Editors comments:

Based on your responses I invite you to submit a revised manuscript, which I will send out for another round of review before taking any decision on its publication. When revising your manuscript please make an effort to carefully adress all the issues raised by the reviewers. I agree with reviewer #1 that it it might be helpful to summarize the criteria you are using to distinguish the land classes and to provide more specific background information. Note that it is possible to add an appendix containing additional information without distracting from the main content of the paper. Reviewer #2 made a strong case for including estimates of flux uncertainties (and their propagation), which should be explicitly accounted for in your revised manuscript. The non-inclusion of peak fluxes (hot moments) and their implications for annual estimates should be discussed in a semi-quantitative way. It would also be helpful if you could take up the suggestion of including an estimate of the errors associated with the temperature changes occurring during the measurements, which could be placed in the methods section. Finally, I encourage you to report on measured negative fluxes of N2O rather than cutting off such data just because they have been rarely reported.

Thank you for your comments. We agree that we need a bit more information on the criteria used for the land classifications and have added these to the manuscript. However, as many of these methods are already published, we do not see the need to add an appendix, instead we refer to these other journal articles for additional information. We also think that it is a good idea to include a bit more information and discussion on the uncertainties and have included this in the methods section and in the discussion. However, although the percent uncertainty may be high, the actual amount of difference that will make for N2O emission estimates is low (i.e. the mean N2O emissions is 0.28 kg N2O-N ha-1 yr-1, so the uncertainty will cause it to range between 0.17 and 0.39 – so even the higher part of the range is still very low). Finally, we have no included the negative fluxes in the analysis now and it has had a negligible effect (most of the negative fluxes were extremely small)

Review of the manuscript “Smallholder African farms in western Kenya have limited greenhouse gas fluxes” by D. E. Pelster et al.
General consideration The paper presents a nice dataset of soil GHG fluxes measured throughout dry and wet season in 59 locations in Kenya. There is no doubt that such measurements are surely missing and are necessary to better calibrate emission factors/ models of C and N cycle and GHG fluxes in tropical areas. What could have been interesting, but was not specifically analysed in the paper, would have been to have a value for background emissions (far from fertilization inputs) and a value of EFs for fertilization events. These might have been compared with IPCC, or other approaches which rely on the two different values (background and EFs). I understand that this paper could be seen as a first step into this direction, especially for what concerns average background fluxes. Less clear from the results is if a more intensive sampling approach is required to really provide reliable EFs and how representative are the presented data of the GHG emissions related to management practices. Maybe some comments on this can be added in the discussion.
Most of the plots did not receive any fertilizer (except for the odd cow / goat / chicken grazing) and so could be considered “background emissions”. Since these did not differ from the fertilized plots (see lines 404-412), we can assume that the emission factor (for the low fertilizer rates) is essentially 0 for the fertilization rates and the fertilizer type applied in these plots. This is also discussed in lines 542-556. We also discuss the uncertainty associated with the sampling frequency and how this may have affected our results (lines 549-551).
Abstract: Comments
A1) It is not clear in the abstract and in the title if the GHG fluxes presented are a net ecosystem

exchange or soil fluxes. It should be specified.
Tall plants (< 10 cm) were excluded from the chambers, some weeds and grasses would be present in the chambers, but these tended to be very short (generally < 5 cm high) and may contribute a bit to the gas fluxes, however with the opaque chambers it is unlikely that there would have been much photosynthesis occurring and therefore what we present likely represents the soil fluxes. This is now clarified in the abstract, title and M&M
A2) Would "pasture plots" be a more suitable definition than "Grazing plots"?
Since the animals actively grazed these plots, we believe it is more appropriate to call these plots "Grazing"
A3) Similarly a treed plot is not an appropriate land cover definition? Agroforestry? Open savannas (grass with some trees)? Orchards? . . .
These were plantations (either Grevillia or eucalyptus), we now clarify both here (line 26) and in the M&M (line 179-180)
A4) page 15302 Lines 18-20: This statement sounds odd. You have just said that emissions are very low, basically these systems are low emitters of GHGs. And this in one fact. The other fact is that crops are not able to take advantage of fertilizer addition as some other factor is limiting. So independently from the global warming the second issue is that production is scarce. And clearly you don't improve it just by pumping on fertilizers. To increase the nutrient use efficiency is really an issue for food security rather than for global warming mitigation here. On the contrary in highly productive systems (polluting systems) which respond fast to fertilizer intensity the two issue are really strongly related and precision farming is a potential solution for GW mitigation.
We believe that the reason why the fertilizer did not cause increased emissions is because the soils are very depleted and the small amount of fertilizer added was utilized immediately by soil microbes, the plants or bound by the soils (and therefore not available for production of N2O). We did not state that other factors limit the use of fertilizers, and the nutrient use efficiency of the crops was not addressed in the manuscript. We still believe that intensification will lead to lower yield scaled emissions and also improve the local food security. There is no room in the abstract however we address this now in the discussion (lines 622-638)

Introduction: general comments The Introduction is well presented and objectives are clear. Table 1 – It might be more interesting to compress the info on time length of measurements in one column (for example 1yr-wkly, or 1 wet season – bewkly) and add a column with infos on the agrosystem type analysed. In Table 1 specify what does the "Flux rate" range, you report, represent. It is not clear. For examples if you have just one site what is the range for? Tot emissions for different crop cycles on the same site? What about when you have more sites? Just specify what are the numbers we are reading.
The ranges are for the different replicates and treatments in the study as it is now mentioned in the table. We have also added what the crop types were for each study.

Materials and methods
Fig 1- the figure as it is doesn't help 1) to localize the study area precisely, 2) to imagine the distribution size of the study area in relation to the geographical location, as no reference is available for the reader in the gray figure except the longitude. I suggest to zoom in the first figure of Kenya to show in which district/town area the star falls (we assume the reader knows Kenya is in Africa), and in the second figure it could be good to have the dots on a google earth kind of background with some reference points clearly shown to help other researchers to immediately identify your study area.
We have altered Figure 1, which now shows that the study site is a little ways SE of Kisumu (see map of Kenya) and then we have adjusted the second half of the figure to show some of the towns and roads in the area.
Comments: MM1) 15305 lines 1-2 – what you mean by "to be broadly representative of

demographics and agro-ecological characteristics of other East African tropical highlands"? demographically speaking? Same average population density?
We have added in a few more details about the representativeness of the site and provided a reference. (lines 100-106)
MM2) 15305 line 3 – Could you specify in which "climatic zone" are the sites (adding the adequate reference)? It helps when categorizations are done in scaling up studies.
We have added the Köppen classification. (line 108)
MM3) 15305 line 16. . .. When you define the soils with a specific classification name, specify which classification system are you using. . .USDA? Other? Cite the reference.
This was FAO and is now cited (line 123)
MM4) Table 2 – In the main text some clarification and better explanation for the brief description given for the 5 land classes is needed. What is moderate size for you? 1 hectar? 10 hectars? What are degradation signs?... How slopy is the slope? Would that contribute to have erosion?...just to understand what are we looking at.
We have added some additional information in the table and in footnotes which address these concerns as well as adding in the specific NDVI metrics that were used to define the different land classes. (lines 143-160)
You need to specify in the legend the soil depth of the analyses you present in Table 2 and the time frame of the presented data? You sampled before starting? I assume C content is total C by CNS? Any calcium carbonate which might give you Tot C > org C? please specify in the column heading if it is total C or organic C.
We now state that we sampled before the gas sampling began. Also, we provide a footnote saying that carbonates were not found in the top 20 cm, so the C content is only organic C.

MM5) page 15307 lines 1-5. I generally do not like to read a paper where the key methodology necessary to understand the meaning of the results requires reading another paper. I think the authors should make an effort to summarize in a comprehensive and transparent way the criteria they are using to distinguish the land classes they will discuss later on and how these sum up to create field types and land classes. Maybe you can add some additional tables where we can see the single parameters and the score they have for each category used to build up the discussed land/field types.
We provide a summary of the criteria in the methods already and have expanded on the discussion to make it more comprehensive and transparent. If the readers still require additional details we believe that an appendix is unnecessary as we provide references on the methods used.
MM6) 2.2 soil core incubation: It is not completely clear to me the procedure you used here, maybe you can explain better at the beginning what are you exactly aiming to before describing the procedure. Drying completely the soil and rewetting it creates a sort of extreme situation where a significant part of the N used by the system can come from the dead organic matter dry-wetting cycle itself. The flux of gas can fade away in a day or more. From the way you describe it you add water, close the jar and measure the efflux at 0, 15, 30 and 45 min. In my experience that flux is not representative of the baseline flux of a site. It is representative of post rain flushes. I understand that in order to increase the WHC you need to start from low WHC, but how do you use the number there after? Are they representative of which soil characteristic or potential, independently from the KNO3 addition?
We were trying to measure the potential for GHG emissions, so we purposely created an "extreme situation" and then measured the emissions. Also, we are not using this to represent baseline flux of a site, but rather just to compare the potential amongst the various sites. We have clarified this in the methods and the discussion. (line 188-192, and lines 557-564)
MM7) 2.3 Field soil GHG flux survey It is not specified the number of chamber replicates you use for each plot. The only time a number is mentioned is when you specified that you pooled gas samples from 4 chambers in one syringe. Does this mean that you had 4 chambers x each site? If

you pool the gas at each sampling time in one sample it means that basically you are measuring just one gas sample per plot? No replicates whatsoever? Spatial or experimental (lab replicates of the same gas sample)?
We had four chambers at each site, which were sampled together following procedure from Arias-Navarro et al 2013, which indeed impedes capturing variability between replicates. We have clarified this and explained why we felt the trade-off (doing this allowed us to sample many more sites) was necessary. (lines 239-251)
MM8) It doesn't seem that the gas sampling pattern follows any specific management practice timetable. Could clarify the rational for this. To clarify what I mean, we know that in particular for N2O, but also for CO2, fluxes of gas occur when something happens (manure or mineral N addition, tillage, crop collection). The flush lasts for a time which can go from few days to some weeks and is proportional to the magnitude of the management practice and soil characteristics. It often makes most of the annual total GHG flux. So to miss the flush means to underestimate the overall crop flux. Isn't this something to take into account when rescaling the magnitude of fluxes in your system? It could be important to have some clarification in the procedure on the relative importance(or irrelevance) of this issue for your system.
We sampled weekly, regardless of management practice. This was done because we were measuring from 59 sites, many of which were difficult to access. Just doing the weekly sampling, still required 4 teams of 2 sampling 4 days per week. This was, by far, the widest range of samples collected in sub-Saharan Africa. As mentioned above though, we have expanded on some of the limitations (as the reviewer mentions above) of doing this in the discussion (e.g. potential for missing peaks, and how this may lead to underestimates).
MM9) 2.6 Environmental data It is not clear for soil moisture and temp how many probes you used? Were they fixed near the climatic stations?
We have added additional information to clarify that we used not only the two weather stations, but also measured soil temperature and moisture at each site, at the time of gas sampling. (see lines 296-308)
MM10) 2.7 Plant production It is not clear what are you doing here. Why are you sampling only 9 plots? Why not 59? What are this only 9 plots for? What are they representative of?
We did not have the capacity to measure all of the sites and so we decided to focus on just the annual crops. We have added some additional information to the methods. (see lines 310-321)
MM11) 15311 line 14. Better use "field"experiment rather than "in vivo", this latter expression is used for biological rather than biogeochemical experiments.
Done.
Results: comments
R1) You are making a statistical comparison among land classes. I don't remember I have seen anywhere specified the number of sites falling in each of the land classes. I assume it is an unbalance statistical design. How much unbalanced? Are some of the classes over represented?
We have added in the N into the methods section. See lines 156-160; lines 172-174; and 179-181.
R2) page 15312 "there were no detectable differences in N2O or CH4 fluxes between crop types" are you considering in this case differences in crop types within each class or independently from the classes?
These were done independently from the samples because the imbalanced design caused too many of the combinations to have too low N values. This is clarified in the methods section. (lines 325-328)
R3) If I understand correctly the field type 1, 2 or 3 combines all the classification scores. Correct? Is it the case that some of the classification scores which build the same field type go into opposite directions in terms of their impact on N2O fluxes?
This is not likely. According to the typology, field type 1 would be the most highly managed (so highest inputs, both fertilizer and carbon), and were found to be the most fertile (see Tittonell et al. 2013 – reference provided in the paper. This is explained in lines 161 to 178.

R4) page 15314 lines 16-19. It would be interested to understand if considering the single sites, the management effect would still be not significant on N2O fluxes, which seem to double in the wet season compared to unmanaged sites.
This is a good point. It is possible that if we used a single site and compared the emissions for fertilized and unfertilized plots, we may see significant differences. There are other studies however that did compare emissions from fertilizer applications at a single site and found very little (or no) difference between fertilized and unfertilized sites. We however were trying to determine if there were landscape variables (e.g. cover type, field type or land class) that had an effect on emissions. This is now briefly discussed in the discussion section. (lines 512-526)

Discussion
D1) 15320 – lines 6-12. Given the very low emissions from these soils, would such a system (cores) be necessary to define management practices, beyond the general criteria used to predict high/low N2O emission potential of agro-sites? (drainage class, C content, fresh C inputs, structure and bulk density, average water content from rainfall or irrigation. . .the usual stuff used in other continents to reason on N2O emissions vs management). Beside, despite the correlation, I assume we cannot predict emissions in the field from emissions from cores, can we?
Correct, we cannot use the incubations to predict field emissions (and we now state this clearly in the discussion). We do think though, that this can still be used to confirm (in a comparative study only), which sites have a higher potential to be hotspots (i.e. we could use the incubations to rank which sites were more likely to have high emissions – and this is why the spearman rank correlation is an effective tool). As suggested, you could also use variable such as BD, water content, C content etc to predict emissions however, we provide here an another alternative for finding hotspots. We briefly mention this in lines 557-561.
D2) page 15321 lines 1-9. I think that the authors should discuss how much influence might have the sampling design on the observed "lack of difference" of GHG emissions among land/field types. GHG emissions and in particular N2O emissions are very spatially and temporally variable. Moreover, in agricultural ecosystem, the budget is strongly linked to any form of N input to the system, with emission peaks following N inputs and requiring intensive analysis after fertilization to avoid missing them. Could the sampling design (time, replicates) have been insufficient to have a complete picture of peak events? Can you discuss this, it is important, it is the drama of each study in agrofields no matter the geographical area. Also, the way the analyses are presented tends to average the fluxes within class blocks derived from your classification system, which includes many parameters a part from fertilization. What happens if we consider only fertilization intensity vs fluxes? Could the sampling design contribute to flatten the results also in this sense?
The classifications that we examined were used because they are supposed to give indications of differences in plant productivity and/or soil fertility that we thought would be related to GHG emissions as well. We sampled 59 different sites, which should be a sufficient number of spatial replicates do differentiate between the different cover types / NDVI land classes / field types. Regarding the temporal variability, given the logistics of sampling 59 sites across a wide area with poor access, we were unable to sample more frequently, however there are a couple of other studies in the region that specifically tested the effects of fertilization and so they sampled more frequently immediately following fertilization events (Hickman et al, 2015 and Rosenstock et al. 2016 – in Press), and neither of them noticed a large N2O peak after applications of N fertilizer at planting (they also used more than 50 kg /ha which was greater than the rates used by the farmers on the plots we measured). Thus we assume that the sampling design was appropriate for our objectives. Unfortunately the farmers either didn't fertilize or fertilized at a very low rate, so I don't think we could consider fertilization intensity. We did examine whether fertilization had any effect during the period of maximum N2O emissions (during the transition from dry to rainy season, and during the period when the farmers applied fertilizer) and found no difference then either. All this is now discussed in the discussion section (lines 512-526)

Comments from referee 2

The paper presents a set of flux measurements measured using traditional chamber methods from an area not well accounted for in current GHG measurement budgets (rural Africa). It is true that data is required from these areas to better account for gas fluxes in the region; however the broad approach and limited number of measurements used in this paper to estimate annual flux values is unlikely to represent well the complexity of the processes occurring at such a large scale. I believe that several of the methods in the paper are flawed and interpolation of the data points is too simplistic to provide reliable tier two annual estimates without large uncertainties, which are missing throughout the study. I would encourage the authors to defend their methodologies and improve upon their uncertainty estimates before publication. Although I have several concerns with the methodology used, the data set may still prove valuable as a starting point to those investigating fluxes in this region. The paper is generally well written with a few grammatical errors creeping in. If the authors can justify their methods and improve on describing uncertainties in their measurements and interpolation of data, then I would consider the manuscript worthy of publishing.

We disagree that this is a limited number of measurements. This study measured emissions from 59 sites for one full year (at weekly intervals). This was an enormous undertaking and one that provides a much greater breadth of information than any previous African study. If you look in Table 1, you will see that there were only 8 previous studies that estimated annual emissions and they measured from less than 4 sites (with the exception of Koerber et al 2009 who measured monthly at 24 sites). In terms of defending our methods, the pooling method is published and is similar to the taking of composite soil samples, which is a very popular method when measuring soil nutrient concentrations. We now provide the estimates of how much the pooling method differed from the unpooled samples (based on the article by Arias-Navarro et al, who measured a difference between the methods of 8 and 4% for CO2 and N2O respectively). We also discuss the methods we used in comparison to the recommendations by Rochette and Eriksen-Hamel (2008) to show that our methods are sound.

Comments:

Introduction

15302 L26 A reference to IPCC values/estimates may be helpful

We reference the Vermeulen paper (2012), which provides a very robust estimate of the contribution of agriculture to global and continental emissions.

P15303 L3 replace 2/3rds with 66 %. All other numbers in the text refer to %

Done

Smallholder farms may account for 80 % land coverage, but do they account for 80 % fertiliser use?

Likely not, but our objective was to focus on smallholder farms, which cover a large area, but are rarely investigated for their role in GHG emissions.

What is the difference between industrial/subsistence farming inputs?

We mention the fertilizer inputs for our plots in lines 115 to 119. We mentioned estimates for industrial agriculture (lines 119-121).

In N2O studies the N (kg ha-1) content of the fertiliser is very important. Without this it is impossible to tell the EF% of the fertiliser events for N2O. 20 Kg ha-1 of manure will have a very small nitrogen content compared to typical European fertiliser applications.

This is true, however we wanted the farmers to use their normal practices, and we were not really interested in calculating emission factors but rather, we were interested in estimating emissions from common practices. Although, as we did not find any difference between fertilized and unfertilized plots though, we can assume there is no emission factor at all, which is consistent

with a couple of other studies in the area that specifically examined the role of fertilizer in N2O emissions (e.g. Hickman et al. 2015, Rosenstock et al. in Press Journal of Geophysical Research – Biogeosciences)

Table 1 Units should be consistent in the table.
The reason for different units is that in some cases there was insufficient information to calculate annual fluxes, in which case we used the cumulative emissions for the period, or the mean rate, depending on what was given in the reference. We highlight this in the table footnote and we have also re-arranged the table into 3 parts and keep the units consistent throughout each section.
There is no mention of the large amount of agricultural goods produced industrially in Kenya. Tea, coffee, cabbages, onions, mangoes etc. . . Although these areas are not covered in the study, the introduction describes Kenya as a sub-Saharan area with low fertiliser input and low productivity. This is not the case across the entire country.
This is true, our main objective was to measure emissions from smallholders, so looking at industrial production is outside the scope of this paper. We instead chose to focus on a much more often neglected potential source of emissions.
Methods
Incubation study
The soil cores were air dried for 2 days at 30 degrees Celsius. Is this to replicate realistic environmental drying conditions or is this beyond what can be considered natural? Removing the cores from the soil and then drying and placing them in jars would change the oxygen content and aeration of the soil significantly (among other physical and biological changes). This would have a serious impact on the gas producing microbiological processes which may nullify the validity of any results obtained using this method. If water was added to the samples in a single step, this does not reflect a rainfall event well and the fluxes measured immediately after will not either. If the soil incubation work is to be included in the article, the method and any assumptions made would need to be better described.
We now state that the incubation study was to compare "potential fluxes", which may not be indicative of the flux rates in the field (see response to reviewer 1)
Field study
Pooling separate air samples from chambers can only reduce representation of spatial variability from the plots. With individual chamber measurements the spatial variability can be assessed statistically (or at least attempted). If GC sampling costs or time were an issue, then decreasing the sample number may have been acceptable; however, in pooling the samples any information on linearity of regression in the individual chambers or spatial variability within the plot is completely lost. Rather than deal with several large sources of uncertainty in scaling the data (spatial variability and regression), using this methodology the uncertainty in the sampling methodology becomes completely incalculable and ignored. Although this method has been published and peer reviewed it is my opinion that it cannot be used to scale fluxes spatially due to large unaccountable uncertainties and possible statistical bias. This method prevents the propagation of any kind of uncertainty in spatial interpolation when calculating cumulative fluxes.
We agree that the pooling results in a loss of on-site variability, however it has been shown that the estimated flux is pretty close (see specific comments below) compared to single chamber measurements. It relies on the same principle used when compositing soil samples for analysis (which is generally accepted). It is therefore the opinion of the authors that this method can be used to scale fluxes as when chambers are sampled individually, and we fail to see how there is a statistical bias that arises from the method. We do lose information regarding the within-site spatial variability, however compromising this information was necessary to be able to sample cross site heterogeneity. Furthermore, the spatial variability is indeed accounted for using true replicates (i.e. different field at different farms), because the within-site variability (i.e. obtained with chambers located at the same plot) doesn´t provide any information beyond the boundaries

of the measured plot.

The assumption that a loss of CO2 represents leaks in the chamber may work in general, but the pooling of samples and the inability to determine which chambers leak, or if the different gases behave differently in each chamber is a real weakness of the method.

It is not perfect, but as shown in the paper by Arias-Navarro it still provides estimates within +-8 and 4% of what is found when sampling the chambers individually, although it is impossible to say which is closer to the true mean as they are both subject to measurement and sampling error. We have added in the accuracy estimates to the M&M (lines 242-245)

Throwing out data with lower values than the precision of the instrument is not good practice. What is the instrumental detection limits for each gas? Is this consistent on a day to day basis or does it change? How is it calculated?

We did not throw out data with values lower than the precision of the sampling method, we rather assumed the flux was equal to 0. This has no effects on the calculation of the cumulative fluxes. The cases where we threw out data were where there was a poor fit, indicating contamination of the sample or leaky chambers. The precision was calculated by calculating the coefficient of variation (calculated for each GC for each day) of the standard gases. If the samples vary less than the standards, we can assume that we are measuring only instrument noise and so the fluxes were assumed to be 0. This interpretation is in agreement with general guidelines for chamber based GHG measurements. E.g. Hutchinson & Livingston (1993) state on page 73: "Estimates if trace gas exchange rates should be ruled valid only when H0 (null hypothesis) is rejected at the preselected significance level; if H0 can not be rejected at the given level of precision of the measurement process, then the best estimate of the exchange rate over the sampling period is zero." Agricultural Ecosystem Effects on Trace Gases and Global Climate Change. Chpater 4 Use of Chamber Systems to Measure Trace Gas Fluxes. Am. Soc. Agron. ASA Special Public. 55

All data should be included and thus the instrumental precision is then un-biased as it is equally positive and negative. In literature CH4 uptake is generally believed and N2O uptake is not. In this paper all N2O fluxes below zero seemed to have been removed while CH4 is allowed (perhaps because it is generally accepted in literature?). This can bias the results. In Figure 2 I see nothing in the CH4 measurements that can prove anything other than instrumental noise is being measured. For N2O it is impossible to tell as the axis has been cut off at zero. Were no negative fluxes of N2O recorded during the study?

The reviewer is correct in that we allowed for uptake of CH4, but not of N2O or CO2 because this is what is generally accepted in the literature. We have now included negative N2O fluxes in the determination of the cumulative fluxes (see earlier comments). Also correct in noticing that the CH4 flux in Fig 2 is likely just instrumental noise

How can detailed regression analysis be used if the chamber samples are already pooled? Each chamber has its own linearity for each gas type depending on conditions.

Pooled samples had the same volume of gas from each chamber, Thus, the linearity of the pooled samples equals the sum of the linearity of the each chamber. For further details we refer to the paper of Arias-Navarro.

How was temperature change accounted for within the chamber? 45 min long chamber times may result in very large temperature changes during the enclosure times, especially during hot days. This can change the physics within the chamber in a way that can affect flux calculations. (Air density, expansion of air, large pressure changes, etc..)

We measured chamber temperature at the start and end of the 45 min deployment and used the mean to calculate the concentrations. We also used insulated chambers covered with reflective tape to minimize temperature changes. In general, the chambers did heat up, which would cause some uncertainty in the calculation of mixing ratios as well as changing the activity of the microbial communities in the soils. This is now mentioned in the methods (lines 229-238).

No uncertainties were calculated for the entire flux process. This is a real weakness in the method which should be addressed if the data is to be published. Any uncertainty in scaling up at the plot

scale is lost in the pooling sample method and no estimate of temporal uncertainty in linear interpolation of the measurements is even discussed.

We had discussed spatial uncertainties and show them in the Figure 4. Regarding the "uncertainty in scaling up", our objective was to examine emissions from typical farming plots, and we had a number of plots that fell into each category, so we were still able to calculate the SD within the field types (or land class or vegetation type), which describes the uncertainty. As stated earlier, investigating the spatial variability at each site was outside of the scope of this paper, so the pooling method was appropriate for our analysis. We understand that we lose information by using the pooling method, however this principle is similar to what has been used for decades in soil sampling (taking composite samples). Moreover it is a published method. The uncertainty associated with sampling and analysis however is now discussed. We have added more information describing how the weekly sampling may miss peaks (particularly for N2O) that cause a lack of accuracy in the estimates, referring to a couple of papers that investigated how much uncertainty is created through weekly sampling. We discuss uncertainties now in lines 631-640.

At the end, all of the plots are averaged out to give a range of uncertainty, but each of these numbers should also have a very large uncertainty associated with it. This number should then propagate through. From the results presented in this paper it is impossible to tell how precise the study has been in its estimates of annual fluxes. Is the method even fit for purpose?

We used well-established and published methods so we do not understand why the reviewer questions whether the method is fit for purpose. According to the paper by Rochette and Eriksen-Hamel (2008) the methods we used were either ranked "good" or "very good" for 15 of the 16 criteria; only the duration of the deployment was "poor" in the ranking (20 – 40 min deployment was good whereas we used a 45 minute deployment). We also report on the range for the cumulative fluxes (lines 424-425) and give the range and percentiles for the cumulative emissions in Fig 4. The weekly sampling could be a problem and could result in either an under or over-estimate of the emissions depending on whether a short-lived peak was captured or missed. As indicated in Barton et al 2015 and Parkin 2008, this will result in uncertainty and this is now discussed in the manuscript (lines 552-556).

Results

Figure 3 No error bars are included in any of the measurements.

We felt that the figure was already "cluttered" and that the addition of error bars would only confuse things further and so we left them out. We still believe that it is the correct decision.

Table 2: should Bulk density have units of mass per volume?

Yes, this has been changed.

More information is required on what the CO2 measurements are actually measuring.

See response to reviewer 1, we are measuring primarily soil respiration as in most of the chambers (grazing plots aside) excluded plants. In the grazing plots, the grass was typically grazed so heavily that they were less than 2 cm high, so we were again likely measuring primarily soil respiration.

Do they contain some plants or just soil? Why measure CO2 from the chambers? What do these measurements tell you?

See above.

The weekly measurements are likely miss peaks in N2O emissions from fertilizer events which can last less than a few days. Any attempt to do a cumulative annual budget for N2O emissions should do more regular measurements at least around fertilization dates.

We agree that this is a potential issue with our methods and briefly discuss it (see response to reviewer 1).

Diurnal effects are not observed due to the manual chamber method being used during the day. Nocturnal emissions will have different temperatures (and light for CO2) which may affect processes in the soil. Differences in night/day fluxes in Africa may differ from those observed in

the more commonly measured areas (Europe etc. . .).
Diurnal patterns in emissions were definitely not observed as they require either automatic chambers (these would require electrical power at the farms, which generally are too remote to have any electricity) or they require people to deploy the chambers multiple times per day/night. This was deemed to be unsafe for the staff and therefore, any investigation into diurnal patterns was considered to be beyond the scope of this study.
Figure 4 Explain what the box plots represent. Quartiles of 59 points?
The boxplot is a standard plot with the mid-line showing the median, the boxes showing the first and third quartile and the "whiskers" extending to the maximum (or minimum) value within the upper (and lower) fence – which is defined as: 1.58 * IQR / sqrt(n). This is roughly equivalent to 95% confidence intervals. We would prefer not to have to explain all of this in the figure caption as we believe it is unnecessary.
Discussion
15321 L15 Assuming that the measurements scale to a continental scale is highly optimistic.
We agree that this is optimistic and have added a bit to state that this requires additional studies. However, we do mention that this only refers to smallholder farms, which often have very low inputs and degraded soils. (see lines 605-608 and 614-617)

# Smallholder farms in western Kenya have limited soil greenhouse gas fluxes

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**Abstract:**

Few field studies examine greenhouse gas (GHG) emissions from African agricultural systems resulting in high uncertainty for national inventories. We provide here the most comprehensive study in Africa to date, examining annual soil $CO_2$, $CH_4$ and $N_2O$ emissions from 59 smallholder plots, across different vegetation types, field types and land classes in western Kenya. The study area consists of a lowland area (approximately 1 200 m asl) rising approximately 600 m to a highland plateau. Cumulative annual fluxes ranged from 2.8 to 15.0 Mg $CO_2$-C $ha^{-1}$, -6.0 to 2.4 kg $CH_4$-C $ha^{-1}$ and -0.1 to 1.8 kg $N_2O$-N $ha^{-1}$. Management intensity of the plots did not result in differences in annual fluxes for the GHGs measured ($P$ = 0.46, 0.67 and 0.14 for $CO_2$, $N_2O$ and $CH_4$ respectively). The similar emissions were likely related to low fertilizer input rates (≤ 20 kg N $ha^{-1}$). Grazing plots had the highest $CO_2$ fluxes ($P$ = 0.005); treed plots (plantations) were a larger $CH_4$ sink than grazing plots ($P$ = 0.05); while $N_2O$ emissions were similar across vegetation types ($P$ = 0.59). This case study is likely representative for low fertilizer input, smallholder systems across sub-Saharan Africa, providing critical data for estimating regional or continental GHG inventories. Low crop yields, likely due to low inputs, resulted in high (up to 67 g $N_2O$-N $kg^{-1}$ aboveground N uptake) yield-scaled emissions. Improving crop production through intensification of agricultural production (i.e. water and nutrient management) may be an important tool to mitigate the impact of African agriculture on climate change.

## 1 Introduction:

Increased atmospheric concentrations of greenhouse gases (GHG: $CO_2$, $N_2O$ and $CH_4$) over the last century have been correlated to increasing mean global temperature (IPCC, 2013), while the $N_2O$ is also the primary ozone-depleting anthropogenically emitted gas (Ravishankara et al., 2009). Globally, agriculture is directly responsible for approximately 14% of anthropogenic GHG emissions while indirect emissions due to conversion of natural landscapes to agricultural systems may contribute an additional 17% (Vermeulen et al., 2012). In less developed countries however,

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agriculture can account for up to 66% of a country or region's total GHG emission (Tubiello et al., 2014), with African GHG emissions from agriculture and other land uses estimated to be 61% of total continental GHG emissions (Valentini et al., 2014).

In parts of the developing world, such as Sub-Saharan Africa (SSA), smallholder farms (farm size < 10 ha) comprise almost 80% of farmland and up to 90% of the farms (Altieri and Koohafkan, 2008). Thus it is likely that smallholder farms have a large effect on the GHG inventories of many Sub-Saharan countries. Unfortunately, there is a dearth of knowledge on agricultural soil GHG emissions from smallholder systems as only a handful of empirical studies (see Table 1) have measured these (e.g. (Baggs et al., 2006; Brümmer et al., 2008; Dick et al., 2006; Predotova et al., 2010). Previous studies in Africa were also limited in scope; measuring emissions from a low number of sites (generally less than 10) for a short time period (i.e. less than one year), often with low temporal resolution. This lack of proper baseline data makes it impossible for many developing countries to accurately assess emissions from soils used for agriculture or to use Tier II methodology, which requires the development and documentation of country specific emission factors, to calculate GHG inventories (IPCC, 2006). Also, because most of the research behind the development of the Tier I methodology has been completed in temperate zones, the differences in climate, soils, and farm management seem to result in consistent overestimates of fluxes (Hickman et al., 2014; Rosenstock et al., 2013b) that likely translate to inflated national agricultural GHG inventories in Africa.

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Soil greenhouse gas emission potentials have been related to many soil properties such as pH (Khan et al., 2011), soil organic carbon (SOC) content (Chantigny et al., 2010), soil texture (Rochette et al., 2008), vegetation (crop) type (Stehfest and Bouwman, 2006) and management operations such as tillage, fertilizer type, crop rotation, amongst others (Baggs et al., 2006; Drury et al., 2006; Grageda-Cabrera et al., 2004; Halvorson et al., 2008; Yamulki and Jarvis, 2002). In contrast to agricultural systems in most OECD (Organisation for Economic Co-operation and Development) states, smallholder farmers differentially allocate resources based on

distance from homestead and perceived soil fertility, specifically manure and fertilizer applications, to their fields resulting in strong gradients in soil fertility (Tittonell et al., 2013). The differences in soil fertility can be predicted using a top-down approach like "Normalized Difference Vegetation Index" (NDVI), which uses remote sensing to determine the magnitude and temporal variability of primary productivity (Paruelo et al., 2001). Differences in fertility can also be predicted using a bottom-up approach using farmer questionnaires to determine how farmers allocate resources to the fields and then using this typology of farming activities (hereafter "field typology") to estimate where soil GHG fluxes would be high. If strong correlations can be demonstrated such fertility gradients may then be upscaled based on either the NDVI or farmer interviews that could allow for effective landscape level predictions based on the field-scale measurements.

The lack of good information on GHG fluxes related to agricultural activities in Africa in general, in Kenya in particular and specifically on smallholder farming systems is a large data gap that needs to be addressed. The objectives of this study were to gather greenhouse gas flux data from smallholder farms of the western Kenyan Highlands that represent both the diversity in farming practices and landscape heterogeneity typically found for many highland regions in East Africa. We hypothesized that a) in view of low rates of fertilizer applications by smallholders the GHG fluxes are generally at the low end of published fluxes from agricultural land, b) the seasonality of hygric seasons is mirrored by fluxes and c) differences in land productivity as reflected by NDVI and field typology, as well as differences in vegetation can be used to explain spatial variability in field-scale soil greenhouse gas fluxes.

## 2 Materials and Methods

The study site was a 10 km x 10 km landscape in Kisumu county of Western Kenya (centered at 35.023E, 0.315S); just north of the town of Sondu (Fig. 1), and ranges from a lowland area at approximately 1200 m asl to a highland plateau at approximately 1800 m asl. The site is one of the sentinel sites for the CGIAR

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**Deleted:** This region was found to be broadly representative of demographics and agro-ecological characteristics of other East African tropical highlands (Braun et al., 1997). The climate is humid with a mean temperature of approximately 23°C and an average annual rainfall of about 1150 mm.

Research Program on Climate Change, Agriculture and Food Security (CCAFS) and is described in much more detail in Sijmons et al. (2013). This site was selected as it was found to be broadly similar in terms of demographics (population density, income, etc) and agro-ecological characteristics (e.g. elevation, temperature, precipitation etc) of other East African tropical highlands (Braun et al., 1997) allowing us to scale up the results to other regions worldwide (Sijmons et al., 2013). Mean annual temperature is approximately 23°C and an average annual rainfall is 1150 mm (Köppen classification of a tropical rainforest climate [AF]). Temperatures tend to be slightly cooler and precipitation slightly higher in the highlands compared to the lower regions of the study site. Precipitation patterns are bimodal with the "long rains" occurring from April to June (42% of annual precipitation) and the "short rains" occurring from October through December (26% of annual precipitation). The site is primarily composed of smallholder farms typically growing maize (*Zea mays*) and sorghum (*Sorghum bicolor*) during the long rains and beans during the short rains. Approximately 27% of farmers applied fertilizers (i.e. manure or synthetic fertilizers) to their plots, although application rates were very low. For manure, application rates were approximately 100 kg manure $ha^{-1}$ while application rates for synthetic fertilizer (two farmers applied diammonium phosphate and one applied urea) were < 50 kg fertilizer $ha^{-1}$ (< 25 kg N $ha^{-1}$). These fertilizer rates are much lower than rates typical for industrial production where application rates often exceed 150 kg N $ha^{-1}$ for maize production.

Soil types in the study area are highly heterogeneous, ranging from well drained, acidic, nitisols in the upper part of the landscape, to eutric and dystric cambisols in mid-altitude areas and poorly drained planosols in the lower parts (IUSS Working Group WRB, 2015). Selected topsoil characteristics for the different land classes identified in the study region are provided in Table 2.

## 2.1 Landscape stratification

Differences in management intensity and vegetation were expected to affect GHG fluxes, and so the landscape was stratified to account for the expected variability. The stratification was based on a mixed method landuse classification combining

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remote sensing and household surveys. For the land classification we followed an approach based on vegetation functioning in terms of the magnitude and the temporal variability of primary productivity (Paruelo et al., 2001). Vegetation primary productivity was assessed through the proxy variable "Normalized Difference Vegetation Index" (NDVI), which allows approximate but widespread characterizations of productivity across space and time and across different ecosystems (Lloyd, 1990; Xiao et al., 2004). We acquired 2001-2012 NDVI data from MODIS (Moderate Resolution Imaging Spectroradiometer). After obtaining the data we selected only those values indicating good to excellent quality conditions (i.e. pixels not covered by clouds, and with a low to intermediate aerosol contamination). Then, we used the program TIMESAT v.3.1. to reconstruct temporal series (Jönsson and Eklundh, 2002).

From the reconstructed temporal series we assessed six functional metrics depicting the magnitude, seasonality and inter-annual variability of productivity. The metrics used were as follows: 1) the mean annual NDVI; 2) the minimum NDVI; 3) the browning rate (rate of NDVI decrease); 4) the peakness of the NDVI; 5) the intra-annual coefficient of variation (CV) of the NDVI; and 6) the inter-annual CV. These metrics allow us to differentiate between land cover types (e.g. cultivated vs. uncultivated) and between different cultivation management approaches (e.g. agroindustrial vs. subsistence) (Baldi et al., 2015). The different elevation bands and soil types resulted in different magnitudes, seasonality and inter-annual variability of productivity with the highlands generally having higher productivity due to the higher rainfall and more fertile soils. We then ran an ISODATA unsupervised classification algorithm (Jensen, 1996), and the resulting spectral classes were aggregated to create patches. After combining minor or sparsely-distributed patches, we ended up with 5 classes, characterized by the following features: 1) lowland subsistence farms with degradation signs (N = 7); 2) lower slopes, moderate sized mixed farms (N = 8); 3) mid slopes, moderate sized, primarily grazing / shrubland (N = 10); 4) upper slopes / highland plateau, mixed farms (N = 22); and 5) mid slopes, moderate sized mixed farms (N = 12).

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We also stratified the plots by field typology using the following variables to define a field type score: 1) crop: this score is the sum of the crops each household is cultivating in one plot; 2) fertilizer use: this score distinguishes organic and inorganic fertilizers; 3) number of subplots: which allows us to capture the spatial and temporal allocation of land to crops, crop mixtures, and combination of annual and perennial crops in intercropping, permanent and seasonal grazing land; 4) location of field: the assumption being that fields close to the homestead receive preferential land management (fertilization, addition of organic amendments, weeding etc) when compared to fields that are far away (Tittonell et al., 2013); and 5) Signs of erosion: fields differing in visible sign of erosion obtained a different score depending on the severity. Plots were scored based on the preceding information and those with a higher score were considered field type 1 (N = 17), those with a low score were considered field type 3 (N = 19) and those intermediate plots were assigned a field type 2 (N = 23). It was assumed that field type 1 was the most highly managed (i.e. more fertilizer /manure additions resulting in higher soil C, etc) and field type 3 the least managed (i.e. none to very low fertilizer additions, degraded, low soil C, etc). For a more detailed description of the stratification process see Rufino et al (2015).

Finally, the plots were also stratified by vegetation (cover) type; treed/bush (generally plantations of either *Grevillia spp* or *Eucalyptus spp*) (N = 7), perennial grasses/grazing (N = 15) and annual cropping (N = 37). Initially, the total number of sample plots was 60 with the number per category based partly on the area covered by each specific land classification/field type/vegetation type combination and partly on logistical constraints (i.e. access). One plot however, was converted into a construction site in late 2013, resulting in only 59 plots being measured for the full year.

## 2.2 Soil core incubation

A soil core incubation study was conducted to examine the effect of soil water content and compare the effects of the different land-classes, field types and cover types on potential soil GHG fluxes; and to test if potentials of soil GHG fluxes under

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standardized conditions in the laboratory mirror differences in annual GHG fluxes at observation sites. Five soil cores were collected from 36 out of 59 plots using a 5 cm long PVC pipe (5.14 cm ID). The cores were left intact and taken back to the lab where they were air-dried (2 d at 30°C). One core from each plot was soaked overnight in water and then freely drained for 2-3 hours and then oven-dried (24h at 105°C) to determine maximum water-holding capacity (WHC). Three replicates of the air dried cores for each plot were then placed into a self-sealing 0.50 L glass jar fitted with a septum at 20°C. Air samples (10 mL) from each jar were collected at 0, 15, 30 and 45 min. The air samples were analyzed immediately for $CO_2$, $CH_4$ and $N_2O$ by gas chromatography on an SRI 8610C gas chromatograph (9' Hayesep D column) fitted with a $^{63}$Ni-electron capture detector for $N_2O$ and a flame ionization detector for $CH_4$ and $CO_2$ (after passing the $CO_2$ through a methanizer). Flow rate for the carrier gas (pure $N_2$) was 20 mL $min^{-1}$. Every fifth sample analyzed on the gas chromatograph was a calibration gas (gases with known $CO_2$, $CH_4$ and $N_2O$ concentrations in synthetic air) and the relation between the peak area from the calibration gas and its concentration was used to determine the $CO_2$, $CH_4$ and $N_2O$ concentrations of the headspace samples. The soil cores were then brought to 25% WHC, left for one hour and then placed in the same jar and the headspace was again sampled and analyzed as above. This was sequentially repeated for the same cores at 35, 55 and 75% WHC. Soil re-wetting is known to result in a flush of nutrients (Birch, 1960) that tends to diminish with subsequent re-wettings. Therefore, for the subsequent re-wettings we also added a dilute $KNO_3$ solution (equivalent to adding 10 mg N $kg^{-1}$ soil).

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### 2.3 Field soil GHG flux survey

At the 59 identified field sites (see above and Fig 1) soil $CO_2$, $N_2O$ and $CH_4$ fluxes were measured weekly starting the week of 12 August 2013 through to 12 August 2014 (one full year including two growing seasons) using non-flowthrough, non-steady state chambers (Rochette, 2011; Sapkota et al., 2014). Given the large number of plots and the difficult access, this required four 2-person crews sampling 4 days per week. Briefly, rectangular (0.35 m x 0.25 m) hard plastic frames were

inserted 0.10 m into the ground. Fields planted with annual crops were ploughed, either using an oxen-pulled plough or by hand, twice during this period, which meant that the bases needed to be removed and then re-installed, however where possible the chamber bases were left undisturbed for the entire period. For fields planted with annual crops, the bases were installed between the rows and were weeded the same week the farmers weeded the rest of the field. The chambers in the grazing and treed plots would have included some vegetation (primarily grasses), but these were kept short (<5 cm long) by the continual grazing by livestock. On each sampling date, an opaque, vented and insulated lid (0.125 m height) covered with reflective tape was tightly fitted to the base (Rochette, 2011). The lid was also fitted with a small fan to ensure proper mixing of the headspace, and air samples (15 mL) were collected from the headspace at 0, 15, 30 and 45 min after deployment, using a syringe through a rubber septum. The air temperature inside the chambers increased during deployment, which may increase soil microbial activity that could cause an overestimate of the flux. Any increase in temperature inside the chambers would also cause some bias in the calculation of mixing ratios, which given the average change in temperature, we estimated this bias to be about 3%.

To increase the number of sites measured while still accounting for the representativeness of flux measurements in view of expected high spatial variability of fluxes at field scale samples were pooled from four replicate chambers (Arias-Navarro et al., 2013) to form a composite air sample of 60 mL. This method has been found to provide flux estimates within 8% and 4% (for $CO_2$ and $N_2O$ respectively) of the estimates calculated by separate sampling, although it is unclear which is the more accurate depiction of the true mean. Also, as noted by Arias-Navarro et al. (2013), this precludes the ability to examine on-site variability, however we believed that given the limitations in our sampling and analytic capacity that the trade-off between on-site variability and sampling a broader range of sites was worthwhile given our aims of characterizing emissions in a way that captured both the diversity in farming practices and landscape heterogeneity typically found for

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many highland regions in East Africa. The first 40 mL of the sample was used to flush 10 mL sealed glass vials through a rubber septum, while the final 20 mL was transferred into the vial to achieve an over-pressure to minimize the risk of contamination by ambient air. The gas samples were analyzed within 10 d of sample collection as described for the soil cores above.

### 2.4 Calculation of soil GHG fluxes

Soil fluxes were calculated by the rate of change in concentration over time in the chamber headspace (corrected for mean chamber temperature and air pressure) for both the soil core incubation and the field survey. We validated the data for each chamber/incubation jar measurement by examining the $CO_2$ concentrations over the 45 minutes. Chambers that experienced a decrease in $CO_2$ greater than 10% between any of the measurement times were assumed to have a leak and when possible, only the final measurement was thrown out. In cases where the change in concentration was lower than the precision of the instrument, we assumed zero flux. Also, negative fluxes for $CO_2$, while negative $CH_4$ and N2O fluxes were accepted, as uptake of either in upland soils is feasible. In general, non-linear models are less biased than linear models however they also tend to be very sensitive to outliers (Rochette, 2011). Therefore, when there was a strong correlation for the non-linear model ($R^2 > 0.95$) we used a second-order polynomial; otherwise, we used a linear model. If however the $R^2 < 0.95$ for the non-linear model and <0.64 for the linear model, we assumed there was no valid flux measurement and the data point was thrown out. Cumulative annual fluxes were estimated for the field plots using trapezoidal integration between sampling dates.

### 2.5 Soil analysis

At the beginning of the experiment and for each sampled site, five replicate soil samples were taken both at 0-5 cm and 5-20 cm depths with the aid of a stainless steel corer (40 mm inner diameter). Samples were individually placed in labelled zip-lock bags. All soil material was oven-dried at 40°C for a week with large clumps being progressively broken by hand. Carbon and nitrogen concentrations were determined on micro-milled powdered samples using an elemental combustion

system (Costech International S.p.A., Milano, Italy) fitted with a zero-blank auto-sampler. Soil pH was measured in a 2:1 water:soil solution. Soil texture was determined gravimetrically as described by (van Reeuwijk, 2002).

In addition soil samples were collected periodically (every 2 months) for determination of inorganic N concentrations. Briefly, the topsoil (0-10 cm depth) was collected using a soil auger. Three samples from each plot were collected and placed into a plastic self-locking bag to form one composite sample. These were taken back to the lab and stored (4° C) for less than one week before extraction (1:5 soil:solution w:v ratio) with 2*M* KCl. Extracts were kept frozen until analyzed. Analysis for $NO_3$-N was done via reduction with vanadium, development of colour (540 nm) using sulfanilic acid and naphtylethylendiamin and measurement of adsorption of light on an Epoch microplate spectrophotometer (BioTek, Winooski, VT, USA). The $NH_4$-N concentrations were measured using the green indophenol method (660 nm) using the same spectrophotomer (Bolleter et al., 1961).

## 2.6 Environmental data

Environmental data were collected at two sites, one in the uplands (S 0.35156°, E 35.05590°, 1676 m asl) and the other in the lowlands (S 0.30847°, E 34.98769°, 1226 m asl). Each of the two weather stations was installed at a farm where we also measured gas emissions. Air temperature was measured using a Decagon ECT air temperature sensor (measurement every 5 minutes), while precipitation data were collected with a Decagon ECRN-100 high resolution, double-spoon tipping bucket rain gauge. Soil moisture and temperature were measured using a Decagon MPS-2 Water potential and temperature sensor (Decagon Devices, Pullman, WA, USA). Data were logged on a Decagon Em50 data collection system and downloaded periodically (typically monthly). Also, air temperature, soil temperature and soil moisture (5 cm depth) were measured at each site, at the time of gas sampling using a ProCheck handheld datalogger outfitted with a GS3 sensor (Decagon Devices, Pullman, WA, USA).

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## 2.7 Plant production

To estimate crop yields and crop N content of annual crops in the region, we randomly selected 9 of the annual cropping plots (4 plots with maize, 4 with sorghum and 1 with green grams [*Vigna radiata*]) where we measured gas fluxes. In June 2013, all the plants within a 2.5 m x 2.5 m square near the center of the field (i.e. to avoid edge effects) were harvested and the grains were removed from the plant; both the stover and grains were dried for 48 hours at 60°C and then weighed. A sub-sample of the grains was then ground and analyzed for C and N content on the same Costech elemental combustion system described above for soil analysis. Yield-scaled GHG emissions (g $N_2O$-N $kg^{-1}$ above ground N uptake) were calculated for each site by dividing the cumulative emissions for the growing season by the grain yields. No estimate of crop yields (or yield-scaled emissions) was done for the second growing season.

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## 2.8 Statistical analysis

For the soil core incubation study, the flux rates for $CH_4$, $CO_2$ and $N_2O$ were compared using ANOVA (AOV in RStudio v. 0.98.953), using the WHC as blocks and cover type, land class, and field type as fixed factors. Because of the imbalanced design, we could not analyze interactions as several combinations had an insufficient number of samples so each of the factors was analyzed independently of the others. When $P < 0.1$, differences between treatments were analyzed using Tukey's HSD. Correlations between maximum flux rates for the intact soil core incubations and total cumulative fluxes for the field measurements were tested using Spearman Rank Correlation, while correlations between GHG fluxes and soil properties were tested using Pearson Correlation. The cumulative field fluxes for a 4-week period during the dry season were compared to cumulative fluxes for a 4-week period during the rainy season using ANOVA, with the season, management practices (ploughed versus not ploughed for $CO_2$ and fertilized versus not fertilized for $N_2O$) as fixed factors along with the two-way interaction terms. Cumulative field annual fluxes were compared with ANOVA using an un-balanced design and cover type, land class and field type as fixed factors. In all cases, the distributions of flux

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measurements were tested for normality using Shapiro-Wilks. Only cumulative $N_2O$ fluxes were not normally distributed and were transformed using the natural log.

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# 3 Results

## 3.1 Soil core incubation

For the laboratory incubations, there was very little $CO_2$ efflux (maximum of 7.5 mg $CO_2$-C $m^{-2}$ $h^{-1}$) when the soils were air-dried, with increased soil respiration only at higher water contents (Fig. 2). For the five investigated soil moisture levels (air dried, 25, 35, 55 and 75% WHC) soil respiration tended to be highest at 55% WHC (Figs. 2, 3 and 4) and was positively correlated with the soil C and N content (r=0.33, $P$ = 0.005 and r=0.35, $P$ =0.003 respectively). The $N_2O$ fluxes were very low when the water content was less than or equal to 35% WHC and increased exponentially when the water content was increased to 55 and 75% (Fig. 2) and were also positively correlated with total C and N (r = 0.24, $P$ = 0.043 and r = 0.31, $P$ = 0.010 respectively). The soil $CH_4$ fluxes (mostly uptake) were generally low, ranging from -20 to 20 µg $CH_4$-C $m^{-2}$ $h^{-1}$ and unlike the previous two GHGs, there were similar flux rates between the three moderate water contents, while there were much lower fluxes at the lowest and highest water contents (Fig 2). Unlike $N_2O$ and $CO_2$ fluxes, $CH_4$ fluxes were not correlated with soil C and N contents.

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Both the $CO_2$ and the $N_2O$ fluxes differed by land class ($P$ = 0.001 and 0.061 respectively) with land class 1 (lowland farms with degraded soils) having lower $CO_2$ fluxes than classes 4 (mid-slope farms and shrub land) and 5 (lowland pasture), while landclass 4 had higher $N_2O$ fluxes than either class 1 or 2 (highland farms) (Fig. 2). As shown in Table 2, land class 1 and 2 also had the lowest soil C and N contents. Grass and grazing plots emitted more $CO_2$ than annual plots ($P$ = 0.069), while there were no detectable differences in $N_2O$ or $CH_4$ fluxes between vegetation types ($P$ = 0.603 and 0.457 respectively). Field type had no detectable difference on $CO_2$, $N_2O$ or $CH_4$ fluxes ($P$ = 0.179, 0.109, and 0.198 respectively).

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### 3.2 Field meteorological and site observations

For the *in situ* experiments, the soils were slightly acidic to circum-neutral, ranging in pH from 4.4 to 7.5 (mean = 6.0), with C and N contents ranging from 0.7 to 4.0% (mean = 2.2) and 0.07 to 0.33% (mean = 0.17) respectively (Table 2). The C/N ratio ranged from 7.7 to 18.1 (mean = 12.6) while the C and N contents in the top 20 cm of soil were highly correlated with each other (R = 0.976; $P < 0.0001$). Annual precipitation (15 August 2013 through 14 August 2014) in the lowlands was 1127 mm while there was 1417 mm of precipitation in the highlands, a 25% increase across the 450 m elevation difference between the two stations. The average minimum and maximum daily temperatures in the lowlands were 15.6 and 30.5°C while temperatures were slightly cooler in the highlands, with an average minimum of 12.6 and an average maximum of 26.9°C. Comparing the precipitation at the sites to a long-term 40-year (1960 to 2000) precipitation data set for the two nearby towns of Kisumu and Kericho (data available at africaopendata.org), we see that annual precipitation was within 10% of the long term average. The monthly rainfalls as well were generally similar to long-term trends as well, with the exception of the rainfall in December, which was 26% of the long-term average, and the rainfall in March, which was 2.4 x the long-term mean

### 3.3 Field scale soil GHG fluxes

Soil $CO_2$ fluxes during August 2013 ranged from 50 to 200 mg $CO_2$-C $h^{-1}$ $m^{-2}$, slowly decreased through to November and remained low (< 100 mg $CO_2$-C $h^{-1}$ $m^{-2}$) until the onset of the long rains during March/April 2014 (Fig. 3). The onset of the long rains increased the soil water content from an average of 0.09 $m^3$ $m^{-3}$ for the week of 3 March 2014 to an average of 0.31 $m^3$ $m^{-3}$ two weeks later (17 March 2014). Within two weeks of this increase in soil moisture, the $CO_2$ fluxes began to increase, reaching a maximum on 14 April 2014 (mean = 189 mg $CO_2$-C $h^{-1}$ $m^{-2}$; Fig. 3).

In general, soil $CH_4$ fluxes were negative indicating net uptake. Uptake rates tended to stay between 0 and 100 µg $CH_4$-C $h^{-1}$ $m^{-2}$ from August 2013 until April 2014, after which the variability decreased varying between 0 and 50 µg $CH_4$-C $h^{-1}$ $m^{-2}$ (Fig. 3). Soil $N_2O$ fluxes were low (generally < 10 µg $N_2O$-N $h^{-1}$ $m^{-2}$) for most of the year; with

fluxes increasing from a mean of 1.6 μg $N_2O$-N $h^{-1}$ $m^{-2}$ for the period from October 2013 to March 2014 to a mean of 10.5 μg $N_2O$-N $h^{-1}$ $m^{-2}$ for the 6-week period just after soil re-wetting in March/April 2014. The inorganic N concentrations in the top 10 cm of soil (approximately 85% N-$NO_3$ and 15% N-$NH_4$) generally remained below 20 mg N $kg^{-1}$ soil, although concentrations did increase to around 30 mg N $kg^{-1}$ soil in late December 2013 / early January 2014, shortly after the annual crops planted during the short rains were harvested but before the onset of the long rains in late March / early April 2014.

A comparison of the cumulative fluxes from four weeks in February (end of the dry season) to four weeks in April (immediately following the start of the rainy season) shows greater cumulative $CO_2$ and $N_2O$ fluxes during the wet season, but no difference in $CH_4$ fluxes (Table 3). This increase in $CO_2$ and $N_2O$ fluxes during the onset of the long rains coincided with farmers ploughing their fields and planting and fertilizing their annual crops. However, even though the increase in $CO_2$ and $N_2O$ fluxes was slightly larger in the managed plots (ploughed for $CO_2$ and fertilized for $N_2O$ comparisons), neither of these management interventions significantly altered emission rates (Table 3).

Cumulative annual fluxes ranged from 2.8 to 15.0 Mg $CO_2$-C $ha^{-1}$, -6.0 to 2.4 kg $CH_4$-C $ha^{-1}$ and -0.1 to 1.8 kg $N_2O$-N $ha^{-1}$. There was no detectable effect on cumulative $CO_2$ fluxes by field type or land class ($P$ = 0.46 and 0.19 respectively; Fig. 4), although grazed plots emitted more $CO_2$ than either annual cropland or treed plots ($P$ = 0.005). Cumulative annual $N_2O$ fluxes also did not differ by either field type or vegetation type ($P$ = 0.67 and 0.59 respectively; Fig. 4), however land class did significantly affect $N_2O$ fluxes ($P$ = 0.09; Fig 4) with the flux from land class 3 (mid-slopes, grazing) higher than the flux from land class 4 (upper slopes, mixed farms). Cumulative annual $CH_4$ fluxes were predominately negative, indicating $CH_4$ uptake. Cumulative $CH_4$ uptake rates, unlike $N_2O$ and $CO_2$, varied by land class ($P$ = 0.01) and land cover type ($P$ = 0.01), but not by field type ($P$ = 0.16; Fig. 4). Uptake of atmospheric $CH_4$ by soils was greatest in land class 2 (lower slopes, degraded),

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greater than classes 1 (lowland farms with degraded soils) or 3 (mid-slopes grazing land; Fig. 4). Uptake was also almost 3x greater in treed plots versus those plots with grasses and or those used for grazing (Fig. 4). The difference seems to be primarily due to one grazing plot that was a $CH_4$ source for 14 of 24 sampling dates (sink for only 4 of 24 sampling dates) between 5 August 2013 and 10 February 2014. This same plot also had the second highest cumulative $N_2O$ fluxes (1.5 kg $N_2O$-N $ha^{-1}$ $yr^{-1}$), however the $CO_2$ fluxes were average (7.2 Mg $CO_2$-C $ha^{-1}$ $yr^{-1}$) and the soil organic C and N contents were relatively low (1.2 and 0.10% for C and N respectively) compared to the rest of the plots (Table 2).

Both the soil C and N content were correlated with cumulative $CO_2$ fluxes (r = 0.411; $P$ = 0.002 and r = 0.435; $P$ < 0.001, for C and N content respectively). However, the C and N content were not correlated with either the cumulative $N_2O$ fluxes ($P$ = 0.321 and 0.365 for C and N respectively) or the cumulative $CH_4$ fluxes ($P$ = 0.188 and 0.312 for C and N respectively). The cumulative $CO_2$ and $N_2O$ fluxes were also not correlated ($P$ = 0.188)

Many of the farmers within the study site complained that the annual crops planted in March 2013 failed due to the poor timing of the rains. Within the 9 fields that we measured, the crop yields ranged from 100 to 300 kg $ha^{-1}$ for maize (n = 4), from 140 to 740 kg $ha^{-1}$ for sorghum (n = 4) and were approximately 20 kg $ha^{-1}$ for mung beans (*Vigna radiata*) (n = 1) during the long rain season (March through June). The low yields resulted in yield-scaled soil $N_2O$ fluxes of up to 67 g $N_2O$-N $kg^{-1}$ aboveground N uptake.

The maximum $N_2O$ fluxes as observed within our soil core study were correlated with the cumulative annual fluxes as observed at the field sites ($\rho$ = 0.399, $P$ = 0.040), while $CO_2$ fluxes followed a similar trend ($\rho$ = 0.349, $P$ = 0.075), however the $CH_4$ fluxes from the soil cores were not correlated with measured flux at the field sites ($\rho$ = -0.145, $P$ = 0.471).

## 4 Discussion

The $CO_2$ fluxes were seasonal, and it was thought that management events, such as ploughing fields or fertilizer applications, would affect the flux rates throughout the year. However, during the commencement of the rainy season in March 2014, which coincided with tilling, the ploughed fields did not show significant increases in soil respiration rates beyond the enhancement in soil $CO_2$ flux due to re-wetting that was also measured in untilled fields. Increased soil respiration due to ploughing however are short-term, usually lasting less than 24 hours (Ellert and Janzen, 1999; Reicosky et al., 2005), so because the chambers needed to be removed before ploughing and were not re-installed until sites were re-visited a week later, the ploughing-induced increase in soil respiration was probably not fully captured. Also, root respiration, which at seeding accounts for 0% of soil $CO_2$ fluxes but can increase to around 45% of fluxes (Rochette et al., 1999), may also result in greater $CO_2$ fluxes during the growing season for the annual cropping systems. However, the increase in soil $CO_2$ fluxes from dry to growing season in annual crops was similar to the increase experienced in the other vegetation types (Table 3; $P = 0.39$). It is therefore likely that the low yields for the annual crops corresponded with poor root growth and low root respiration rates.

Soil $CO_2$ fluxes showed cumulative fluxes, (2.7 to 14.0 Mg $CO_2$-C $ha^{-1}$ $yr^{-1}$), well within the range of other African studies (Table 1) and were not related to land class or field type, although the higher soil respiration rates from grazing land was inconsistent with a previous study that found similar rates between perennial tropical grasslands, croplands and tree plantations (Mapanda et al., 2010). However, because we did not differentiate between root and microbial respiration it could be that the continual vegetation cover in the grazing plots contributed more root respiration over the year than was found in the annual crops and treed plots.

Methane was generally taken up by these upland soils, however these rates also varied through the year (Fig. 5b). During August 2013, the soils were sinks for $CH_4$, however as the soils dried, the emission / uptake rates became more erratic until

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the long rains started again in late March 2014. The $CH_4$ flux at the soil surface is the result of the balance between production and consumption (Le Mer and Roger, 2001), so the low rates of atmospheric $CH_4$ uptake during the long rains may be caused by greater soil $CH_4$ production due to higher soil moisture and anaerobic conditions at depth (e.g. (Butterbach-Bahl and Papen, 2002) overriding the existing methanotropic activity.

The $CH_4$ uptake from these sites were consistent with previous studies in upland agricultural soils and indicate that soils of smallholder farms are sinks for atmospheric $CH_4$ (Le Mer and Roger, 2001). There were no differences between field types, but regarding cover types, grazing plots took up less $CH_4$ than treed plots and land class 1 took up less than land class 2 (Fig. 4). The difference between cover types is consistent with previous studies that found that forest soils were greater $CH_4$ sinks than agricultural soils (MacDonald et al., 1996; Priemé and Christensen, 1999) and high degrees of degradation in land class 1 was likely responsible for reduced $CH_4$ oxidation rates

The $N_2O$ flux rates remained below 20 μg $m^{-2}$ $h^{-1}$ with the exception of the onset of the rainy season in March 2014 (Fig. 4). According to Linn and Doran (1984) maximum aerobic activity occurs at approximately 60% water filled pore space (approximately 40% WHC for our study), above which anaerobic processes such as denitrification can occur. The soils in the study area were typically drier than this threshold suggesting that $N_2O$ fluxes were limited by a lack of anaerobic conditions and that the increase in soil water content was responsible for the increases in $N_2O$ fluxes during March 2014. However, soil moisture was greater than 35% WHC during September/October 2013 and March 2014, but it was only in the latter period large increases in $N_2O$ fluxes were observed. The high amounts of soil moisture in March coincided with an increase in inorganic N likely caused by drying and rewetting (Birch, 1960), which can also stimulate $N_2O$ fluxes (Butterbach-Bahl et al., 2004; Davidson, 1992; Ruser et al., 2006). Commencement of the rainy season was also when farmers fertilized, although application rates were low (1-25 kg N ha-

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**Deleted:** the drying–rewetting cycle (Birch, 1960). The stimulation of $N_2O$ fluxes during drying-rewetting cycles is also documented in previous studies (Butterbach-Bahl et al., 2004; Davidson, 1992; Ruser et al., 2006) However, commencement of the rainy season was also when farmers applied fertilizers. Fertilizer applications though, were low (1-20 kg N $ha^{-1}$) and were did not have a detectable affect on soil $NO_3$, $NH_4$ or total inorganic N concentrations ($P$ = 0.384, 0.113 and 0.984 respectively). There was however, higher soil inorganic N concentrations at the start of the re-wetting period, (Fig. 5), confirming the release of $NO_3$ and $NH_4$ due to the rewetting of the soils.

$^{1}$) and did not have a detectable effect on soil inorganic N concentrations, or $N_2O$ emissions (Table 3)

The inability to discern between fertilized and unfertilized plots suggests that the differences in soil fertility and primary productivity were too low to have a noticeable effect on GHG emissions. Alternatively, it is also possible that the sensitivity of the monitoring approach was not enough to catch differences between fields. For instance, the fixed sampling frequency may have caused to miss some short-lasting emission peaks following fertilization, resulting in an underestimation of cumulative emissions. However, sampling during a "hot moment" would result in an overestimate of emissions due to incorrect extrapolations. Previous studies have found that weekly sampling resulted in an average uncertainty of ± 30% of the "best estimate" (Barton et al., 2015; Parkin, 2008) and that this uncertainty changes with the coefficient of variation in measured emission rates. However, the fertilizer was applied at a low rate (< 25 kg N $ha^{-1}$). Application of synthetic fertilizers up to 70 kg N $ha^{-1}$ at planting in the region had no detectable effect on annual $N_2O$ emissions (Hickman et al., 2015) suggesting that our weekly sampling did not miss relevant $N_2O$ /GHG pulses.

There was a much larger response to re-wetting in land class 3 (mid-slopes, grazing land; Fig. 5) compared to land class 4 (upper slopes/plateau, mixed farms), which was primarily due to two (of 10) plots, both located on the same farm that emitted around 4 to 6 times more $N_2O$ than the rest of the landclass 3 plots and 15 to 23 times more $N_2O$ than the average for all other plots. The reason for the much higher fluxes after the re-wetting compared to other sites is not yet understood as the topsoil C and N contents were 1.45 and 0.12% respectively, well within the range of values for that land class (Table 2). The presence of $N_2O$ emission hotspots are quite common though as denitrification activity can vary dramatically across small scales (Parkin, 1987).

Annual $N_2O$ fluxes, were low (<0.6 kg N $ha^{-1}$ $y^{-1}$) when compared with fertilized field in Brazil (Piva et al., 2014) or China (Chen et al., 2000), with fluxes up to 4.3 kg $N_2O$-

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**Deleted:** pH was 6.3 and bulk density was 1.09 g $cm^{-3}$; all of which were well within the range of values for that land class (Table 2). The presence of $N_2O$ emission hotspots are quite common though as denitrification activity can vary dramatically across very small scales (Parkin, 1987). However, we used the gas pooling technique (Arias-Navarro et al., 2013), which should have reduced small-scale flux variability.

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**Deleted:** The soil core incubations and field studies were consistent in that, contrary to expectations, there were no detectable differences in GHG fluxes between the different field types. We had expected differences in fluxes because a previous study in the same region indicated that there were differences in input use, food production, partial N and C balances and soil fertility (Tittonell et al., 2013); and these variables often affect soil GHG fluxes (Buchkina et al., 2012; Jäger et al., 2011). However, differences between field types in total soil C and N were only important when considering each farm individually (Tittonell et al., 2013), which, in our study, may have resulted in greater within-type variation that masked differences between the field types. ... [2]

N $ha^{-1}$ $y^{-1}$. However our results were similar to previous studies in low input African agro-ecosystems (Table 1). The low cumulative fluxes were most likely a result of low substrate (inorganic N) availability, in addition to low soil moisture limiting denitrification through much of the year. Similar to the $CO_2$ fluxes, the cumulative $N_2O$ fluxes did not differ by cover type, field type or by land class. However, it is possible that differences between the classes could be too small to detect given the low cumulative $N_2O$ fluxes, high microsite variability typical of $N_2O$ fluxes (Parkin, 1987) and weekly sampling (Barton et al., 2015; Parkin, 2008).

There are additional sources of uncertainty associated with the sampling methods (chamber architecture, instrumentation sensitivity, etc). To minimize this uncertainty, we used methods that were ranked as either "good" or "very good" for 15 of the 16 criteria selected by Rochette and Eriksen-Hamel (2008), with only the deployment time exceeding the recommended time by about 10%. According to Levy et al. (2011), the uncertainty of the methods then would be about 20%, which when combined with the uncertainty around the weekly sampling would be about 50%. Although this may sound high, this is similar to the majority of other studies (e.g. see Helgason et al. (2005)) measuring GHG emissions and better than many of the studies so far in Africa (Table 1).

Soil core incubations do not reflect site conditions and should not be used to predict baseline emissions on the field. Still, the rankings for the maximum soil core $N_2O$ and $CO_2$ fluxes were correlated with in-situ cumulative annual fluxes indicating that, they can be used as a quick and relatively inexpensive method to determine which sites have a higher likelihood of being emission hotspots. On the contrary, 5 cm long soil cores were probably too short to properly capture the activity of methanotrophic bacteria (Butterbach-Bahl and Papen, 2002), which is a requisite to infer net $CH_4$ soil-atmosphere exchange rates.

Both the soil core incubations and field studies showed no detectable differences in GHG fluxes between the different field types, contrary to our expectations. We had anticipated differences in GHG fluxes because of differences among field types in

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**Deleted:** a significant amount of the variability in soil $CO_2$ fluxes in agro-ecosystems can be explained by NDVI (Sánchez et al., 2003) and crop type (Mapanda et al., 2010) we expected that both land class, which was based on NDVI, and cover type would also have significant effects on soil $CO_2$ fluxes. However, annual soil $CO_2$ fluxes were not related to land class or field type ($P$ = 0.229 and 0.540 respectively; Fig. 4), although the cumulative fluxes, (2.7 to 14.0 Mg $CO_2$-C $ha^{-1}$ $yr^{-1}$), were well within the range determined for other African studies (Table 1). Higher soil respiration rates from grazing land was inconsistent with a previous study that found similar rates between rain-fed perennial tropical grasslands, croplands and eucalyptus plantations in Zimbabwe (Mapanda et al., 2010). However, because we did not differentiate between root and microbial respiration it could be that the continual vegetation cover contributed more root respiration over the year than was found in the annual crops and treed plots. ... [3]

input use, food production, partial N and C balances and soil fertility as previously reported in the region (Tittonell et al., 2013); and these variables often affect soil GHG fluxes (Buchkina et al., 2012; Jäger et al., 2011). We further hypothesized that land class and cover type would also have significant effects on soil $CO_2$ fluxes since a significant amount of the variability in soil $CO_2$ fluxes in agro-ecosystems can be explained by NDVI (Sánchez et al., 2003) and cover type (Mapanda et al., 2010), while differences in NDVI also indicate differences in primary productivity (Xiao et al., 2004). We found however no clear effect of field or land type on soil GHG fluxes. Tittonell et al. (2013) reported important differences between field types only at each farm individually (Tittonell et al., 2013), which in our case, may have resulted in greater within-type variation that masked differences between the field types. Moreover, the small differences in the degree of inputs and labour may have not been enough to provoke distinct GHG fluxes, because the whole region/study site is characterized by low nutrient availability. For example, manure inputs have previously been found to increase soil C content (Maillard and Angers, 2014), but the inputs in our study area were very low (4-6 wheelbarrow loads or approximately 100 kg C $ha^{-1}$) and probably not enough to cause field-level differences. Further, considering that a previous study found that N is being rapidly mined from soils in the Lake Victoria basin (Zhou et al., 2014), it is likely that soil C is also being lost across the landscape. As most of this area has been converted from natural forests, and forests generally have higher SOC stocks than croplands (Guo and Gifford, 2002), time since conversion could play a larger part in determining the SOC content, which could mask any effects that management activities have on soil respiration rates in these low input systems.

Crop yields from the annual cropping systems (100 – 750 kg $ha^{-1}$ for one growing season) were lower than the range (600 to 2800 kg $ha^{-1}$) for rain-fed smallholder farms previous reported across SSA (Sanchez et al., 2009). The farmers complained of poor timing of the rains that caused lower yields than normal. However, the results of the two studies suggest that low yields are common within this region. Increased nutrient inputs and water management are likely required to increase

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**Moved up [1]:** However our results were similar to previous studies in low input African agro-ecosystems (Table 1).

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**Moved up [2]:** Similar to the $CO_2$ fluxes, the cumulative $N_2O$ fluxes did not differ by cover type, field type or by land class.

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**Deleted:** However, it is possible that differences between the classes could be too small to detect given the low cumulative $N_2O$ fluxes and high microsite variability typical of $N_2O$ fluxes (Parkin, 1987). This study was completed to gain an an understanding of GHG flux rates from smallholder farms in East Africa and determine if there is an easy way to stratify the landscape to enable upscaling to national and regional scales. We had expected differences between the different field types due to the differences in soil fertility found by Tittonell et al. (2005) . Separate NDVI classes as well, typically indicate differences in primary productivity (Xiao et al., 2004), which was also expected to result in differences in GHG fluxes. While there were some differences between the land classes and the crop types for the soil cores, differences were not detected in the field plots suggesting that although there may be the potential for greater fluxes from certain land classes, these may not express themselves in the field due to other factors such as water content(Barton et al., 2015; Parkin, 2008).

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yields (Quiñones et al., 1997), which may result in increased GHG fluxes. However, it is expected that increases in GHG fluxes will be lower than the corresponding increase in crop yields following addition of nutrients (Dick et al., 2008), thus resulting in lower GHG intensities. The mean yield scaled fluxes calculated for the eight maize and sorghum sub-samples was 26.6 g $N_2O$-N $kg^{-1}$ above-ground N uptake (range = 2.9 to 67.0), approximately three times higher than the 8.4 g $N_2O$-N $kg^{-1}$ above-ground N uptake for plots fertilized at 180 – 190 kg N $ha^{-1}$ in a European meta-analysis (van Groenigen et al., 2010). These data suggest that intensification and N fertilization along with improved agronomic performance through better nutrient, water management in East Africa has a strong potential to lower yield-scaled fluxes from smallholder farms in SSA.

## 5 CONCLUSION

This study indicates that GHG fluxes from low-input, rain-fed agriculture in western Kenya are lower than fluxes from other agricultural systems with greater management intensities (e.g. sub-tropical systems in China and Latin America). The input intensity for these farming systems is currently low, and so GHG fluxes were not related to management activities at the farm level. Given that this type of smallholder, low-input farming is very common across SSA, it is likely that our findings are valid at a much wider scale, although additional studies are required to confirm this hypothesis. However, even though absolute emissions were low, high yield-scaled GHG fluxes in western Kenya could be reduced through interventions to increase yields (e.g. increased fertilizer, improved soil and water management). As far as we know, this study provides the most comprehensive estimate of GHG emissions from smallholder African farms, in terms of number of sites, monitoring duration and temporal frequency of the measurements. However, more studies are needed to capture annual variability as well as examining baseline emissions in other regions of the continent. These baseline studies are required to compare with proposed low emission development strategies to ensure that improvements in

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**Deleted:** This type of production system is the predominant agricultural production system in sub-Saharan Africa, suggesting that our findings might be valid even at a continental scale. Moreover, because input intensity is low, GHG fluxes were not related to management activities at the farm level. Increased use of mineral fertilizers to improve crop productivity is expected to have a positive impact on reducing soil GHG flux intensities.

agricultural production continue to minimize GHG emissions, while also examining how intensification affects yields and GHG fluxes.

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**Moved up [3]:** CONCLUSION

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**Deleted:** Fluxes of GHG from low-input, rain-fed agriculture in western Kenya were low with no discernable difference between field types (proxy for management), with only minor differences between different land classes and crop types. The lack of differences between management activities was likely due to the low input rates and is likely representative of low input smallholder farming across much of sub-Saharan Africa. We suggest that time since conversion may be a significant factor in soil respiration rates for this region, masking the effects of management, that needs to be investigated further. Given the low yields common in western Kenya, yield-scaled fluxes can likely be reduced through various interventions to increase yields (e.g. increased fertilizer), which would also reduce the depletion of soil nutrients. However further studies that examine how intensification affects yields and GHG fluxes are required in order to minimize any increases in GHG fluxes from the much-needed intensification of agriculture in this region. ... [4]

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Tables:

Table 1. List of *in situ* empirical studies of greenhouse gas fluxes from agricultural systems in sub-Saharan Africa

| Reference | Location (& crop type / treatment) | | | | |
|---|---|---|---|---|---|
| Annual Flux Estimates | | | | | |
| (Brümmer et al., 2008; Brümmer et al., 2009) | Burkina Faso (sorghum, cotton or peanut) | 4 | June – Sept 2005<br>April – Sept 2006 | 1 – 3X per week | $N_2O$: 0.19 – 0.67 kg $ha^{-1}$ $a^{-1}$<br>$CO_2$: 2.5 – 4.1 Mg $ha^{-1}$ $a^{-1}$<br>$CH_4$: -0.67 – -0.7 kg $ha^{-1}$ $a^{-1}$ |
| (Dick et al., 2008)[1] | Mali (pearl millet with / without legume intercropping) | 3 | Jan 2004 – Feb 2005 | Monthly | $N_2O$: 0.9 – 1.5 kg $ha^{-1}$ $a^{-1}$ |
| (Hickman et al., 2015) | Kenya (maize) | 1 | Mar 2011 – July 2011<br>Apr 2012 – Jan 2013 | Daily to weekly | $N_2O$: 0.1 – 0.3 kg $ha^{-1}$ $a^{-1}$ |
| (Koerber et al., 2009)[2] | Uganda (vegetables) | 24 | July 2005 – Sept 2006 | Monthly | $CO_2$: 30.3 – 38.5 Mg $ha^{-1}$ $a^{-1}$ |
| (Lompo et al., 2012)[3] | Burkina Faso (urban gardens) | 2 | Mar 2008 – Mar 2009 | 2X per day ("several" times per cropping period) | $N_2O$: 80.5 – 113.4 kg $ha^{-1}$ $a^{-1}$ $CO_2$: 22-36 Mg $ha^{-1}$ $a^{-1}$ |
| (Makumba et al., 2007) | Malawi (maize with agroforestry) | 1 | Oct 2001 – Apr 2002 | Weekly | $CO_2$: 2.6 – 7.8 Mg $ha^{-1}$ $a^{-1}$ |
| (Predotova et al., 2010)[2] | Niger (urban and peri-urban gardens) | 3 | Apr 2006 – Feb 2007 | 2X per day for 6 days (repeated 8 - 9X per year) | $N_2O$: 48 – 92 kg $ha^{-1}$ $a^{-1}$<br>$CO_2$: 20 – 30 Mg $ha^{-1}$ $a^{-1}$ |
| (Sugihara et al., 2012)[2] | Tanzania (maize, with / without residue) | 2 | Mar 2007 – June 2010 | 1 – 2X per month | $CO_2$: 0.9 – 4.0 Mg $ha^{-1}$ $a^{-1}$ |
| Seasonal Flux Estimates | | | | | |
| (Baggs et al., | Kenya (maize with | 1 | Feb – June 2002 | Weekly | $N_2O$: 0.2 – 0.6 kg $ha^{-1}$ |

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|---|---|---|---|---|---|
| 2006) | agroforestry, till / no till) | | (Rainy Season) | | $CO_2$: 1.8 – 2.3 Mg ha$^{-1}$<br>$CH_4$: 0.1 – 0.3 kg ha$^{-1}$ |
| (Chapuis-Lardy et al., 2009) | Madagascar (maize with soybean) | 1 | Nov 2006 – April 2007 (Rainy Season) | Weekly | $N_2O$: 0.3 kg ha$^{-1}$ |
| (Chikowo et al., 2004) | Zimbabwe (maize / improved fallow) | 1 | Dec 2000 – Feb 2001 (Rainy Season) | Weekly | $N_2O$: 0.1 – 0.3 kg ha$^{-1}$ |
| (Mapanda et al., 2011)[2] | Zimbabwe (maize, with different fertilizer rates and types) | 2 | Nov 2006 – Jan 2007<br>Nov 2007 – Apr 2008<br>Nov 2008 – Apr 2009 (Rainy Seasons) | 1X per 2 months | $N_2O$: 0.1-0.5 kg ha$^{-1}$<br>$CO_2$: 0.7 – 1.6 Mg ha$^{-1}$<br>$CH_4$: -2.6 - +5.8 kg ha$^{-1}$ |
| Mean Flux Rates from Short Duration Studies | | | | | |
| (Kimetu et al., 2007) | Kenya (maize) | 1 | Mar 2000 – June 2000 (Rainy Season) | 3X per month | $N_2O$: 1.3 – 12.3 µg m$^{-2}$ h$^{-1}$ |
| (Mapanda et al., 2010)[2] | Zimbabwe (grassland/grazing, tree plantations and maize) | 12 | Nov 2006 – Mar 2007 (Rainy Season) | 2X per month to 1X per 2 months | $N_2O$: 1.0 – 4.7 µg m$^{-2}$ h$^{-1}$<br>$CO_2$: 22.5 – 46.8 mg m$^{-2}$ h$^{-1}$<br>$CH_4$: -9.4 - +6.9 µg m$^{-2}$ h$^{-1}$ |
| (Thomas, 2012) | Botswana (grazing) | 2 | Feb, April, July, Nov 2010 (Both Rainy and Dry Season) | 7X per day; 12 separate days only | $CO_2$: 1.1 – 42.1 mg m$^{-2}$ h$^{-1}$ |

[1] Study includes fertilization up to 200 kg N ha$^{-1}$

[2] Sampling is too infrequent for accurate estimates of cumulative fluxes (Barton et al., 2015)

[3] Uses photoacoustic spectroscopy, which has recently had questions raised about its accuracy (Rosenstock et al., 2013a)

[4] Note: flux rates are given as the range of values from the various replicates used in the studies (i.e. the spatial variability and where available [Mapanda et al. 2011 and Thomas 2012], the temporal variability as well), and are reported as N- $N_2O$, C- $CO_2$ and C- $CH_4$.; Please also note units: where possible, annual cumulative fluxes are presented, however in cases with insufficient data to estimate cumulative annual fluxes, we present either mean flux rates, or the cumulative for the given period.

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Table 2: Soil properties (± 1 SEM) for 0 to 20 cm depth, sampled immediately before initiation of gas sampling for the different land classes

| Land class | C[2] content (%) | N content (%) | CN ratio | pH | Bulk Density (g cm$^{-3}$) |
|---|---|---|---|---|---|
| (1) Lowland small (<2 ha) mixed farms with degradation[1] signs | 1.38 ± 0.13 | 0.10 ± 0.01 | 13.18 ± 0.51 | 6.61 ± 0.09 | 0.86 ± 0.03 |
| (2) Lower slopes[3], moderate (2-5 ha) sized mixed farms with degradation signs | 1.18 ± 0.14 | 0.10 ± 0.01 | 11.60 ± 0.58 | 6.58 ± 0.16 | 1.14 ± 0.08 |
| (3) Mid-slopes, moderate sized grazing land | 2.27 ± 0.37 | 0.18 ± 0.03 | 12.16 ± 0.42 | 6.02 ± 0.21 | 0.98 ± 0.07 |
| (4) Upper slopes/highland plateau, mixed farms | 2.67 ± 0.17 | 0.21 ± 0.02 | 12.69 ± 0.52 | 5.46 ± 0.24 | 0.80 ± 0.06 |
| (5) Mid-slopes, isolated moderate sized farms | 2.83 ± 0.36 | 0.24 ± 0.02 | 13.02 ± 0.81 | 5.84 ± 0.20 | 0.71 ± 0.04 |

[1] degradation signs were bare soil and evidence of erosion visible on MODIS images.
[2] due to lack of carbonates, total C equals organic C
[3] Sloped areas went from the lowlands (approx. 1200 masl) up to the highlands (approx. 1800 masl) ranging from 10 – 30%.

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Table 3: Comparison of mean (± 1 SEM) cumulative $CO_2$-C, $CH_4$-C and $N_2O$-N fluxes for four weeks during the dry season (February 2014) and rainy season (April 2014) for differently managed sites in western Kenya.

| GHG | Dry Season | | Wet Season | | P values | | |
|---|---|---|---|---|---|---|---|
| | Annual Crop | Other | Annual Crop | Other | Season | Management[1] | Interaction |
| $CO_2$-C (g $m^{-2}$) | 19.4 ± 2.8 | 20.0 ± 3.8 | 76.6 ± 5.0 | 62.7 ± 5.7 | < 0.0001 | 0.393 | 0.204 |
| $CH_4$-C (mg $m^{-2}$) | -7.4 ± 4.4 | 2.2 ± 6.7 | -3.7 ± 3.6 | -15.0 ± 3.5 | 0.610 | 0.873 | 0.044 |
| | Fertilized | Not Fertilized | Fertilized | Not Fertilized | | | |
| $N_2O$-N (mg $m^{-2}$) | 0.52 ± 0.23 | 1.44 ± 0.40 | 9.87 ± 4.23 | 5.35 ± 1.14 | < 0.0001 | 0.562 | 0.112 |

[1] Management refers to ploughing versus no ploughing for the $CO_2$ and $CH_4$ and to fertilized versus no fertilizer for the $N_2O$

Figures:

Fig. 1. Map of study area showing the sampling location by the different vegetation cover types

Fig. 2. $CO_2$ (mg C- $CO_2$ $m^{-2}$ $h^{-1}$), $CH_4$ (µg C- $CH_4$ $m^{-2}$ $h^{-1}$), and $N_2O$ (µg $N_2O$-N $m^{-2}$ $h^{-1}$) flux rates from intact soil cores taken from 36 sites across 5 different land classes in western Kenya incubated at 20°C and 5 different water content (0 [air dried], 25, 35, 55, and 75% WHC).

Fig. 3. $CO_2$ (mg C- $CO_2$ $m^{-2}$ $h^{-1}$), $CH_4$ (µg C- $CH_4$ $m^{-2}$ $h^{-1}$), and $N_2O$ (µg $N_2O$-N $m^{-2}$ $h^{-1}$) fluxes over 1 year, as well as precipitation (mm), soil moisture content at 5 cm depth ($m^3$ $m^{-3}$) and inorganic N ($NO_3$ + $NH_4$) soil concentrations for 59 different fields in western Kenya by land class. Note: Vertical dotted lines correspond to planting and vertical dashed lines correspond to harvesting of annual crops. (Land class 1 = degraded lowland farms; class 2 = degraded farms, lower slopes; class 3 = mid slopes, grazing; class 4 = upper slopes/plateau, mixed farms; and class 5 = mid slopes moderate sized farms)

Fig. 4. Box and whisker plots of cumulative annual fluxes of $CO_2$ (Mg $CO_2$-C $ha^{-1}$ $year^{-1}$), $CH_4$ (kg $CH_4$-C $ha^{-1}$ $year^{-1}$) and $N_2O$ (kg $N_2O$-N $ha^{-1}$ $year^{-1}$) from 59 different fields in western Kenya split by land class.

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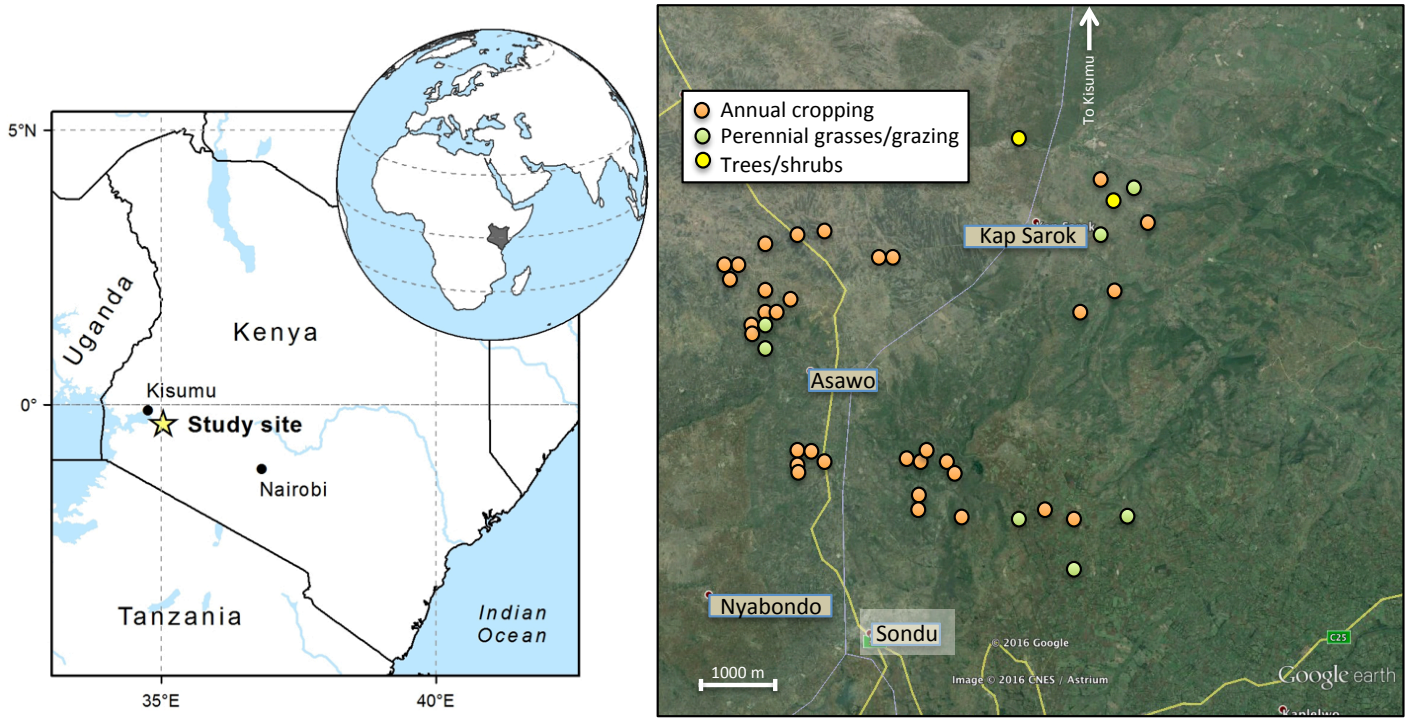
Fig. 1

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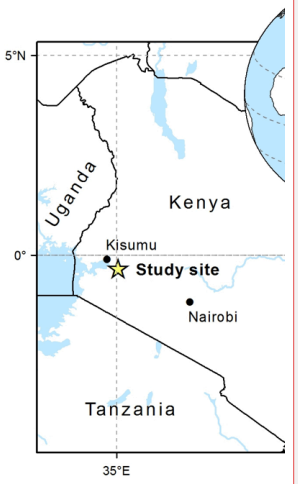


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Fig. 2

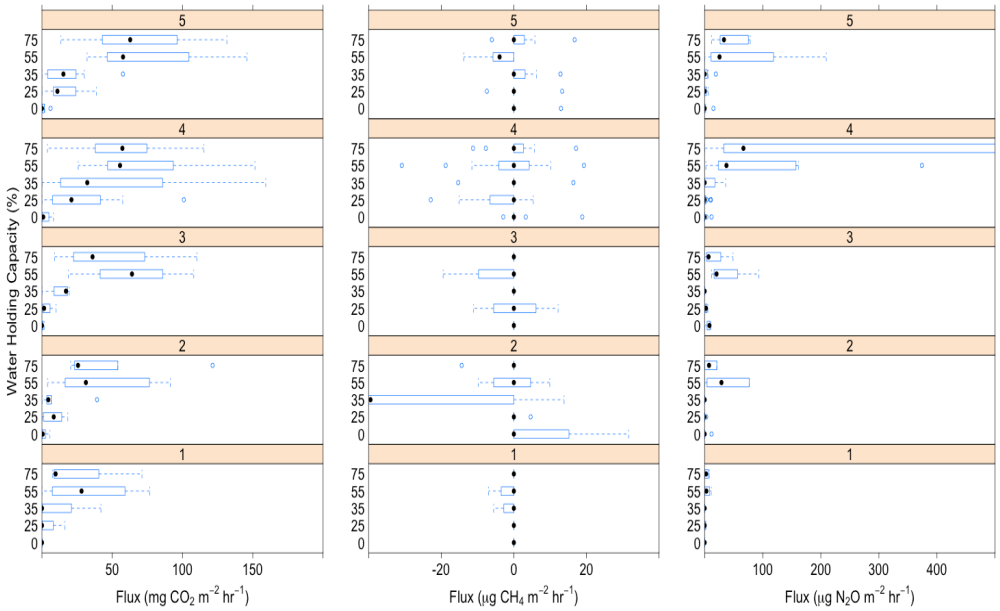

Water Holding Capacity (%)
5
4
3
2
1
75
55
35
25
0
50
100
150
-20
0
20
100
200
300
400
Flux (mg $CO_2$ $m^{-2}$ $hr^{-1}$)
Flux (µg $CH_4$ $m^{-2}$ $hr^{-1}$)
Flux (µg $N_2O$ $m^{-2}$ $hr^{-1}$)

Fig. 3

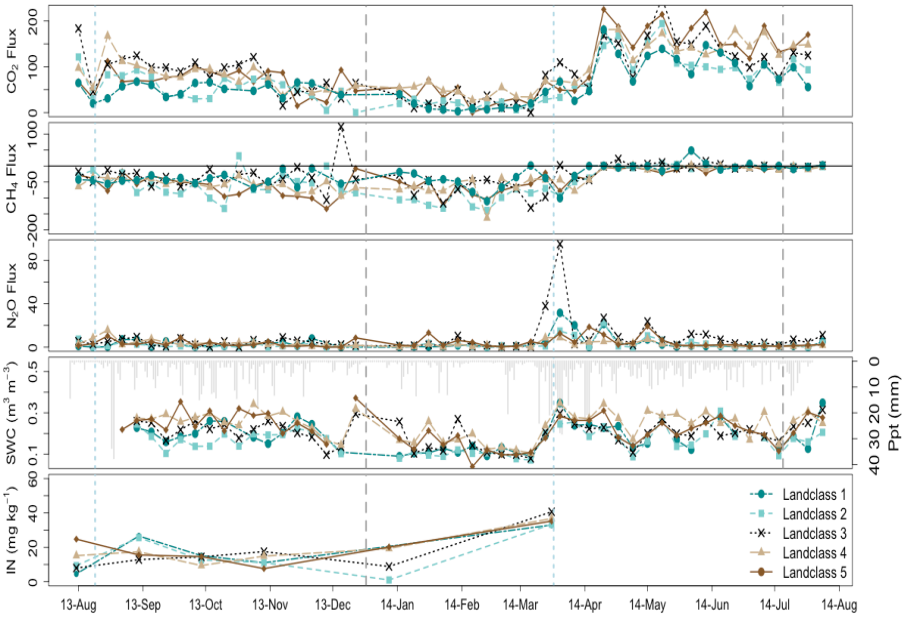
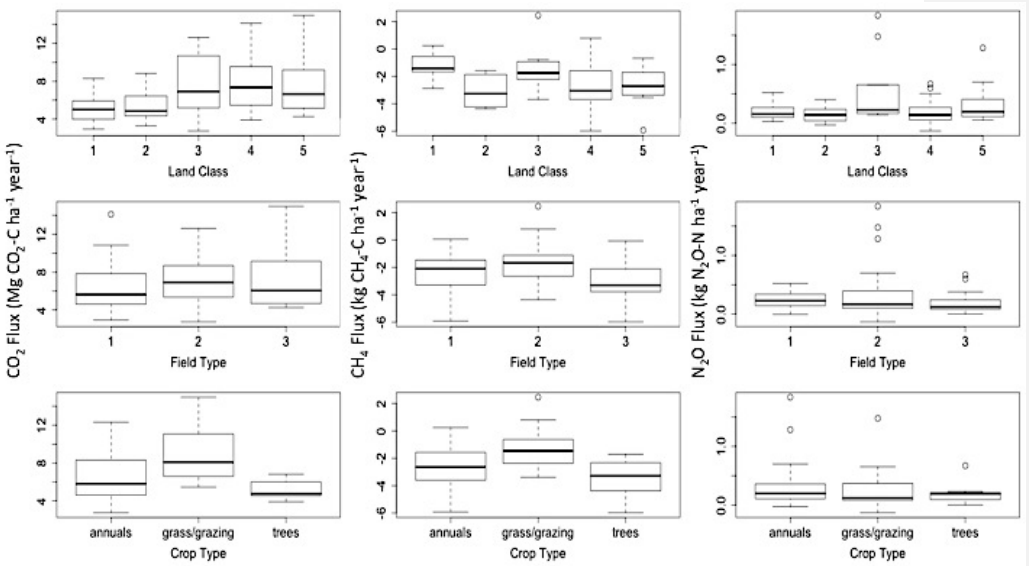

CO2 Flux
CH4 Flux
N2O Flux
SWC (m3 m-3)
Ppt (mm)
IN (mg kg-1)
Landclass 1
Landclass 2
Landclass 3
Landclass 4
Landclass 5
13-Aug
13-Sep
13-Oct
13-Nov
13-Dec
14-Jan
14-Feb
14-Mar
14-Apr
14-May
14-Jun
14-Jul
14-Aug

Fig. 4


CO2 Flux (Mg CO2-C ha-1 year-1)
CH4 Flux (kg CH4-C ha-1 year-1)
N2O Flux (kg N2O-N ha-1 year-1)
Land Class
Field Type
Crop Type
annuals
grass/grazing
trees

.

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Methane was generally taken up by these upland soils, however these rates also varied through the year (Fig. 5b). During August 2013, the soils were sinks for $CH_4$, however as the soils dried, the emission / uptake rates became more erratic until the long rains started again in late March 2014. In general, the $CH_4$ flux at the soil surface is the result of the balance between production and consumption (Le Mer and Roger, 2001), so it could be that the low rates of atmospheric $CH_4$ uptake during the long rains was caused by greater $CH_4$ production in the soil overriding the existing methanotropic activity since the rainfall causing higher soil moisture and likely anaerobic conditions at depth (e.g. (Butterbach-Bahl and Papen, 2002).

Seasonal effects were also apparent for the $N_2O$ fluxes. Flux rates remained below 20 $\mu g\ m^{-2}\ h^{-1}\ m^{-2}$with

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The soil core incubations and field studies were consistent in that, contrary to expectations, there were no detectable differences in GHG fluxes between the different field types. We had expected differences in fluxes because a previous study in the same region indicated that there were differences in input use, food production, partial N and C balances and soil fertility (Tittonell et al., 2013); and these variables often affect soil GHG fluxes (Buchkina et al., 2012; Jäger et al., 2011). However, differences between field types in total soil C and N were only important when considering each farm individually (Tittonell et al., 2013), which, in our study, may have resulted in greater within-type variation that masked differences between the field types.

We had hypothesized that field type, which is related to the degree of inputs and labour, would be a significant predictive factor since field type 1 would have much more manure added than, for example, field type 3 and this may result in greater $CO_2$ fluxes. Also, since previous studies found that

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a significant amount of the variability in soil $CO_2$ fluxes in agro-ecosystems can be explained by NDVI (Sánchez et al., 2003) and crop type (Mapanda et al., 2010) we expected that both land class, which was based on NDVI, and cover type would also have significant effects on soil $CO_2$ fluxes. However, annual soil $CO_2$ fluxes were not related to land class or field type ($P$ = 0.229 and 0.540 respectively; Fig. 4), although the cumulative fluxes, (2.7 to 14.0 Mg $CO_2$-C $ha^{-1}$ $yr^{-1}$), were well within the range determined for other African studies (Table 1). Higher soil respiration rates from grazing land was inconsistent with a previous study that found similar rates between rain-fed perennial tropical grasslands, croplands and eucalyptus plantations in Zimbabwe (Mapanda et al., 2010). However, because we did not differentiate between root and microbial respiration it could be that the continual vegetation cover contributed more root respiration over the year than was found in the annual crops and treed plots.

As indicated earlier, there was a strong correlation between soil C and N content and cumulative $CO_2$ fluxes, and while manure inputs have previously been found to increase soil C content (Maillard and Angers, 2014), inputs in our study area were very low (between 4 and 6 wheelbarrow loads or approximately 90 to 135 kg C $ha^{-1}$), which may be too little to cause field-level differences in soil C content. Other factors may also affect soil organic C content such as soil texture (Burke et al., 1989; Franzluebbers et al., 1996), clay mineralogy (Powers et al., 2011) and land use history. Considering the strong correlation between soil C and N and that a previous study found that N is being rapidly mined from soils in the Lake Victoria basin (Zhou et al., 2014), it is likely that soil C is also being lost across the landscape. As most of this area has been converted from natural forests, and forests generally have higher SOC than croplands (Guo and Gifford, 2002), time since conversion could play a larger part in determining the soil organic C content that masks any effects that management activities may have on soil respiration rates in these low input systems.

The $CH_4$ uptake from these sites were consistent with previous studies in upland agricultural soils and indicate that soils of smallholder farms are sinks for

atmospheric $CH_4$ (Le Mer and Roger, 2001). Unlike the $CO_2$ fluxes, although there were no differences in cumulative $CH_4$ uptake between field types, there were differences between cover types as grazing plots took up less $CH_4$ than treed plots and also between land classes with land class 1 taking up less $CH_4$ than land class 2 (Fig. 4). The difference between cover types is consistent with previous studies that found that forest soils were greater $CH_4$ sinks than agricultural soils (MacDonald et al., 1996; Priemé and Christensen, 1999). However, given the higher bulk density in land class 2 (Table 2) and the propensity for denser soils to have reduced $CH_4$ oxidation rates (Hansen et al., 1993; MacDonald et al., 1996; Teepe et al., 2004), we expected that land class 2 would have uptake less $CH_4$ than class 1.

Annual $N_2O$ fluxes (between 0.15 and 0.58 kg $N_2O$-N $ha^{-1}$ $y^{-1}$), were low when compared with fertilized plots in sub-tropical Brazil (Piva et al., 2014) or China (Chen et al., 2000), where fluxes ranged up to 4.26 kg $N_2O$-N $ha^{-1}$ $y^{-1}$.

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Fluxes of GHG from low-input, rain-fed agriculture in western Kenya were low with no discernable difference between field types (proxy for management), with only minor differences between different land classes and crop types. The lack of differences between management activities was likely due to the low input rates and is likely representative of low input smallholder farming across much of sub-Saharan Africa. We suggest that time since conversion may be a significant factor in soil respiration rates for this region, masking the effects of management, that needs to be investigated further. Given the low yields common in western Kenya, yield-scaled fluxes can likely be reduced through various interventions to increase yields (e.g. increased fertilizer), which would also reduce the depletion of soil nutrients. However further studies that examine how intensification affects yields and GHG fluxes are required in order to minimize any increases in GHG fluxes from the much-needed intensification of agriculture in this region.

ACKNOWLEDGEMENT

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$N_2O$: 0.2 – 0.6 kg $ha^{-1}$
$CO_2$: 1.8 – 2.3 Mg $ha^{-1}$
$CH_4$: 0.1 – 0.3 kg $ha^{-1}$

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| | | | | | |
|---|---|---|---|---|---|
| (Brümmer et al., 2008) | Burkina Faso | 4 | June – Sept 2005<br>April – Sept 2006 | 1 – 3X per week | $N_2O$: 0. |
| (Brümmer et al., 2009) | Burkina Faso | 4 | June – Sept 2005<br>April – Sept 2006 | 1 – 3X per week | $CO_2$: 2.<br>$CH_4$: -0. |
| (Chapuis-Lardy et al., 2009) | Madagascar | 1 | Nov 2006 – April 2007 | Weekly | $N_2O$: 0. |
| (Chikowo et al., 2004) | Zimbabwe | 1 | Dec 2000 – Feb 2001 | Weekly | $N_2O$: 0. |
| (Dick et al., 2008)[1] | Mali | 3 | Jan 2004 – Feb 2005 | Monthly | $N_2O$: 0. |
| (Hickman et al., 2015)[1] | Kenya | 1 | Mar 2011 – July 2011<br>Apr 2012 – Jan 2013 | Daily to weekly | $N_2O$: 0. |
| (Kimetu et al., 2007) | Kenya | 1 | 4 weeks | 3X per month | $N_2O$: 1. |
| (Koerber et al., 2009)[2] | Uganda | 24 | July 2005 – Sept 2006 | Monthly | $CO_2$: 30 |
| (Lompo et al., 2012)[3] | Burkina Faso | 2 | Mar 2008 – Mar 2009 | 2X per day | $N_2O$: 80<br>$CO_2$: 22 |
| (Makumba et al., 2007) | Malawi | 1 | Oct 2001 – Apr 2002 | Weekly | $CO_2$: 2.6 |
| (Mapanda et al., 2010)[2] | Zimbabwe | 12 | Nov 2006 – Mar 2007 | 2X per month to 1X per 2 months | $N_2O$: 1.<br>$CO_2$: 22<br>$CH_4$: -9. |
| (Mapanda et al., 2011)[2] | Zimbabwe | 2 | Nov 2006 – Jan 2007<br>Nov 2007 – Apr 2008<br>Nov 2008 – Apr 2009 | 1X per 2 months | $N_2O$: 0.<br>$CO_2$: 0.<br>$CH_4$: -2. |
| (Predotova et al., 2010)[2] | Niger | 3 | Apr 2006 – Feb 2007 | 2X per day for 6 days (repeated 8 - 9X per year) | $N_2O$: 48<br>$CO_2$: 20 |
| (Sugihara et al., 2012)[2] | Tanzania | 2 | Mar 2007 – June 2010 | 1 – 2X per month | $CO_2$: 0.9 |
| (Thomas, 2012) | Botswana | 2 | Feb, April, July, Nov 2010 | 7X per day; 12 separate days only | $CO_2$: 1. |