., 2013). Gas samples were collected by 60 ml plastic syringes with a stopcock valve and a sampling needle, and immediately transferred to pre-evacuated 20 ml sealed glass vials. The vials were over-pressured to minimise the chance of leakage or contamination. Samples were analysed at the Word Agroforestry Centre (ICRAF) and the International Livestock Research Institute (ILRI) in line with procedures outlined by Butterbach-Bahl et al. (2016).

2.5. Soils

Prior to the start of the experiment, soil samples were collected at a depth of 0–20 cm and 20–50 cm in a zigzag pattern from four points in each plot. The four sub-samples from each soil depth were then mixed thoroughly and a 500 g composite sample taken for laboratory analysis. A composite sample of manure was also collected from a heap of manure to be analysed alongside the soil samples. Soil pH was determined in 1:25 (soil water) suspension. Soil texture was analysed using a Bouyoucos hydrometer after pre-treatment with H_2O_2 to remove organic matter (Okalebo et al., 2002). Total N and the organic carbon of the soil and manure samples were analysed by elementary analysis using a C/N analyser (Thermal Scientific Flash EA 1112). Samples for soil bulk density were collected from the undisturbed soil surface using a 100 cm^3 coring ring and calculated from the weight of the oven-dried soil sample (at 105 °C for 48 h).

During the experiment, soil samples from each treatment were taken periodically, when resources allowed, at a depth of 0–10 cm. Samples were mixed evenly to obtain a composite sample for each treatment to determine the inorganic N and soil moisture content. Samples for inorganic N – ammonium (NH_4^+) and nitrate (NO_3^-) – were immediately transferred and kept in cool boxes while being transported to the laboratory for analysis. Extraction of soil inorganic N was performed within 12 h of sampling by shaking 20 g fresh soils with 100 ml of 2MKCl solution for 60 min. The solution was filtered using Whatman filters, frozen and then analysed for the concentration of NO_3^--N and NH_4^+-N using an ultraviolet spectrophotometer (Aquakem 200: Thermo Scientific). Total inorganic N for each treatment was obtained by adding NO_3^--N and NH_4^+-N together. Field-moist soils were weighed, oven dried for 48 h at 105 °C and then reweighed to calculate soil moisture, expressed as water-filled pore space (WFPS) and corrected on the basis of soil bulk density and volumetric water content.

2.6. Economic performance

Costs of production were determined based on a survey of 12 smallholder farmers cultivating African nightshade, with three farmers per treatment (soil management strategies). Data on inputs, labour, and other costs as well as the revenue (returns to land) from the African nightshade cultivated were obtained by interviewing the selected farmers using a structured questionnaire. The economic performance of each treatment was calculated based on the costs derived from the survey.

2.7. Rainfall

Rainfall during the experimental period was measured using two rain gauges. The rain was measured manually every day using a graduated cylinder. Air temperature and soil temperature at a depth of 10 cm were measured using portable digital thermometers during each gas sampling event.

2.8. Data analysis

Cumulative estimates of N_2O emissions from each treatment were calculated for seasons I and II according to their respective growing periods. Seasonal cumulative emissions and mean fluxes for each treatment were estimated based on the total growing period of the two growing seasons. This was done based on the mean flux of the three chambers in each treatment plot and linearly interpolated between sampling events using the trapezoidal rule. Seasonal N_2O emission factors for DAP, manure and mixed were calculated following the method used by Rashti et al. (2015) as follows:

$$\text{EF}\,(\%) = \frac{N_2O\ \text{emission}_{\text{N treatment}} - N_2O\ \text{emission}_{\text{control}}}{N_{\text{input}}} \times 100 \tag{1}$$

where EF (%) is N_2O emission factor in percentage, N_2O emission $_{\text{N treatment}}$ is N_2O emission in N input, N_2O emission $_{\text{control}}$ is control treatments with no N fertiliser additions (kg N_2O-N ha^{-1}), and N $_{\text{input}}$ is the amount of added N (kg N ha^{-1}).

Gross margin (GM) analysis was used in the economic evaluation of each soil fertility management strategy and was calculated as revenue minus variable production cost. The benefit-cost ratio (BCR) was estimated by dividing GM by the total variable cost.

Nitrous oxide emission intensity per unit kg of fresh vegetable yield (N_2OI) was calculated by dividing the seasonal cumulative N_2O emissions for each treatment by the corresponding total fresh vegetable yields. Similarly, nitrous oxide emission economic intensity (N_2OEI) was determined by dividing the seasonal cumulative N_2O emissions for each treatment by the corresponding GM. Differences between the effects of the different treatments on N_2O emissions per land area, total vegetable yield, GM, N_2OI and N_2OEI were tested *via* ANOVA using

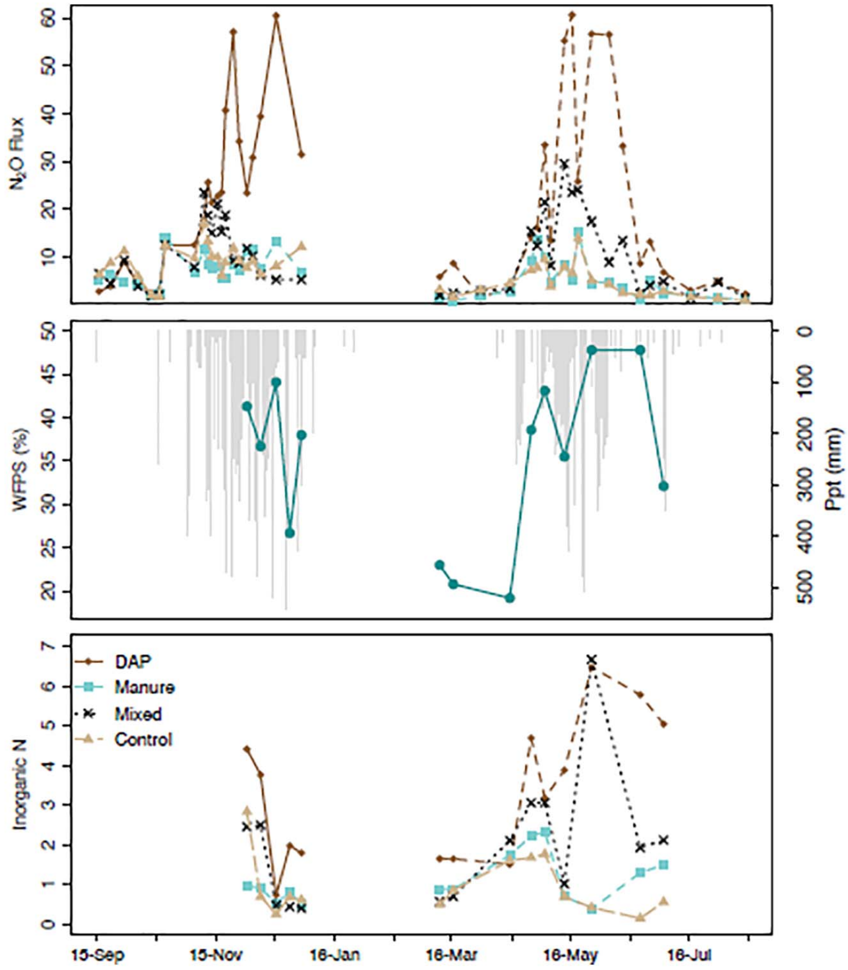

Fig. 1. N_2O (μg N_2O-N m^{-2} h^{-1}) fluxes for the two growing seasons (seasons I and II), WFPS (%) at 10 cm soil depth, precipitation (mm) and inorganic N (kg ha^{-1}) for the DAP, manure, mixed and control treatment plots.

SPSS (version 23). Furthermore, the effects of the main driving factors on N_2O emissions were determined by pairwise correlations using SPSS.

3. Results

The two growing seasons spanned 278 days. Season I started on 2 September and ended on 19 December 2015, lasting a total of 120 days. Season II comprised 158 days, starting on 24 February and ending on 30 July 2016. November received the highest mean monthly rainfall of 227 mm, while February was the driest month with no precipitation (Fig. 1). Soil temperature ranged from 15.7 to 24.8 °C with a seasonal mean of 20.2 °C. Air temperature ranged from 14.5 °C to 25.1 °C with a seasonal mean of 20.3 °C.

3.1. Soil characterisation

Soil physical and chemical properties were similar in all the experimental plots (Table 2). Average soil bulk density was 0.8 g cm^{-3} while the pH was 6. Total soil nitrogen (TN) in the top 20 cm soil depth was 0.3% whereas at 20–50 cm it was 0.2%. Soil organic carbon in the top 20 cm and 20–50 cm soil were 3.1% and 2.5% respectively. Total nitrogen obtained from the manure sample was 1.6%, while the total carbon content was 23%.

3.2. N_2O fluxes

N_2O emission from the DAP treatment increased after N fertilisation and the onset of rainfall, reaching 57.14 μg N_2O-N m^{-2} h^{-1} (10/11/15) before gradually declining to 23.4 μg N_2O-N m^{-2} h^{-1} after one week (Fig. 1). The fluxes then increased again steadily for a further two weeks (to a maximum of 60.6 μg N_2O-N m^{-2} h^{-1} on 1/12/015) before decreasing to 31.5 μg N_2O-N m^{-2} h^{-1}.

As in season I, DAP had the largest N_2O fluxes in season II. However, N_2O emissions remained elevated (above 55 μg N_2O-N m^{-2} h^{-1}) for a longer period (about three weeks) from 28/4/16 to 21/5/16 (except on 5/5/16 when it reduced to 25 μg N_2O-N m^{-2} h^{-1}), before gradually declining to background emission levels for the rest of the growing period.

The temporal pattern of N_2O emissions from the manure and control treatments was comparable and below 15 μg N_2O-N m^{-2} h^{-1} across the two seasons. The fluxes from the mixed treatment were similar to those of the manure and the control except for 26/10/15 and 6/11/15 (season I) and 18/4/16 to 5/5/16 (season II) when N_2O emissions were higher (between 15.3 and 29.5 μg N_2O-N m^{-2} h^{-1}). The lowest N_2O flux was recorded from the manure treatment at 0.7 μg N_2O-N m^{-2} h^{-1} (Fig. 1).

Cumulative N_2O emissions from the DAP treatment for season I and seasonal cumulative N_2O emissions were significantly higher ($p = 0.003$) than those from the three other treatments, which were similar to one another. In season II, the seasonal cumulative N_2O emission from manure and the control were also similar and significantly lower than those from the DAP and mixed treatments, which were also dissimilar ($p = 0.003$) from one other. Emission factors for DAP, and mixed treatments were 2.6% and 0.7% respectively while manure treatment had zero EF (Table 3).

Table 2
Soil characterisation.

Plots	Depth in cm	Bulk density ($g\ cm^{-3}$)	pH	Soil texture			TN (%)	Total C (%)	Organic C (%)
				Sand	Silt	Clay			
1	0–20	0.8	6.0	4.3	9.7	85.9	0.3	3.5	3.5
	20–50			1.1	6.2	92.5	0.2	2.8	2.8
2	0–20	0.8	5.9	3.7	18.0	78.1	0.3	3.4	3.4
	20–50			1.1	7.8	91.0	0.2	2.4	2.5
3	0–20	0.8	5.9	3.2	13.6	83.1	0.3	3.6	3.6
	20–50			1.7	12.4	85.7	0.2	2.5	2.6
4	0–20	0.9	6.0	3.5	10.1	86.2	0.3	3.4	3.5
	20–50			1.5	16.1	82.3	0.2	2.6	2.5
5	0–20	0.8	6.0	3.8	17.7	78.4	0.3	3.2	3.2
	20–50			1.3	9.7	88.8	0.2	2.1	2.2
6	0–20	0.8	6.0	4.1	16.8	79.0	0.2	2.9	3.1
	20–50			0.5	3.9	95.5	0.1	2.1	2.0
7	0–20	0.8	6.0	2.8	19.2	77.9	0.2	3.1	3.0
	20–50			1.1	5.8	92.9	0.2	2.0	2.1
8	0–20	0.9	6.0	4.2	11.6	84.1	0.3	3.2	3.2
	20–50			1.6	6.7	91.6	0.2	2.3	2.2
9	0–20	0.8	6.0	3.6	10.0	86.2	0.2	3.0	3.2
	20–50			1.4	7.5	91.0	0.1	2.1	2.1
10	0–20	0.8	6.1	1.2	6.1	92.5	0.2	2.9	2.9
	20–50			1.0	7.2	91.7	0.2	2.4	2.4
11	0–20	0.8	6.0	3.6	11.8	84.5	0.2	3.1	2.9
	20–50			1.1	6.2	92.5	0.2	2.2	2.2
12	0–20	0.8	6.0	3.3	7.2	89.4	0.3	3.1	3.1
	20–50			0.6	5.0	94.3	0.2	2.5	2.5
Manure	Composite		7.4	58.9	26.4	14.5	1.6	23.0	22.0

Table 3
Estimated cumulative N_2O emissions from each treatment for seasons I and II and seasonal cumulative N_2O emissions for both seasons in kg N_2O-N ha^{-1} as well as N_2O emission factor expressed in percentages (EF %).

Treatment	Season I	Season II	Seasonal cumulative	Emission factors
DAP	1.3 ± 0.3a	1.7 ± 0.2a	3.0 ± 0.7a	2.6
Manure	0.4 ± 0.1b	0.4 ± 0.1b	0.8 ± 0.1b	0.0
Mixed	0.6 ± 0.1b	0.8 ± 0.1c	1.4 ± 0.2b	0.7
Control	0.5 ± 0.1b	0.4 ± 0.0b	0.9 ± 0.1b	–

Data are the mean of three replicates with standard deviations and emission factors. Lowercase letters, within columns, indicate significant differences at $p < 0.05$.

Table 4
Pairwise correlations of the main driving factors of soil temperature (Temp) at 10 cm depth, WFPS (%), NH_4^+-N and NO_3^--N on the fluxes of N_2O.

	NH_4^+-N	NO_3^--N	N_2O	Temp
NO_3^--N	0.44**			
N_2O	0.28*	0.43**		
Temp	0.19	0.04	− 0.18	
WFPS	− 0.08	0.21	0.50**	− 0.65**

*, ** indicates significance at $p < 0.05$ and 0.01 respectively.

Table 5
Fresh yields of African nightshade vegetable (t ha^{-1}) from the on-farm experiment for each treatment for seasons I and II, and the total yields for both seasons.

Treatment	Fresh vegetable yields		
	Season I	Season II	Total
DAP	8.3 ± 1.6a	8.6 ± 1.3a	16.9 ± 2.4a
Manure	2.5 ± 0.8b	3.6 ± 0.8b	6.1 ± 2.1b
Mixed	5.5 ± 1.2a	7.9 ± 1.1a	13.4 ± 3.3a
Control	1.1 ± 0.5b	1.7 ± 0.49b	2.8 ± 1.1b

Data are the mean of three replicates with standard deviations. Lowercase letters, within columns, indicate significant differences at $p < 0.05$.

3.3. Soil inorganic nitrogen and WFPS

The temporal pattern of total soil inorganic N concentrations from each treatment was similar to the corresponding N_2O emissions from each treatment across both seasons (Fig. 1). Total inorganic N (kg ha^{-1}) in dry soil varied from a high of 6.5 (DAP) to a low of 0.14 from the control (Fig. 1). The soil NO_3^-N in the dry soil ranged from a maximum of 5.3 (DAP) to a minimum of 2.0 (control) kg NO_3^-N ha^{-1}, whereas NH_4^+-N was between 3.3 (DAP) and 0.02 (manure) kg NH_4^+-N ha^{-1}. Soil WFPS varied from 17.9% to 48.7%, with a mean of 33.7%.

3.4. Correlation between N_2O fluxes and environmental factors

N_2O fluxes were found to be significantly affected by NO_3^-N, WFPS and NH_4^+-N (Table 4), but not by soil temperature.

3.5. Yield

The highest yields (up to 20.2 t/ha) were obtained from the DAP treatment, while the control had the lowest (1.6 t/ha). The mean of total yields from both seasons for the DAP, manure and mixed treatments and the control were 16.9 ± 2.4; 6.1 ± 2.1; 13.4 ± 3.3 and 2.8 ± 1.1 t ha^{-1} respectively (Table 5). When these means were compared, yields from the DAP and mixed treatments were similar and significantly ($p = 0.0001$) higher than those from the manure treatment and the control, which were similar to one another. On a seasonal basis, the yields from the mixed and manure treatments obtained in season II were 30% higher than the corresponding harvest in season I. Yields from the control and DAP treatment harvested in season II were 35% and 3% higher respectively when compared to the harvest in season I.

3.6. Economic performance

Fertilisation from inorganic sources (DAP) showed the best economic performance in terms of GM, land and labour productivity (Table 6). In general, GM from the four soil fertility management strategies varied from 2707.8 to 290.1 USD ha^{-1}, while the benefit-

Table 6

Economic valuation (USD ha^{-1}) of each soil fertility strategy (treatment) based on data collected from smallholder farmers cultivating African nightshade.

Variables	Treatments (soil fertility management strategies)			
	DAP	Manure	Mixed	Control
Input cost				
Seed	57.1 ± 0.0	57.1 ± 0.0	57.1 ± 0.0	57.1 ± 0.0
Fertilisers	231.1 ± 0	152.8 ± 7.7	190.3 ± 6.5	–
Pesticides/herbicides	71.4 ± 0.0	71.4 ± 0.0	71.4 ± 0.0	71.4 ± 0.0
Labour				
Land preparation	114.2 ± 0.0	114.2 ± 0.0	114.2 ± 0.0	114.2 ± 0.0
Planting	41.2 ± 5.5	19.0 ± 0.0	47.6 ± 9.5	9.5 ± 0.0
Weeding	82.5 ± 10.9	107.8 ± 10.9	76.1 ± 0.0	111.6 ± 0.0
Pesticides application	21.5 ± 0.0	21.5 ± 0.0	21.5 ± 0.0	21.5 ± 0.0
Harvesting	111.2 ± 0.0	57.1 ± 0.0	95.1 ± 0.0	38.1 ± 0.0
Total cost of labour	370.6 ± 9.5	319.6 ± 10.9	354.5 ± 9.5	294.9 ± 0.0
Other cost	3.9 ± 0.0	–	1.9 ± 0.0	–
Total variable costs (a)	733.9 ± 9.5a	600.8 ± 12.5a	675.2 ± 12.6a	423.2 ± 0.0a
Total labour hours	686 ± 14.0	736 ± 36.0	696 ± 16.4	607 ± 11.0
Labour productivity kg/h	18.5 ± 0.9	8.1 ± 1.1	15.8 ± 3.0	5.1 ± 0.6
Area productivity (t/ha)	12.8 ± 0.7	5.9 ± 0.5	11.0 ± 0.6	3.1 ± 0.3
Gross output (b)	3441.7 ± 48	1484.5 ± 287	3001.3 ± 268	713.3 ± 74
Gross margin (b-a)	2707.8 ± 46a	883.7 ± 290b	2326.1 ± 279a	290.1 ± 74b
Gross margin labour h^{-1}	3.9 ± 0.0a	1.2 ± 0.5b	3.3 ± 0.8a	0.5 ± 0.1b
Benefit-cost ratio (b/a)	4.6 ± 0.0a	2.4 ± 0.5b	4.4 ± 0.5a	1.7 ± 0.2b

Data are the mean with standard deviations of three replicates of each soil fertility strategy. Lowercase letters, within columns, indicate significant differences at $p < 0.05$. The exchange rate was 1 USD = Ksh 103.85 on 2 January 2017.

cost ratio (BCR) ranged from 4.6 to 1.7. Net income per labour hour varied from 3.9 to 0.5 USD. The lowest economic performance was recorded from no N-input (control) plots.

GM, BCR and net income per labour hour from the DAP and mixed treatments were similar, but significantly ($p = 0.001$) higher than those of the manure treatment and the control. The most labour intensive soil fertility management strategy was the use of manure, with a labour input of 736 working hours ha^{-1} in both seasons. The control was the least labour intensive, with 607 working hours ha^{-1} in both seasons.

3.7. N_2OI and N_2OEI

The N_2OI for the four soil fertility management strategies varied from a low (mixed) of 0.08 to a maximum (control) of 0.5 g N_2O-N kg^{-1} fresh yields. The mean N_2OI for the DAP, manure, mixed and control treatments were 0.2 ± 0.1, 0.1 ± 0.0, 0.1 ± 0.0 and 0.4 ± 0.3 respectively (Table 7). The N_2OI from the mixed and manure treatments plots were significantly lower compared to that of the control ($p = 0.04$). N_2OI from DAP was similar to those of the other three treatments.

The N_2OEI from the experiment ranged from a minimum (mixed) of 0.5 to a maximum (control) of 3.72 g N_2O-N USD^{-1}. N_2OEI from the control was significantly higher ($p = 0.0001$) than that from the other three treatments, which were alike. The lowest mean N_2OEI was from the mixed treatment (0.6 ± 0.0 g N_2O-N USD^{-1}), while those from DAP, manure and the control were 1.1 ± 0.3; 1.0 ± 0.3 and 3.3 ± 0.6 g N_2O-N USD^{-1} respectively.

Table 7

Nitrous oxide emission intensity (N_2OI) and nitrous oxide emission economic intensity (N_2OEI) for each treatment.

Treatment	N_2OI (g N_2O-N kg^{-1})	N_2OEI (g N_2O-N USD^{-1})
DAP	0.2 ± 0.1ab	1.1 ± 0.3a
Manure	0.1 ± 0.0a	1.0 ± 0.3a
Mixed	0.1 ± 0.0a	0.6 ± 0.0a
Control	0.4 ± 0.3b	3.3 ± 0.6b

Data are the mean of three replicates with standard deviations. Lowercase letters, within columns, indicate significant differences at $p < 0.5$. The exchange rate was 1 USD = Ksh 103.85 on 2 January 2017.

4. Discussion

Greenhouse gas emission intensity (i.e. GHG emissions assessed as a function of crop yield) has become one of the most commonly used metrics for assessing the climate impacts of agricultural practices because it accounts for both negative and positive outcomes from agriculture (Mosier et al., 2006; van Groenigen et al., 2010; Linquist et al., 2012). This measure of efficiency, however, ignores the fact that although crop yields often correlate to economic performance, there are times when they do not. Given that economic performance typically drives farmers' decision-making and adoption of agricultural management practices in many circumstances, an indicator of economic efficiency of emissions was developed and applied for the first time in an *in situ* N_2O gas measurement study to represent more effectively the trade-offs between livelihoods and climate change mitigation.

The results of the present study demonstrate how the choice of indicator could alter the selection of best-fit soil management strategies. When considering N_2O emissions from the four treatments, the highest emissions per unit hectare came from DAP, followed by the mixed treatment, and the lowest from manure and the control. However, after N_2O emissions were expressed as a function of yield (N_2OI), the mixed and manure treatments performed best (*i.e.* had the lowest N_2OI values). It is a different story with N_2OEI, however, because the mixed treatment had the lowest value and so would be the soil fertility management strategy that best optimises economic and environmental performance.

While this is the first study to use N_2OEI in N_2O measurements, other studies have investigated N_2OI in vegetable production. The present findings are 40% (taking an average of 1.5 from the four treatments) higher than N_2O emission levels (0.9 kg N_2O-N ha^{-1} yr^{-1}) reported from two experimental fields of low-input vegetable production in the rural highlands of Kenya (Rosenstock et al., 2016). Higher emissions from our study may be partly attributed to high clay content in the soil of our experimental plots (Table 2) which could contain inherent N supply. However, the present results were approximately 97% and 69% lower than N_2O emissions and average N_2O EF respectively reported from urban vegetable gardens in Niger and Burkina Faso

(Predotova et al., 2010; Lompo et al., 2012). The reason for this difference could be the high N application rates (seven times greater) in addition to higher soil moisture (more than double) from the year-round irrigation of urban vegetable gardens.

In general, the present findings are consistent with previous studies that intensification of crop production potentially reduces the intensity of N_2O emission (Nyamadzawo et al., 2014a; Hickman et al., 2014). This is evident by the lower amounts of N_2OEI and N_2OI from the DAP, manure and mixed treatments compared to the control. Nyamadzawo et al. (2014b) reported reduced N_2OI of up to 55% from fertiliser intensification compared to the control with no fertiliser input, which is in agreement with the present results. Lower emission intensity from these three treatments was mainly due to higher margins and yields compared to the control. The higher margins and yields are probably due to improved nitrogen use efficiency in the DAP, manure and mixed treatments compared to the control.

Despite the lack of significant differences in the amount of N_2OEI and N_2OI between the DAP and mixed treatments (possibly due to high inter-plot variability), the mixed treatment yielded the best economic performance with minimum negative environmental impact, reducing N_2OEI and N_2OI by 45.5% and 50% respectively. However, this was associated with 14%, 20.7% and 15% less economic, yield and returns to labour when compared to those of DAP. The manure treatment had the second lowest environmental impact, but was associated with higher economic (67%) and yield (64%) trade-offs. Therefore, sustainable intensification appears to be achieved by applying nitrogen fertilisers from a mix of organic and inorganic sources. However, farmers are likely to opt for DAP since it offers the greatest economic benefits and has lower labour requirements. The forgone economic benefits (14% economic trade-off) of deciding to use nitrogen fertilisers from a mix of organic and inorganic sources needs to be reduced. This may be done by providing farmers price premiums in market places (*e.g.* supermarkets) for AIV produced with more environmentally sound methods.

This study has shown that intensification can optimise livelihood and climate trade-offs, but these systems still generate emissions. Elevated N_2O emissions were observed, lasting between two and three weeks following N fertilisation and rainfall events. A similar temporal pattern of N_2O emissions has been observed in experimental maize plots and smallholder mixed farming systems in Kenya (Hickman et al., 2014; Pelster et al., 2017). In the present study, N_2O flux rates remained below $15\,\mu g\ N_2O\text{-}N\ m^{-2}\ h^{-1}$ in all the treatments except in periods following N fertilisation and rainfall events when N_2O flux rates were higher from the DAP and mixed treatments. N_2O is emitted from the soil as a result of nitrification and denitrification processes occurring in the soil (Mosier et al., 1998; Robertson and Groffman, 2007). Denitrification is an anaerobic microbial process that is strongly regulated by soil moisture and gaseous diffusion (de Klein et al., 2003) and occurs mostly when soil moisture reaches and exceeds the threshold (60%) (Linn and Doran, 1984). Furthermore, denitrification is strongly controlled by the availability of N and increases with rising N availability (Beauchamp, 1997; Castaldi and Smith, 1998). A significant positive correlation was found between N_2O emissions and soil NO_3^- N, NH_4^+-N and WFPS. Therefore, the low N_2O emissions observed could likely be attributed to limited available N and a low soil moisture content during the present study while the temporal fluctuation in the N_2O flux, particularly from the DAP and mixed treatments, is a function of the combined effects of N fertilisation and rainfall events.

The significantly high seasonal cumulative N_2O emissions from the DAP treatment could be the consequence of high available N in the soil. This is reflected in greater concentrations of NO_3-N in soil samples from DAP than from the other three treatments. It is likely that a fraction of this NO_3-N was absorbed by the plant and used for growth, resulting in greater yields from the DAP treatment. However, another fraction may have remained as soil NO_3-N and been converted to N_2O through the denitrification process, which caused the greater cumulative N_2O emission from the DAP treatment.

Initial immobilisation and the delayed release of N, poor quality of the manure and poor storage methods (1.6% N of dry weight) might also have contributed to the low cumulative N_2O emissions from the mixed and manure treatments. Dick et al. (2008) reported reduced N_2O emissions of up to 58% from a mix of urea, manure and phosphate compared to adjacent soils treated with urea from a continuous cereal and cereal/legume rotation in Mali. The authors also attributed this reduction to the initial immobilisation of N due to the low quality of the manure. A low N content in the manure may be due to poor quality feed. Cattle feed in SSA is usually comprised of native pasture and grasses that have low digestibility and a low N content (Rufino et al., 2006; Castellanos-Navarrete et al., 2015). Feed composition and digestibility affect the C/N ratio in the manure, which may, in turn, affect N_2O emissions (Cardenas et al., 2007).

It is also possible that residual N_2O emissions particularly from manure was not captured during the fallow period (no sampling during fallow period) raising the question whether this resulted to underestimation of cumulative emissions. However, during the fallow period, no or very minimal rainfall was received (Fig. 1). This implies that the soil was dry most of the time which could largely limit microbial processes and emissions as also reported by Chadwick et al. (2011). Further, N_2O fluxes were measured until they reverted back to background emissions in season II and each treatment showed similar temporal pattern as in season I. Also there was minimal difference between N_2O emissions from season I and II from manure treatment. This suggests that residual N_2O emission that might not have been captured during fallow period is negligible and, hence, does not influence cumulative emissions from manure treatment.

5. Conclusions

This study has shown that the inclusion of economic value *versus* just productivity alone may change conclusions around the selection of which soil management practice is the best fit for purpose when wanting to optimise climate and livelihood trade-offs. Although limited in scope, these data provide a first indication of the importance of taking the trade-off analysis one step further to include economic value. It is therefore concluded that soil fertilisation from a mix of organic and inorganic nitrogen fertilisers is a promising agronomic pathway towards achieving optimal combined economic and environmental outcomes from vegetable production in peri-urban Kenya. Future work in this field should consider the limitations of considering productivity alone when trying to reflect the true nature of the trade-offs faced by farmers.

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