Response to Reviewer #1

General comments: This paper reports results from an experiment conducted in Ethiopia measuring yields and GHG fluxes from maize cultivated as monocrop and intercropped with 2 legumes. There is an urgent need to increase the empirical base quantifying GHG fluxes from agricultural systems in Sub-Saharan Africa and therefore this study could be a valuable contribution to the literature. Understanding the interactions between cereal and legume crops and quantifying C footprints are also commendable scientific goals, and requirements to design future climate-smart farming.

However, this study seems to have a number of experimental shortcomings that require at least clarification to be able to assess its suitability for publication in Biogeosciences.

Response: We thank the reviewer for constructive comments and criticism. The reviewer's main points of critique can be summarized as i) lack of ancillary data (e.g. soil mineral N) and N-fluxes (e.g. quantification of BNF) and ii) too much speculation about underlying processes. We agree with the reviewer that our study has experimental shortcomings, but we believe that our research has some salient points worth communicating to a broader audience:

- Intercropping and mulching legumes to maize under Rift Valley conditions did not cause major N_2O emissions, nor inhibit CH_4 uptake during a dry and a wet year
- Legume intercropping therefore appears as a viable option for climate-smart intensification which is urgently needed in the region
- Even though being highly insecure, numbers of leguminous N input, N_2O-EFs, etc. presented in our paper can be used as first estimates in the absence of better data

We understand the reviewer's frustration about the lack of ancillary data (soil moisture in 2015, mineral N content, below ground legume biomass, etc.) but as in any empirical study, there are limitations to the number of variables which can be measured, particularly so when relying on local research infrastructure.

1. The introduction doesn't follow a logical flow. It includes interesting hypotheses, although the authors either do not properly attempt to answer the hypotheses or do it insufficiently. Example: "Legumes affect emissions by providing organic N or by modulating the completion between roots and microbes for soil N". The authors could have added how these processes are 'modulated', and use the appropriate methods to quantify species competition and microbial processes.

Response: Studying legume-rhizobia interactions is not trivial (see for example Raji et al., 2019). Species competition and microbial processes were not the primary focus of our study. Instead, we were interested in the overall effect of forage legume intercropping and its management on N_2O and CH_4 fluxes. We rephrased the sentence to "*…or by modulating the competition between plants and microbes for soil N, for example by acting as an additional N sink prior to nodulation*".

2. The methods are poorly described to assess the value of the experimental data. I indicated shortcomings in Specific comments below.

Response: We address these shortcomings in response to the specific comments below.

3. The discussion is mostly a compilation of literature conducted elsewhere reporting GHG fluxes from intercropping including legumes. I would expect a reflection of the results against the relevant literature.

Response: Comparing our flux estimates with those found in other GHG studies in Sub-Saharan Africa is an important first step to scrutinize and contextualize our measurements. The remainder of the discussion tries to interpret treatment effects by linking fluxes to measured variables (weather, legume biomass, etc.), necessarily drawing on the general literature. We are not entirely sure what the reviewer means by "relevant literature". Even though intercropping with forage legumes is a common practice in the Ethiopian Rift Valley, there are no published studies on how these practices affect N2O and CH4 fluxes. We therefore compared our N2O fluxes and emission factors to those reported for humid tropical maize production systems with intercropping, which – at least geographically – come closest to the system studied by us. We would be grateful to learn about relevant literature we have missed out.

A modest aim for this paper could have been simply documenting the GHG flux measurements and explaining the patterns observed, using all the data collected and conducting a sensitivity analysis for the fluxes that have been roughly estimated, such as the contribution of the legumes to N inputs, the emission factors and the emissions intensity.

Response: Estimating emission factors necessitates estimating N inputs, which is particularly challenging in experiments involving N input from BNF, green manuring or crop residue retention. Our estimates of N input by BNF are based on assumptions of legume shot-root ratios and residue decomposition rates, which we anchored in the literature, as outlined in chapter 2.4. We believe that this approach does not lend itself to "sensitivity analysis for the fluxes" as we do not use statistical models to explain variations in flux. We decided to abstain from such models because of the inherent insecurity of underlying variables such as legume N input. Instead, we resorted to simple linear regression using measured aboveground legume N yield and N_2O emission intensity (Fig. 3). We want to emphasize that all variables and their derivations (cumulative flux, emission intensity and factors) were estimated or calculated on a per plot level before averaging them, giving at least some measure of dispersion (e.g. Figures 2, 5 and Table 2).

Because there are very few experiments measuring GHG fluxes in Africa, I would suggest a thorough revision addressing the shortcomings, to re-consider this manuscript for publication.

Response: A thoroughly revised manuscript will be provided addressing all points raised by the reviewers.

These are the most important issues to be addressed:

Specific comments Introduction

L39: The use of inorganic fertilisers does not necessarily reduce the soil methane sink. Please explain.

Response: No, it does not. Our introduction tries to detail the conditions potentially leading to reduced CH_4 uptake by citing a meta-study that found an overall higher propensity for reduction in CH4 uptake at mineral N fertilization rates > 100kg N ha^{-1} y^{-1} (Aronson and Helliker, 2010). We further outline possible mechanisms regulating CH_4 uptake in fields with intercropping in Lines 81-91 of the original text. At no point, we claim that inorganic fertilizers invariably reduce the soil's sink strength for methane. The sentence in line 39 now reads: *"Abundant ammonium (NH4+) may also reduce the soil CH4 sink by competing with CH4 for the active binding site of methane monooxygenase, the key enzyme of CH4 oxidation (Bédard and Knowles, 1989)"*

L40 remove 'by contrast'. It doesn't follow naturally from the previous sentence

Removed

L41 the concept of CSA – coined by FAO – doesn't talk about profits. Please revisit original source

Response: The reviewer is right. We remove 'profits'.

L43: I don't think the understanding of GHG fluxes in SSA is limited. There is a scarcity of quantified GHG fluxes in SSA, and limited experimentation on which CSA practices would be suitable for the SSA context. Please rephrase.

Response: We agree with the reviewer that sources and sinks of GHGs in SSA are well understood, in principal, and rephrase the sentence to "*However, greenhouse gas emission measurements in SSA crop* *production systems are scarce and proof-of-concept for the mitigation potential of specific CSA practices is missing (Kim et al., 2016, Hickman et al., 2014b)."*

L49: Crop production can be a major source of N2O emissions when fertilisers are used. This is not often the cause in East African agriculture. There are empirical studies that show that

Response: Food production in SSA has to double by 2050 to feed a growing population. This requires intensification of crop production, be it by increasing nitrogen fertilization or by other approaches, such as legume intercropping. We therefore believe that studying and documenting intensification effects on N_2O emissions are important in the wider context of GHG mitigation in the global agrifood system. We agree that N2O emissions in rainfed SSA crop production appear small per date, but given the enormous productivity increase needed, also crop production in SSA may become a major source of N_2O. In the revised version, we state explicitly "*Emission rates of N2O reported for SSA crop production so far are low (Kim et al., 2016) owing to low fertilization rates, but may increase with increasing intensification."*

L53: strange reference to 'upland soils' here. Please explain why the focus is suddenly shifted towards upland soils

Response: The term "upland" was removed as the statement refers to factors that control N_2O production in soils in general.

L58: soil management practices are not the only controls of the factors affecting soil N2O fluxes. Soil type and climate are major determinants, which don't depend on management

Response: The reviewer is right! We rephrase the statement and add soil type and climate as important factors for N2O emissions, including two new references. The sentence added reads: "*Other important factors are soil type (Davidson et al., 2000) and temperature (Schaufler et al., 2010)."*

L59: The position of the two first references in this sentence is not logical. Please revise.

Revised

L68: diversification, rotation and intercropping do not always enhance productivity. Please rephrase

Response: The reviewer is right. We rephrased the sentence to: *"Crop diversification by combining legumes with cereals, both in rotation and intercropping, enhances overall productivity and resource use efficiency, if managed properly (Ehrmann and Ritz, 2014)"*

L71 please add reference that shows that legume improve N uptake of the cereal crop in the Rift Valley (this is a large area across countries!). There is evidence in favor and against this.

Response: A reference was added *(Sime and Aune, 2018)*, describing the general benefits of legume inclusion in farming systems in the region.

L86 rates of 100 kg N per hectare are very uncommon in Africa. Please consult the literature on fertilizer use for the continent.

Response: This statement refers to the general relationship between N rates and methane uptake as elucidated by the meta-study of Aronson and Helliker (2010) and not to common N fertilization rates in SSA.

L89: increasing. Remove or replace 'accordingly', doesn't seem to fit the meaning of the sentence.

Done

L93: add 'the' to 'the' release. Please explain how root exudates release 'extra N'

Done

L95-96: are these the hypotheses this study wanted to test?

Response: No. This sentence refers to the background of how legumes may cause extra N_2O emissions. The hypotheses of the study are given in L109 -115 in the original text.

L110-112: these hypotheses don't have any mechanistic underpinning, and are therefore weak. Time measured in weeks is unlikely to be a fixed effect, since the effects of management such as sowing date, choice of species and cultivar on yields and GHG fluxes will depend on soil and weather.

Response: The competition for nutrients after under-sowing the intercrop, as well as the benefit of the main crop from N transfer depend in deed on a variety of factors, particularly those which control the initial growth of maize and hence its shading effect on the legume. Our study is a good illustration for this: equal sowing dates produced vastly different legume aboveground biomasses in a dry and a wet year (Table 1). Yet, among all factors, the sowing date of the legume (relative to the main crop) is the one, which potentially could be controlled by the farmer, preferably in response to prevailing weather conditions.

In response to the reviewer's righteous remark, we modify the respective conclusion in the discussion section to *"Our study therefore points to optimizing the sowing date in response to expected emergence and growth of maize as a promising option to control growth of the intercrop and hence to deal with the risk of increased N2O emissions associated with high legume biomass"*.

L115: because there are so few experiments measuring GHG fluxes in Africa, and more modest aim for this paper could have been simply documenting these measurements and explaining the patterns observed.

Response: Our study served two aims, documenting fluxes and evaluating intercropping strategies with respect to GHG mitigation. We agree that a merely descriptive study of fluxes in different treatments would have been the least risky approach, but mitigation needs causation if it is to be widely adopted. Therefore, we chose to link seasonal emissions to stipulated legume N input and climatic variability, which we believe are the key drivers for N_2O emissions in sub-Saharan intercropping systems.

Methods

L121-126 please report soil type using a known classification, e.g. WSD. And please add measure of dispersion to the reported soil properties, and weather variables.

Response: We now include the soil type and SD for the bulk density. For analysis of soil texture and chemical composition, we used composite soil samples and hence cannot give measures of dispersion.

L128: Please explain the 6 treatments clearly here. No clear which are the treatment is Table1,and how they were imposed. Treatments seem to be listed inTable2, although there is no consistency in labels used in Tables and Figures.

Response: A treatment list is now included in the Materials and Method section; label inconsistencies in tables and figures are corrected.

L130: only one cultivar? Wouldn't the researchers have expected cultivar effects on the treatments?

Response: Farmers' preference was considered in choosing the maize cultivar for the trial. This cultivar is widely used and we focused on legume species and intercropping times rather than maize cultivar as a factor.

L131: only one sowing date each year? I understood from the objective and hypothesis that the authors wanted to test the effect of sowing date (L110) on GHG fluxes.

Response: Our objective was to test the effect of legume species and sowing date of the legumes relative to maize in combination with interannual weather variation, and not the effect of the sowing date of maize itself.

L133: fertiliser rates per hectare? I am surprised to read that N fertiliser was applied to the intercropping treatment. Was there a scientific basis to half the rate? If yes, please add reference to previous experimental work.

Response: Mineral N fertilization followed national recommendations, which are low. Annual legume intercrops are used, among others, to bring additional nitrogen into the soil, both during growth and after harvest. As outlined in line 134 ff., the rate of annual mineral N fertilization was halved in the second year there where legume mulch was applied, to test whether biologically fixed N could replace mineral N, which in itself would be a climate-smart approach. Cutting down on mineral fertilization is a common goal and practice when using catch or cover crops as green manure.

L136 I would have expected an effect of plant density. These were fixed.

Response: The numbers given for legume density are the planting densities, which did not result in "fixed" densities during the growing season. Much to the contrary, in terms of legume aboveground biomass, there was a huge variability across the two years. Aboveground dry matter varied from 186 to 2221 kg ha^{-1} for lablab and 65 to 1516 kg ha^{-1} for crotalaria across the two years. We used this variation to explore the effect of legume biomass on N_2O emissions, which indeed showed a significant effect in the dry year 2015 (Figure 3).

L141: why half removed? did you measure this variable amount of mulching applied to the plots? This is not really a welcome variation to the treatments, and could have affected the data analysis and assumptions on treatment effects.

Response: The idea of removing 50% of the biomass and mulching the rest was motivated by livestock feed shortage in the mixed farming systems of the region. Providing feed through intercropping provides an added "climate smart" value by alleviating the pressure on crop residues otherwise used as feed, thus increasing residue retention and building/stabilizing soil carbon. It is true that different mulching rates introduced additional variation. However, applying equal mulching rates to all plots would have negated plot-specific differences in soil fertility and hence belowground input. We therefore decided to scale the rate of mulch applied according to the plot-wise legume yield, as would be done by practitioners in real fields. In this way, we created a wide range of legume biomasses and likely also of N inputs, which allowed us to explore the effect of legume growth on N_2O emissions (Fig. 3).

L151: why didn't the measurements of fluxes start before planting to capture background GHG fluxes?

Response: The flux study was restricted to two growing season due to logistic reasons. Two control treatments with maize monocrops were included, one with recommended mineral fertilization and one without. Thus, background fluxes are captured. We agree that flux measurements outside the cropping season would be desirable.

L152: what was the frequency of sampling? Weekly? There is evidence that less than weekly sampling doesn't capture the variation of GHG fluxes in a crop's cycle. See Barton et al. 2015 Scientific Reports volume 5, Article number: 15912 (2015)

Response: Flux sampling was conducted weekly as indicated in line 151 of the original manuscript

L159: Helium filled?

Yes. Corrected.

L185: these treatments were not introduced before.

Response: The treatments M+Cr3w and M+Lb3w are now introduced at the beginning of the Materials and Method section.

L187 Was bulk density measured? If yes, how?

Response: A description of how it was measured is now added.

L195-L198: Not having assessed belowground biomass and the amount of N fixed by the legumes is an important shortcoming of this study. Especially because the authors pose the hypothesis in the introduction (L95-96) that "Legumes affect emissions by providing organic N or by modulating the completion between roots and microbes for soil N". Without having quantified belowground N and N2 fixation, the results are less useful as a contribution to test this hypothesis.

Response: The question of whether and how biologically fixed N affects N_2O emissions is a long-standing issue. Our study is a modest attempt to address this issue for sub-Saharan conditions. It was however not designed to capture the exact mechanisms of competition between crops and microbes, nor did we hypothesize that it would. Instead, our working hypothesis was that legumes inter-cropped early in the season would increase N2O emissions if fertilized at the same time (L. 113). The reviewer is right that determining the amount and N content of belowground biomass would strengthen our approach, but given the number of field plots and the clayey soil (which makes it difficult to extract roots), the effort to do so would have been exorbitant. We therefore used aboveground biomass and its N content as a proxy for "potential" legume N input by scaling up literature based shoot-root ratios for lablab and crotalaria and estimating N release factors from literature.

L199: until here, it wasn't indicated that there were different sowing times for maize and legumes. Treatments must be clearly explained at the beginning.

Response: Additional explanations about the treatments have been added to the Materials and Methods section

L202-204: this is another shortcoming, having assumed the 'release' of 50% and 30% of the N during the growing season doesn't help with hypothesis testing. The authors could have followed at least inorganic N in the soil.

Response: We agree that mineral N contents would have supplemented our dataset in a meaningful way, but frozen storage of extracts prior to shipment out of the country was not possible due to frequent power cuts. As to the estimated release factors for legume N in the two years, we give detailed rationale for the underlying assumption (L.201 – 212, original version).

L213: this emission factor is not meaningful given all the assumptions used to estimate N input.

Response: We agree in principal, but seasonal emission factors for N_2O have been used in the literature previously and may be considered useful for comparing different crop management strategies in regions with scarce flux data (see f. ex. Kim et al., 2016)

L221 Was grain moisture content measured?

Response: Yes, we used a digital grain moisture meter.

Results

L236-237: to be able to measure peaks, N2O fluxes must be measured continuously after fertiliser application. There is typically a peak 6-48 hours after application. The dataset unfortunately doesn't show baseline emissions that happened before the treatments were imposed.

Response: The term "peaks" has been removed

L 280-295: I find this section on EFs speculative because there are large uncertainties in the estimation of N input as described in the methods section.

Response: See answer to L. 213 above.

L318: this should be explained in the methods section with all assumptions and reported as absolute emissions not GWP. This section is not clear, and need to consistently explain Fig 2 and 5. Fig 5 doesn't include letters showing the contrasts.

Response: We thank the reviewer for drawing our attention to missing indicators in Figure 5. GWP is replaced with "total non-CO_2 GHG emissions" as suggested.

Discussion

L330-340: this belongs more to results than to discussion.

Response: See our response to your general comment #3

L349-354: because the researchers didn't measure N2 fixation, this sentence is speculative. Also attributing the lack of relationship between N input and legume N yield and N2O fluxes to the variability of fluxes is speculative, since the estimation of the N input and yield are very uncertain and based on strong assumptions.

Response: Therefore, we talk about "potential leguminous N input" and not actual N input. We agree that our estimates of N input are insecure, but our analysis does not do more than examining the relationship of cumulative N2O emissions and "potential leguminous N input" on a plot for plot basis, before problematizing this approach in the discussion following L. 349.

L375-378: the data shown in Fig 2 doesn't show that intercropping legumes increases emissions 'risk' further than cultivating fertilized maize. If that were the case, there would be a consistent effect across years, and all legumes would increase emissions

Response: We believe that the sentence *"Our data suggest that excessive accumulation of leguminous biomass in SSA maize cropping enhances the risk for elevated N2O emissions"* summarizes our findings in an appropriate way based on the analysis shown in Figure 3. In the discussion following L. 275, we are explicit about other factors such as rainfall early in the season potentially overriding this relationship.

L381: unfortunately the experimental data of the one experiment in Ethiopia presented here is insufficient to claim that N2O fluxes in the sub-sequent year are negligible under SSA conditions. It is unfortunate that the researchers didn't follow the dynamics of inorganic N in the soil or plant N uptake when they sampled GHG fluxes.

Response: We agree. Therefore, we added a disclaimer to this paragraph (L. 383-395). Future studies will examine N carry over between cropping seasons following mulching of the legumes in more detail, involving mineral N measurements and nutrient modelling.

L385: it is also unfortunate that the researchers don't present data of N2O fluxes and soil N dynamics off-season. So this observation remains speculative.

Response: Unfortunate, yes, but at least we draw N leaching into consideration.

L385: not clear what is meant with 'emissions were at par', neither why this is striking.

Response: Emission "at par" means emissions were at the same level. To avoid further confusion, we replace this expression with "comparable".

L395: the lack of explanation to the effect on mulching actually calls to explain this by measuring consistently the factors driving N2O fluxes such as moisture content and availability of substrate (inorganic N) over time.

Response: Absolutely! The sentence now reads: *"… calls for studies tracing cumulative mulching effects over multiple years and exploring their driving factors in more detail."*

L397: the relative effect of soil moisture vs inorganic N could have been tested if the researchers would have collected such data. Now this conclusion leads to speculation.

Response: Yes; see answer above.

L398-410: this study doesn't present solid evidence to sustain this claim, because sowing date doesn't control per se GHG fluxes, but determines the state of soil and weather that the soil+crop system will experience. So giving prescriptions of sowing dates that are not tied to indications of environmental conditions wouldn't be useful at all. In addition, this research didn't find any consistent evidence that legumes increase the emissions beyond the fertilized crop according to Fig 2, which shows that one treatment had higher N2O fluxes than the control.

Response: Sowing date of legumes in our study had a clear effect on legume development (aboveground biomass yield). We agree that our data provide no basis for prescribing sowing dates, and it was never our intention to do so. The sentence now reads: *"… emerge as viable management factors for controlling the accumulation of legume biomass between the maize rows and hence the risk for increased N2O emissions"*. See also our response to L. 110.

L412-420,this section needs re-writing to make a comparison instead of a list of studies and their findings.

Response: We do compare emission factors; see line 423 in the original version

L420-424 for this comparison to be useful, please report the biomass measured that was added in year 2 across treatments.

Response: See Table 1

L428, in my opinion the EFs should be re-worked with uncertain parameter ranges to be able to assess how far there are from IPCC. This statement is too crude given the procedures used to estimate the EF.

Response: We agree but want to point out that we use our emission factors solely to compare our numbers with emission factors compiled by Kim et al. (2016) for other SSA agricultural systems, which also were scaled up from a limited number of measurements. It is by no means our intention to challenge IPCC default values. One may be critical to the concept of IPCC Tier 1 emission factors for regions with few flux data, but they are the only tool, for the time being, to compare systems with respect to their propensity to emit N2O from added reactive N and hence an important criterion when studying intensification effects.

L433 the levels of N inputs could have been underestimated because there were no measurements of the real contributions of the legumes. Which soil has been used over decades? Not clear. Intense use of soils usually leads to loss of fertility not enrichment.

Response: Smallholder farmer in the Rift Valley use little if any fertilization and remove all crop residues for feeding animals, thus they have a negative nutrient balance and lose soil fertility. In comparison, the experimental fields of the university farm are relatively "fertile" as they have experienced N and P fertilization, residue retention and N input from legumes BNF for many years. We believe it is important to point this out, when generalizing our findings for the region.

L441: dynamics of inorganic N not measured.

Response: Yes; that is why we have to speculate here.

L454-474: this piece of text is not needed because it cannot be compared with the experimental results reported here. I would suggest contrasting the experimental results with the literature and avoiding listing all that is known for legumes in completely different climates.

Response: This part discusses benefits and risks of legumes intercropping from the perspective of smallholder farming in the region. We believe that this discussion is important and integral to CSA and the question how to sustainably intensify crop production. Since there are no published studies on legume intercropping covering GHG emissions from this region so far, we resort to similar studies in other regions, trying to relate legume quality and management to nutrient release and N_2O emissions.

L482-482: I understood that the researchers didn't measure the N 'carry over effects'. So this point is speculative.

Response: Yes, we speculate here.

L485-487: this statement could be verified at least against the soil moisture data.

Response: Daily rainfall is shown in figures 1d, 1g and 4d, 4g.

L494: please consider environmental conditions instead of referring to sowing date alone. You could also discuss what would be the incentives for farmers to reduce N_2O emissions.

Response: We agree. We added a sentence reading: *"This is complicated by the annual variability in growth conditions and requires active planning of sowing and mulching time by the farmers."*

L500: indeed more studies would be needed to confirm and to explain the results obtained. I would suggest reflecting on the need to quantify N_2 fixation, and to follow N mineralisation, especially key for legumes.

Response: We fully agree and have changed the sentence accordingly: *"Future studies should attempt to combine flux measurements with inorganic N dynamics and BNF measurements".*

Anonymous Referee #2

Received and published: 13 September 2019

This study looking at soil N_2O and CH_4 in agricultural systems of Sub-Saharan Africa addresses a significant gap in the body of literature exploring GHG exchange in intensively-managed soils, both through its location in an understudied area, and the aim to understand the relationship between inter-crop timing and N_2O emissions. Although the article does need to be further edited for grammar/phrasing, it is generally well written. However, there are some issues with clarity I'd like to see addressed, which I expand on below. Specific comments: Note: Phrases in quotations are suggested changes.

Response: We thank the reviewer for recognizing the validity of our study, and particularly for noticing our efforts to elucidate the relationship between intercrop timing, legume biomass development and N_2O emissions.

Introduction Line 40: Specifically define what CSA means in terms of management. The previous sentence defined intensification as 'increased use of inorganic fertilizers', and then CSA is introduced as, 'in contrast...' but the text doesn't in fact provide a contrast, instead outlining the ideals of the CSA concept.

Response: The reviewer is right. We remove 'by contrast' because there is no contrast.

Line 82: As you go on to explain, abundant NH4 can inhibit methanotrophs, but may not always. Important to make that distinction here.

Response: We agree. The sentence has been rephrased using conditional "… might inhibit methanotrophs" to avoid misunderstanding.

Materials and Methods

In general, please try to provide as much detail as possible, grouping information in a way that it is easy to find.

Line 120: "The field experiment was conducted for two years (2015-2016) at the Hawassa..."

Rephrased

Line 128-145: List exactly what the six treatments were, before going on to give details about planting and fertilizer application. Also, be specific about what happened when in each treatment, including when and how the legumes were mulched and applied.

Response: Thank you for drawing our attention to this omission. We now added a detailed treatment description including the exact timing of mulching.

Line 147: Were there live plants in the chambers during sampling or were those first removed?

Response: Legumes were included in the chambers, on average 3 lablab plants and 4-5 crotalaria plants.

Line 149: Are the chambers used in this study the same as those in Rochette et al.? If not, as the chambers were custom-made, a bit more detail about them would be useful. Some information to include: The chambers did not have permanent bases, correct? How deep into the soil were they pressed?

Response: No, they were not identical to the chambers devised by Rochette et al. (2008). By accident we cited the wrong study by Rochette et al. (2008). This ref has now been replaced by Rochette, P., Eriksen-Hamel, N.S.: Chamber measurements of soil nitrous oxide flux: Are absolute values reliable? Soil Sci. Soc. Am. J., 72, 331-342, 2008, which gives a general outline of the static chamber method. The chambers did not have permanent bases but were pushed gently about 3 cm into the soil and sealed with moist clay from outside. The insertion depth is now added to the text.

Was the volume provided in the text (Line 148), the volume before or after the chamber was pressed into the soil? How much time was there between deployment and the first sample? Were they always measured in the same location? Do you think that soil disturbance from deployment may have affected the samples? Were the chambers vented?

Response: The number given in the text denotes the chamber volume after pushing it into the soil. The chambers were deployed randomly within the same maize row of each treatment plot to avoid disturbance. The chambers were not vented, but the sampling septum was removed when pressing the chambers into the soil to avoid perturbation of the concentration gradient. This information has now been added.

Line 153: The four samples were at 0, 15, 30 and 45 minutes? Or 15, 30, 45 and 60?

Response: Immediately after closing the chamber and sealing with soil, sampling starts (1 minute) and then at 15 minute intervals, hence 0, 15, 30, 45 minutes. The text has been changed accordingly.

Line 172: Were all results less than R2=0.85 rejected? (I.e. were net 0 emissions/uptake rejected?) If so, do you think that may have biased your results?

Response: No fluxes were rejected. Regression coefficients were generally >0.85

Results

Line 243: "Irrespective of legume species, the highest emission rates..."

Corrected

Line 244-247: What about the sixth treatment? Was it significantly different than that?

Response: Thank you for drawing our attention to this. N2O emissions were significantly higher than in the fertilized control in both the 3-weel lablab and the 3-week crotalaria systems. The text is changed accordingly.

Discussion

In this section, it would be helpful to go back to the original hypotheses and specifically outline how the results compared and why.

Response: We added a sentence contrasting the findings discussed in chapter 4.1. with our original hypothesis.

Line 333: Provide range from Pelster et al.

Done

Line 341-342: Is that consistent with other mulching studies?

Response: There are not many studies to compare our results with, particularly not in SSA. Moreover, findings on the effect of mulching on N2O emissions are inconsistent, presumably because they depend on weather (soil moisture) as in our study. See also Basche et al. (2014), doi:10.2489/jswc.69.6.471

Line 344: You provide a topic sentence here, which ends with: species, inter-cropping time and weather. I'd suggest following that up by expanding on each of those in the order you present them in that sentence.

Response: The text is now rearranged and expanded following the reviewer's suggestion.

Line 353: Can you provide a reference for 'notoriously high'?

Response: We added Flessa et al (1995) who measured in various cropping systems, including cover and catch crops.

Line 363-366: Remove details of how the data was analyzed (that is in the results section) and just focus on the meaning of the results shown in the figure.

Removed

Line 380-382: Is that consistent with other mulching studies?

Response: Increased N cycling in spring after mulching is occasionally observed. We added Campiglia et al. (2011) as a reference for this

Line 386-389: I don't understand this. Something was at par and then not significantly different? Please rephrase and perhaps provide a reference to the Table/Figure with the results that you are discussing.

Rephrased

Line 487: Provide reference to Table/Figure.

Done

Tables and Figures

Note that these should always be able to stand alone (i.e. all necessary information required to understand them should be included). For all tables and figures, please define any abbreviations (i.e. Table 1 – DMY), remove references to previous sections (i.e. Table1–refer to M/M, Fig. 5–refer to Fig. 2), and include basic information about the study (e.g. Table 1 – N inputs from forage legumes and fertilizer application in plots of maize inter-cropped with legumes 3 and 6 weeks after planting.)

Response: We thank the reviewer for the these editorial remarks which we follow eagerly

Technical corrections:

Line 114/115: Rephrase.

Response: The sentence was rephrased to: "*Choosing legume species, and sowing date and accounting for potential N inputs from legume intercrops, thus could allow to for better management of legume intercropping in SSA with reduced GHG emissions*"

Line 212: Capitalization.

Done

Line 314: Remove neither/nor and just use 'or'.

Done

There are many small editing errors in the Discussion that need to be corrected. Some examples:

Line 334: Owing?

Rephrased

Line 337: "was too small"

Fixed

Line 371: "owing to early"

Fixed

Line 374: "legume and main crops"

Fixed

Line 380: Capitalization

Table 1 – consider reformatting using spacing rather than lines, as the bold lines make it difficult to read

Reformatted

Effect of legume intercropping on N_2O emission and CH_4 uptake during maize production in the Ethiopian Rift Valley

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Abstract

Intercropping with legumes is an important component of climate smart agriculture (CSA) in sub-Saharan Africa, but little is known about its effect on soil greenhouse gas (GHG) exchange. A field experiment was established at Hawassa in the Ethiopian rift valley, comparing nitrous oxide (N_2O) and methane (CH_4) fluxes in minerally fertilized maize (64 kg N ha^{-1}) with and without crotalaria (*C. juncea*) or lablab (*L. purpureus*) as intercrops over two growing seasons. To study the effect of intercropping time, intercrops were sown either three or six weeks after maize. The legumes were harvested at flowering and half of the above-ground biomass was mulched. In the first season, cumulative N_2O emissions were largest in 3-week lablab, with all other treatments being equal or lower than the fertilized maize monocrop. After reducing mineral N input to intercropped systems by 50% in the second season, N_2O emissions were ~~at par~~comparable with the fully fertilized control. Maize yield-scaled N_2O emissions in the first season increased linearly with above-ground legume N-yield (~~p~~P=0.01), but not in the second season when early rains resulted in less legume biomass because of shading by maize. Growing season N_2O-N emission factors varied from 0.02 to 0.25 and 0.11 to 0.20% of the estimated total N input in 2015 and 2016, respectively. Growing season CH_4 uptake ranged from 1.0 to 1.5 kg CH_4-C ha^{-1} with no significant differences between treatments or years, but setting off the N_2O-associated ~~global warming potential~~ emissions by up to 69%. Our results suggest that ~~high yielding~~ leguminous intercrops ~~entail some risk for increased~~may increase N_2O emissions when ~~used together with recommended fertilization rates~~developing large biomass in dry years, but when mulched, can replace part of the fertilizer N

~~without compromising maize yields in the following year and~~in normal years, thus ~~support~~supporting CSA goals while intensifying crop production in the region.

Key words: yield-scaled N_2O emissions, CH_4 uptake, legume-intercropping, maize, Africa

1. Introduction

With a rapidly increasing population and declining agricultural land in Sub-Saharan Africa (SSA), increasing productivity per area (intensification) is the only viable alternative for producing sufficient food and feed (Hickman et al., 2014a). Intensification entails increased use of inorganic fertilizers, which may cause ~~N_2O~~ emissions ~~and~~ of nitrous oxide (N_2O). Abundant ammonium (NH_4^+) may also reduce the soil CH_4 sink ~~(Castro et al., 1994, Xie et al., 2010).~~by competing with CH_4 for the active binding site of methane monooxygenase, the key enzyme of CH_4 oxidation (Bédard and Knowles, 1989). Climate smart agriculture (CSA~~), by contrast,~~) has been proposed as a way forward to simultaneously increase agricultural productivity~~ and profits~~, while increasing climate resilience and reducing greenhouse gas (GHG) emissions (Neufeldt et al., 2013). However, ~~understanding of~~ greenhouse gas ~~emissions from~~ emission measurements in SSA crop production ~~in SSA in general~~systems are scarce and ~~CSA in particular is limited and~~proof-of-concept for the mitigation potential of ~~crop production in SSA as a source or sink of the greenhouse gases CO_2, N_2O, and CH_4 is understudied~~specific CSA practices is missing (Kim et al., 2016, Hickman et al., 2014b). Moreover, modelling studies predict significant negative impacts of climate change on crop productivity in Africa (Blanc and Strobl, 2013) and it is largely unknown how these and the countermeasures taken to maintain agricultural productivity will affect GHG emissions.

Crop production is a major source of ~~nitrous oxide (~~N_2O~~),~~, the third-most important anthropogenic GHG after CH_4 and CO_2 (IPCC, 2014). Emission rates of N_2O reported for SSA crop production so far are low (Kim et al., 2016) owing to low fertilization rates, but may increase with increasing intensification. Inorganic and organic N added to soil provide ammonium (NH_4^+) and nitrate (NO_3^-) for nitrification and denitrification, respectively, which are the two main processes of microbial N_2O production in soil (Khalil et al., 2004). The rate of N_2O formation ~~in upland soils~~ depends greatly on the extent and distribution of anoxic microsites in soils, which is controlled by~~ soil~~ moisture, texture and the distribution of decomposable organic matter and NH_4^+ fueling heterotrophic and autotrophic respiration, respectively (Schlüter et al., 2019, Wrage-Mönnig et al., 2018). The magnitude of soil N_2O emissions depends on O_2 availability as controlled by soil moisture and respiration, availability of mineral N and readily decomposable C (Harrison-Kirk et al., 2013) and soil pH (Russenes et al., 2016), all of which ~~depend on soil~~ are affected by management practices. Other important factors are soil type (Davidson et al., 2000) and temperature (Schaufler et al., 2010). The N_2O yield of nitrification ~~(Nadeem et al., 2019)~~ and the production and reduction of N_2O during denitrification ~~(Bakken et al., 2012)~~ are further controlled by soil pH (Bakken et al., 2012, Nadeem et al., 2019) and by the balance between oxidizable carbon and available NO_3^- (Wu et al., 2018). Mulching and incorporation of crop residues leads to increased N mineralization and respiratory O_2 consumption, thus potentially enhancing N_2O emissions both from nitrification and denitrification (Drury et al., 1991), if soil moisture is sufficient to support microbial activity and restrict O_2 diffusion into the soil. Accordingly, N_2O emissions are variable in time, often following rainfall events (Schwenke et al., 2016).

Crop diversification by combining legumes with cereals, both in rotation and intercropping, enhances overall productivity and resource use efficiency, if managed properly (Ehrmann and Ritz, 2014). Intercropping of maize with grain legumes is common in the rift valley of Ethiopia and central component in CSA (Arslan et al., 2015). In low input systems common to the Rift Valley, integration of legumes with cereals diversifies the produce and improves ~~the nitrogen nutrition of the cereal.~~farm income and nutritional diversity for smallholder farmers (Sime and Aune, 2018). Moreover, by partially replacing energy-intensive synthetic N, intercropping with legumes may increase the sustainability of the agroecosystem as a whole (Carranca et al., 2015). However, to make best use of the resource use complementarity of inter and main crop, the planting time of the intercrop has to be optimized so that the maximum nutrient demand of the two components occurs at different times (Carruthers et al., 2000). The timing of intercrops could also affect N_2O emissions if N mineralization from legume residues is poorly synchronized with the N requirement of the cereal crop. This can be counteracted by reducing mineral N additions to intercropping systems, but the timing of the intercrop (sowing date relative to the cereal crop) remains an issue that has, to the best of our knowledge, not been studied with regard to N_2O emissions.

Intercropping and mulching may also affect the soil's capacity to oxidize atmospheric CH_4 as abundant NH_4^+ ~~inhibits~~might inhibit methanotrophs (Laanbroek and Bodelier, 2004). However, field studies with incorporation of leguminous or non-leguminous catch crops have been inconclusive (e.g. Sanz-Cobena et al., 2014). In a meta-study on CH_4 fluxes in non-wetland soils, Aronson and Helliker (2010) concluded that N inhibition of CH_4 uptake is unlikely at fertilization rates below 100 kg N ha^{-1} y^{-1} and that much to the contrary, N addition may stimulate CH_4 uptake in N-limited soils. Ho et al. (2015) found that incorporation of organic residues stimulated CH_4 uptake even in fairly N-rich Dutch soils. ~~Intercrops~~Apart from providing reactive nitrogen to the soil, leguminous intercrops may ~~indirectly~~also affect CH_4 uptake by lowering soil moisture and thus ~~increase~~increasing the diffusive flux of atmospheric CH_4 into the soil. ~~Accordingly~~For instance, Wanyama et al. (2019) found that CH_4 uptake ~~to be~~in soil was negatively correlated with mean annual water-filled pore space in a study on different land use intensities in Kenya.

In a review on N_2O fluxes in agricultural legume crops, Rochette and Janzen (2005) concluded that the effect of legumes on N_2O emission is to be attributed to the release of extra N by ~~root exudation~~rhizodeposition of soluble N compounds and decomposition of nodules rather than to the process of nitrogen fixation itself. Intercropped legumes may thus affect N_2O emissions in two ways: by directly providing organic N or by modulating the competition between plants and microbes for soil N~~.~~, for example by acting as an additional N sink prior to nodulation. Compared to mineral fertilizers, N supply from biological fixation is considered environmentally friendly as it can potentially replace industrially fixed N (Jensen and Hauggaard-Nielsen, 2003), provided that crop yields remain the same. However, combining easily degradable crop residues with synthetic N can lead to elevated N_2O emissions (Baggs et al., 2000), potentially compromising the environmental friendliness of intercropping in CSA. It is well known that the effect of crop residues on N_2O emission depends on a variety of factors such as residue amount and quality (C:N ratio, lignin and cellulose content), soil properties (e.g. texture), placement mode (mulching, incorporation) and soil moisture and temperature regimes (Sanz-Cobena et al., 2014, Li et al., 2016). So far, there is only a limited number of studies addressing the effect of legume intercropping on N_2O emissions and CH_4 uptake in SSA crop production (Baggs et al., ~~2000~~2006; Millar et al., 2004; Dick et al., 2008).

The main objective of the present study was to evaluate the effects of forage legume intercropping ~~of~~with maize on N_2O and CH_4 emissions during maize production in the Ethiopian Rift Valley. We hypothesized that forage legumes increase N_2O emissions and decrease CH_4 uptake depending on above-ground biomass, legume species and sowing date; legumes intercropped three weeks after sowing of maize would result in higher yields than those intercropped six weeks after maize and lead to increased N_2O emissions if used with full-dose mineral fertilization. With late intercropping, ~~legumes~~legume yields would be suppressed having no or little effect on N_2O ~~emission. Choosing~~emissions. Hence, choosing legume species~~ and~~, sowing date and accounting for potential N inputs from legume intercrops~~, thus~~ could allow ~~to manage~~for better management of legume intercropping in SSA with reduced GHG emissions.

2. Materials and methods

2.1 Study area

The field experiment was conducted during two years (2015-2016) at the Hawassa University Research Farm, 07°3’3.4”N and 38°30”20.4’E at an altitude of 1660 m a.s.l~~.~~.. The mean annual rainfall is 961 mm, with a bimodal pattern. The rainy season between June and October accounts for close to 80% of the annual rainfall. Average maximum and minimum monthly temperatures are 27.4 and 12.9°C, respectively. The soil is ~~a~~ clay~~-~~-loam (46% sand, 26% silt, 28% clay) derived from weathered volcanic rock (Andosols), with a bulk density of 1.25 ± 0.05 g cm^{-3}, a total N content of 0.12%, an organic C content of 1.64~~ ~~%, an available Olsen P content of 175 mg kg^{-1} and a pH_{H2O} of 6.14.

2.2 Experimental design and treatments

Experimental plots (20 m^2) with six treatments were laid out in a complete randomized block design (RCBD) with four replicates~~ (Tab. 1).~~: unfertilized maize monocrop (M-F), fertilized maize monocrop (M+F), crotalaria intercropping three (M+Cr3w) and six (M+Cr6w) weeks after sowing maize and lablab intercropping three (M+Lb3w) and six (M+Lb6w) weeks after sowing maize (Table 2). Seed bed was prepared in both years by mold board plow to a depth of 0.25 m followed by harrowing by a tractor. A hybrid maize variety, BH-540 (released in 1995) was sown on May 30 and May 7 in 2015 and 2016, respectively. Maize was planted at a density of 53,333 plants ha^{-1}. Following national fertilization recommendations, diammonium phosphate (18 kg N, 20 kg P) was applied manually at planting and urea (46 kg N) four weeks after sowing maize, except for the unfertilized control. The N fertilization rate was halved for the intercropping treatments in the 2016 season to account for carry-over of N from forage legumes grown in the previous year. The forage legumes crotalaria (*C. juncea*) and lablab (*L. purpureus*) were planted between maize rows at a density of 500,000 and 250,000 plants ha^{-1}, respectively.

The above-ground forage legume biomass was harvested at flowering and half of it was removed. The remaining half was spread manually between the maize rows after cutting the fresh biomass into ~10 cm pieces. Three- and 6-week intercrops were mulched on 27 July and 4 September and 2 August and 8 September in 2015 and 2016, respectively. As the mulching was done plot wise, plots within the same treatment received different amounts of mulch depending on the legume yield of each plot. In the 2016 growing season, all treatments were kept on the same plots as in 2015, capitalizing on plot-specific N and C input from previous mulch. Aboveground dry matter yield was determined by drying a subsample at 72^{o}C for 48 hours and C and N contents were measured by an element analyser.

2.3 N_2O and CH_4 fluxes and ancillary data

GHG exchange was monitored ~~between~~weekly at random spots within the middle maize ~~rows~~row by static, non-vented chambers (Rochette et al., 2008~~), using~~). We used custom-made aluminum chambers with an internal volume of 0.144 m^3 and a cross-sectional area of 0.36 m^2. ~~Upon deployment, the~~The chambers were pushed gently ~3 cm into the soil including 2 - 5 legume plants before closing the septum and ~~sealed~~sealing the chambers around their circumference with moist clay~~ to minimize leakage~~.

Sampling was carried out weekly during the period June to September~~,~~ in 2015 and May to September~~,~~ in 2016 on 15 and 17 sampling dates, respectively. Gas samples were collected between 9:00 ~~AM~~am and 2:00 ~~PM~~pm. For each flux estimate, four gas samples were drawn from the chamber headspace at 15 min intervals, ~~using~~starting immediately after deployment. Samples were taken with a 20 ml polypropylene syringe equipped with a 3-way valve. Before transferring the sample to a pre-evacuated 10 cc serum vial crimp-sealed with butyl septa, the sample was pumped 5 times in and out of the chamber to obtain a representative sample. Overpressure in the septum vials was maintained to protect the sample from atmospheric contamination during storage and shipment to the Norwegian University of Life Sciences, where the samples were analyzed by gas chromatography. ~~He~~Helium-filled blank vials were included to evaluate contamination, which was found to be less than 3% of ambient.

All samples were analyzed on a GC (Model 7890A, Agilent Santa Clara, CA, USA) connected to an auto-sampler (GC-Pal, CTC, Switzerland). Upon piercing the septum with a hypodermic needle, ca. 1 ml sample is transported via a peristaltic pump (Gilson minipuls 3, Middleton, W1, USA) to the GC's injection system, before reverting the pump to backflush the injection system. The GC is configured with~~ two back-flushed pre-columns and~~ a Poraplot U wide-bore capillary column connected to a thermal conductivity, a flame ionization and an electron capture detector to analyze CO_2, CH_4 and N_2O, respectively. Helium 5.0 was used as carrier and Ar/CH_4 (90:10 vol/vol) as makeup gas for the ECD. For calibration, two certified gas mixtures of CO_2, N_2O and CH_4 in ~~He~~Helium 5.0 (Linde-AGA, Oslo, Norway), one at ambient concentrations and one ca. 3 times above ambient were used. A running standard (every tenth sample) was used to evaluate drift of the ECD signal. Emission (CO_2, N_2O) and uptake (CH_4) rates were estimated by fitting linear ($R^2 \geq 0.85$) or quadratic functions to the observed concentration change in the chamber headspace and converting them to area flux according to eq. 1

$$F_{GHG\ (\mu g\ m^{-2} h^{-1})} = \frac{dc}{dt} * \frac{Vc}{A} * \frac{Mn}{Vn} * 60 \qquad \text{Eq. (1)}$$

where, F_{GHG} is the flux (μg N_2O-N m^{-2} h^{-1} in case of N_2O; μg CH_4-C in the case of CH_4), $\frac{dc}{dt}$ the rate of change in concentration over time (ppm min^{-1}), V_c the volume of the chamber (m^3), A the area covered by the chamber (m^2), M_n the molar mass of the element in question (g mol^{-1}) and Vn the molecular volume of gas at chamber temperature (m^3 mol^{-1}). A quadratic fit was only used in cases where N_2O accumulation in the chamber showed a convex downwards and CH_4 uptake a convex upwards trend (i.e. decreasing emission or uptake rates with time) to estimate time-zero rates. Fluxes were cumulated plot-wise by linear interpolation for each growing season.

In 2016, soil moisture and temperature at 5 cm depth were monitored hourly using data loggers (Decagon EM50, Pullman, WA, USA) together with ECH$_2$O sensors (Decagon) for volumetric soil water content (VSWC) and temperature at five points across the experimental field. The sensors were placed in ~~control, M+Cr3w and M+Lb3w (2).~~the experimental field at 5 random spots. No data are available for the 2015 season, due to equipment failure.

~~Intact soil~~Soil bulk density was measured at 10 random spots in the experimental field using 100 cm^3 steal cylinders and ~~an assumed particle density of 2.65g cm^{-3} were used to~~drying them at 105

°C for 24 hours. To calculate daily water filled pore space values for the 2016 growing season, a particle density of 2.65 g cm^{-3} was assumed:

$$WFPS = VSWC/(1 - \frac{BD}{PD}) * 100 \qquad \text{Eq. (2)}$$

where *WFPS* is the water filled pore space, *VSWC* the volumetric soil water content, *BD* the bulk density and *PD* the particle density~~ which was set to 2.65 g cm^{-3}~~~~.~~. Daily rainfall data were collected using an on-site rain gauge~~ monitored daily during the growing season~~.

2.4 Estimating N inputs and N_2O emission factors

N input from forage legume crop residues was estimated from measured above-ground dry matter yield, its N content and the amount of mulch applied. To account for belowground inputs a shoot to root ratio of two was assumed for both crotalaria and lablab (Fageria et al., 2014). Dry matter yields of forage legumes differed greatly depending on sowing time, with generally larger yields in 3-week than 6-week intercropping. Also, forage legumes sown three weeks after maize grew faster and were harvested and mulched earlier than those sown six weeks after maize. We assumed that 50% of the legume N (mulched and belowground) was released during the growing season but reduced this amount to 30% for the aboveground component (mulch) of the 6-week treatments to account for the later mulching date. The proportions becoming available during the growing seasons are conservative estimates based on Odhiambo (2010), who reported that about 50% of N contained in crotalaria, lablab and mucuna was released during a 16-week incubation experiment at optimal temperature and moisture conditions. Placing litter bags into dry surface soil, Abera et al. (2014) found that legume residues decomposed rapidly under *in situ* conditions in the Ethiopian Rift Valley, releasing up to 89% of the added N within 6 months.

For the second year, 50% of the N left after the growing season (below and aboveground) was assumed to become available, on top of the N-input from the newly sown forage legumes. Dry matter yields of forage legumes and estimated N input for the two years are presented in ~~table~~Table 1.

Treatment-specific, growing-season N_2O emission factors were calculated as:

$$N_2O\ EF = \frac{(N_2O_{treatment} - N_2O_{control})}{N\ input} * 100 \qquad \text{Eq. (3)}$$

where $N_2O\ EF$ is the N_2O emission factor (% of N input lost as N_2O-N), $N_2O_{treatment}$ the cumulative N_2O-N emission (from sowing to harvest) in the fertilized and intercropped treatments, $N_2O_{control}$ the emission from the 0N0P treatment (background emission) and N_{input} the estimated total input of N.

Non-CO_2 GHG emissions were calculated as CO_2 equivalents balancing cumulative seasonal N_2O-N emissions with CH_4 uptake on the plot level and averaging them for treatments (Table 2, Fig. 5).

2.5 Grain yields and yield-scaled N_2O emissions

Maize grain yield was determined by manually harvesting the three middle rows (to avoid border effects) of each plot, and was standardized to 12.5% moisture content~~.~~ using a digital grain moisture meter. All values were extrapolated from the plot to the hectare. To estimate yield-scaled N_2O emissions (g N_2O-N ton^{-1} grain yield), cumulative emissions were divided by grain yield.

2.6 Statistical analysis

Differences in cumulative CH_4 and N_2O emissions between treatments in each cropping season were tested by analysis of variance (ANOVA) with LSD used for mean separation after testing the data for normality and homoscedasticity. Cumulative seasonal N_2O emissions for 2015 were log-transformed. Statistical significance was declared at $P \leq 0.05$.

3. Results

3.1 Weather conditions

The year 2015 was one of the most severe drought years in decades and, as a result, sowing in 2015 was delayed by 3 weeks as compared to 2016. Rain fell late during the growing season and the cumulative rainfall for April to October was about 100 mm lower in 2015 than in 2016 (Fig. 1d~~ and 1g~~, g).

3.2 N_2O fluxes

N_2O emission rates in 2015 (treatment means, n=4) ranged from 1.1 to 13.7 μg N m^{-2} h^{-1} for the control treatment~~, with no obvious peaks~~ (Fig. 1a). Similarly, for fertilized maize, N_2O emissions ranged from 2 to 23.5 μg N m^{-2} h^{-1}. Emission fluxes were generally larger for the intercropped treatments: crotalaria treatments emitted N_2O at rates of 1.7 - 34.3 and 2.1 – 24.2 µg N m^{-2} h^{-1} when intercropped 3 or 6 weeks after maize, respectively, while maize-lablab emitted 1.9 – 62.7 µg N m^{-2} h^{-1} when sown 3 weeks and 1.5 - 10.7 µg N m^{-2} h^{-1} when sown 6 weeks after maize. The generally low emission rates in the latter system (6-weak lablab intercropping) corresponded to poor growth of lablab due to shading by the maize plants. Irrespective of legume species, the highest emission rates were found for intercrops planted three weeks after maize (Fig. 1b~~ and 1c~~, c). A peak of N_2O emission occurred in the 3-week ~~maize-lablab system~~intercropping systems around mid-August, 2015, which was significantly larger than in the unfertilized control (P=0.013), the fertilized maize monocrop (P=0.001), ~~or~~ and the 6 weeks crotalaria (P=0.021) and lablab (P=0.002) ~~intercropped 6 weeks after maize~~intercrops.

During the 2016 season, N_2O emission rates in the 0N-control varied between 2.5 and 22.8 µg N m^{-2} h^{-1}, peaking at the beginning of the season when WFPS was >50%. There were no significant differences in WFPS values between treatments (data not shown). Fertilized maize had similar rates (3.1 - 24.2 µg N m^{-2} h^{-1}) peaking at around four weeks after planting. Maize-forage legume treatments had larger emission rates, ranging from 1.8 to 40.2 and 3.2 to 58.6 for crotalaria planted 3 and 6 weeks after maize, respectively and 3.9 to 38.0 and 1.9 to 45.2 µg N m^{-2} h^{-1} for lablab planted 3 and 6 weeks after maize, respectively. In general, emission rates were higher in the beginning than in the end of the cropping season (Fig. 1d-f). Despite higher fluxes for intercropping treatments than in the unfertilized control in week 1 (P=0.162) and 4 (P=0.061), there were no statistically significant differences in flux rates between the treatments.

3.3 Cumulative N_2O emissions

During the 2015 growing season, all treatments had equal or higher cumulative N_2O emissions than the unfertilized control, with the 3-week lablab intercropping system emitting significantly more N_2O than the unfertilized control (p=0.006) and the 6-week lablab intercrop (Fig. 2a). Comparing intercropping treatments with the fertilized control, lablab sown ~~three~~3 weeks after maize clearly increased N_2O emissions but not significantly (P=0.35), whereas all other intercropping treatments had cumulative N_2O emissions comparable with fertilized maize control. Regarding sowing date, 3-week lablab had significantly higher N_2O emissions (P<0.01) than its 6-week counterpart, whereas no such effect was seen for crotalaria.

During the 2016 growing season, lablab intercropping 3-weeks after maize showed significantly higher ($P<0.01$) cumulative N_2O emissions than the unfertilized control, but there was no difference between fully fertilized maize monocrop and intercropped maize treatments fertilized with 50% of the mineral N applied in 2015, nor was there any effect of intercropping date (3 vs. 6 weeks; Fig. 2b).

3.4 Legume and maize yields

Aboveground yields of lablab were generally higher than those of crotalaria (Table 1). Intercropping three weeks after maize resulted in higher biomass yields compared to six weeks for both legume species. Both legumes grew poorly during the second growing season, particularly crotalaria. Maize grain yields differed greatly between the years and were roughly 20% higher in the wetter year of 2016 (Table 2). Better growth conditions for maize in the second year resulted in smaller yields of intercrop legumes.

3.5 N_2O emission factor and intensity

Growing-season emission factors (EF) varied from 0.02 to 0.25 and 0.11 to 0.20% in 2015 and 2016, respectively (Table 2). Of the intercropped treatments, lablab intercropped ~~three~~3 weeks after maize resulted in a significantly larger emission factor than fertilized maize and other intercropping treatments, whereas there was no significant difference in 2016. Overall, growing-season N_2O emission factors were ~ 40% higher in 2016 than in 2015, which is mainly due to the smaller N input in 2016 which was 25 to 45% lower than in 2015, except for the 3-week lablab system which had an estimated 18% higher N input in 2016 than 2015 (Table 1). The latter was due to the extraordinary high lablab yield in the previous year and its stipulated carryover (Table 1).

Mean yield-scaled N_2O emissions in 2015 varied between 25 to 55 g N_2O ton^{-1} grain yield. In 2015, 3-week lablab had a higher N_2O intensity than 6-week lablab, whereas all other differences were insignificant. In 2016, with mineral N fertilization reduced to 50%, N_2O emission intensities varied from 26 to 37 g N_2O ton^{-1} grain, with no significant effect of legume species, sowing date or N fertilization (Table 2).

To further explore the variability of N_2O emissions, we plotted cumulative N_2O emissions plot-wise against legume N yield, but found no relationship (not shown). However, when plotting yield-scaled N_2O emission over legume N yield, a significant positive relationship ($P=0.01$) emerged for

2015, but not 2016 (Fig. 3a~~ and 3b~~, b), suggesting that leguminous N input increased N_2O emissions more than maize yields in the dry year of 2015.

3.6 CH_4 fluxes

All treatments acted as net sink for CH_4, with uptake rates ranging from 31 to 93 µg C m^{-2} h^{-1} in 2015 (Fig. 4a-c). Uptake rates in 2015 were rather constant in time with somewhat elevated uptake rates towards the end of the season. There were no obvious treatment effects. By contrast, in the wetter year of 2016, CH_4 uptake showed a pronounced maximum in the beginning of June with uptake rates of up to 140 µg C m^{-1} h^{-1} irrespective of treatment (Fig. 4d-f), when WFPS values declined to values below 25% (Fig. 4g). Methane uptake during this period tended to be greatest in the unfertilized control, while intercropping treatments had smaller uptake rates, which, however, were not significantly different from maize monocrop treatments. Differences between treatments at single sampling dates were insignificant throughout the season. Highest CH_4 uptake in 2016 was recorded with lowest WFPS (~10%).

3.7 Cumulative CH_4 uptake

Cropping season cumulative CH_4 uptake exceeded 1 kg C ha^{-1} in both years with no significant effect of intercropping, legume species or time of intercropping (Fig. S1a~~ and S1b). Plots~~, b). Maize intercropped with crotalaria tended to take up less CH_4 but this effect was not statistically significant in ~~neither ~~2015 ~~nor~~or 2016 (P=0.056). Plotting cumulative CH_4 uptake plot-wise over legume dry matter yield did not result in a significant relationship, but highest seasonal uptake rates occurred in plots with lowest legume dry matter yield (data not shown).

3.8 ~~Non~~Total non-CO_2 ~~GWP~~

~~Non-CO_2 global warming potentials (GWP) were calculated as CO_2 equivalents balancing cumulative seasonal N_2O-N~~**GHG emissions**~~ with CH_4 uptake on the plot level and averaging them for treatments (Table 2, Fig. 5).~~

The relative contribution of CH_4 to the non-CO_2 ~~GWP~~GHG emission of the different cropping systems varied between 22 and 69% and was highest in the non-fertilized maize monocrop. Three-week lablab intercropping resulted in significantly higher ~~GWP~~total emissions compared with 6-week lablab intercropping and maize mono-cropping (Table 2). By contrast, in 2016, legume species but not intercropping time affected the ~~GWP~~non-CO_2 GHG emission balance (P<0.05). Lablab intercropped 3 weeks after maize resulted in significantly higher (P<0.05) ~~GWP~~total GHG emission than the unfertilized control but was indistinctive from the fertilized maize monocrop, or other intercrop treatments (Table 2, Fig. 5a~~ and 5b~~, b).

4. Discussion

4.1 Maize-legume intercropping and N_2O emissions

Background N_2O emissions (in unfertilized maize monocrop) fluctuated between 1.1 and 23.0 µg N_2O-N m^{-2} h^{-1}, which is in the range of previously reported emission rates for soils in SSA with low N fertilizer input (0 – 20 µg N_2O-N m^{-2} h^{-1}; Pelster et al., 2017). Baseline emissions were somewhat higher in the wetter season of 2016, owing to ~100 mm more rainfall in the beginning of the season (Fig. 1d~~ and 1g~~, g). Elevated emission rates >30 µg N_2O-N m^{-2} h^{-1} occurred in 2015 on few occasions in intercrop treatments, notably in mid-August when ~~rainfall occurred~~rain fell right after mulching of the ~~three~~3-week intercrops. Mulching of the ~~six~~6-week intercrops did not affect N_2O ~~emission~~emissions, probably because the mulched legume biomass was too small to affect the flux (Fig. 1b, ~~1c~~c; Table 1). In 2016, mulching of the 3-week legumes was followed by rainfall, increasing the WFPS to 50% (Fig. 1g), however, without resulting in elevated N_2O emission rates (Fig. 1e, ~~1f~~f). Together, this suggests that the direct effect of mulching on N_2O emission ~~depends~~is highly dependent on soil moisture and the amount of ~~mulched biomass,~~mulch and ~~can hence not~~cannot be generalized~~.~~, contrary to our hypothesis that legume intercrops would invariably increase N_2O emissions.

Legume dry matter yields varied strongly (100 to 3000 kg ha^{-1}) throughout the two experimental years (Table 1, Fig. 3), depending on species, intercropping time and weather. ~~Three-week intercrops performed generally better than six-week intercrops, which appeared to be inhibited in growth by shading through maize. This was particularly apparent for the low-growing lablab legume. In terms of legume biomass, lablab~~Lablab grew more vigorously and realized larger dry matter yields than crotalaria (Table 1). Moreover, lablab is known to be a better N_2 fixer than crotalaria (Ojiem et al., ~~2007).~~2007), presumably leading to higher N input, which would explain larger N_2O emissions with this intercrop (Fig. 2). Three-week intercrops performed generally better than 6-week intercrops. This was particularly apparent for the low-growing lablab (Table 1). Weather in the beginning of the season played a major role for the growth performance of the intercrops by controlling maize growth, which in turn controlled legume growth by shading. Together, this resulted in a wide range of potential leguminous N-inputs in our experiment, which could be used to examine their overall effect on N_2O emissionemissions on a seasonal basis under the semi-arid conditions of the central Ethiopian rift valley conditions on a seasonal basis. Surprisingly, we did not find any significant relationship between estimated total N input or legume N yield and cumulative N_2O emission. This may be due to the notoriously high spatial and temporal variability of N_2O emissions rates within treatments,(Flessa et al., 1995), or reflect the fact that intercropping had no or opposing effects on N_2O forming processes. Cumulative N_2O emissions and legume N yields integrate over the entire season and do not capture seasonal dynamics of soil N cycling and N uptake, which could obscure or cancel out transient legume effects on N_2O emissions. Possibly, N released in intercropping treatments was effectivelyefficiently absorbed by the main crop, even though intercropping did not lead to significantly higher maize grain yields in our experiment. Alternatively, changes in physicochemical conditions brought about by intercrops, such as potentially lower soil moisture due to more evapotranspiration, may have counteracted the commonly observed stimulating effect of legume N on N_2O emissions (Almaraz et al., 2009, Sant'Anna et al., 2018).

To further elucidate the N_2O emission response to legume intercropping, we plotted cumulative N_2O emissions normalized for grain yields ("N_2O intensity") plot-wise over measured legume N yields, thereby utilizing the wide range of potential leguminous N inputs provided by our experiment. A significantlyWe found a significant positive relationship between N_2O intensity and legume N yields emerged forin 2015, suggesting that intercropped legumes indeed increase N_2O emissions relative to maize yields (Fig. 3a). It is impossible to say, however, whether this relationship was driven by the extra N entering the system through biological N fixation, or whether an increasing legume biomass affected physicochemical conditions in the rhizosphere favoring N_2O formation. In 2016, legume dry matter yields were much lower than in 2015, owing to early rains favoring maize growth, and no significant relationship with N_2O intensity was found (Fig. 3b). This illustrates that the effect of legume intercropping on N_2O emissions is highly dependent on sowing date and weather, both of which control the growth of legume and main cropcrops and ultimately the amount and fate of leguminous N in the intercropping system. Our data suggest that excessive accumulation of leguminous biomass in SAASSA maize cropping enhances the risk for elevated N_2O emissions.

We expected N_2O emissions to respond more strongly to intercropping in the second year (2016), as legume mulches were applied according to their plot-wise aboveground yields in the previous year. Indeed, N_2O emission rates were clearly higher in intercropping ~~plots~~treatments on the first sampling date in 2016 (~~fig~~Fig. 1e~~ and 1f~~, f), indicating increased N cycling in mulched plots~~.~~ (Campiglia et al., 2011). This difference vanished quickly, however, suggesting that the effect of intercrop mulches, even at high amounts (Table 1), on N_2O emissions in the subsequent year ~~is~~was negligible~~ under SSA conditions~~. It is noteworthy that our estimates of the fraction of N carried over between the years were based on literature data (Table 1), and that a considerable part of the mulched N may have been lost during abundant rainfalls (300 mm) early in the 2016 season before crops were sown.

~~It is striking that cumulative~~Cumulative N_2O emissions ~~were at par~~from intercrops, with mineral fertilization rate halved, were comparable to those in the fully fertilized maize monocrop in 2016. ~~This effect, however, was short-lived and no significant difference in average flux rates was seen during the remainder of the season resulting in statistically indistinguishable cumulative N_2O emissions.~~ This may be partly due to the 50% reduction in mineral N application to intercrop treatments, as found by others (Tang et al., 2017). Another reason may be that a considerable proportion of the cumulative emission in 2016 occurred before or shortly after 3-week intercrops were sown, and was thus unaffected by growing legumes. Overall, cumulative N_2O emissions were equal or higher in 2016 than in 2015, despite reduced mineral N addition to intercrops and lower legume biomass. Ultimately, the lack of a clear emission response to legume intercropping in the second year calls for studies tracing cumulative mulching effects over multiple years~~.~~ and exploring their driving factors in more detail. In our study, amount and timing of rainfall appeared to be more important for N_2O emissions in the second year than amount and carryover of legume N.

Given our finding that N_2O intensity responded positively to legume biomass and its N content in a drought year with poor maize growth, intercrop species ~~and~~as well as sowing and harvest ~~date~~dates (relative to the main crop) emerge as viable management factors for controlling ~~N_2O emissions in SSA intercropping systems~~the accumulation of legume biomass between the maize rows and hence the risk for increased N_2O emission. Legume species and cultivar in intercropping systems are known to be critical for N loss, both during the intercropping and the subsequent seasons (Pappa et al., 2011, Weiler et al., 2018). The stimulating effect of crop residues on N_2O

emission has been reported to depend on residue quality and soil moisture, with denitrification being the likely process (Li et al., 2016). Our study provides evidence that vigorous growth of high yielding legume intercrops can enhance N_2O emissions in years unfavorable for maize growth, whereas in years with sufficient water availability early in the growing season, maize growth is favored preventing excessive growth of the intercrop. Our study therefore points to optimizing the sowing date in response to expected emergence and growth of maize as ~~the most~~a promising option to control growth of the intercrop ~~relative to the main crop~~ and hence to deal with the risk of increased N_2O emissions ~~with legume intercrops~~.

4.2 Seasonal N_2O and CH_4 emission, EF_{N2O} and ~~GWP~~total GHG emission

Growing season N_2O emissions in fertilized treatments varied from 0.17 to 0.33 and 0.23 to 0.3 kg N_2O-N ha^{-1} in 2015 and 2016 covering 107 and 123 days, respectively (Fig. 2), and a range of estimated total N inputs from 36.4 to 97.8 kg N ha^{-1} (Table 1). There are no N_2O emissions studies for maize-legume intercropping in the Ethiopian Rift valley so far. Hickman et al. (2014a) reported N_2O emissions of 0.62 and 0.81 kg N ~~per~~ ha ~~and~~$^{-1}$ over 99 days for 100 and 200 kg N input ha^{-1}, respectively, for a maize field without intercropping in humid western Kenya~~.~~, which seems to be higher than seasonal emissions we found. Baggs et al. (2006), working in the same region with maize intercropped with legumes in an agroforestry system reported N_2O emissions ranging from 0.2 to 0.6 kg N ha^{-1} with higher emissions in tilled intercropping treatments~~.~~; our values are in the lower end of the range they reported. The largest seasonal N_2O emission for intercropping reported so far from SSA is 4.1 kg N ha^{-1} (84 days) after incorporating 7.4 t ha^{-1} of a *Sesbania-Macroptilium* mixture in humid western Kenya (Millar et al., 2004). Compared to the N_2O emissions reported for humid tropical maize production systems, our data suggest that maize-legume intercropping based on mulching in the sub-humid to semi-arid ~~Rift~~rift valley appears to be a minor N_2O source~~.~~, mainly because of the relatively small amount of legume biomass mulched (Table 1). Growing season N_2O emission factors (EF) in our study ranged from 0.02 to 0.25 and 0.11 to 0.20% of the estimated total N input in 2015 and 2016, respectively, including assumed N inputs from legume mulch as well as belowground additions and carryover between the years (Table 1). Even if the estimated EF is doubled to account for off-season emissions, it is still lower than the annual IPCC default value of 1% N_2O-N per unit added N (IPCC, 2014). Our estimated EFs thus seem to be at the lower end of those reported by Kim et al. (2016) for SSA smallholder agriculture estimated from literature data (0.01 to 4.1%). The reasons for the low EFs in our study are probably the high background emissions in the fertile soil of the Hawassa University research farm which supports high maize yields even in the unfertilized control (Table 1) and the low levels of N input. The soil has been used over decades for agronomic trials with various fertilization rates with and without crop residue retention and legume intercropping (e.g. Raji et al., 2019). Thus, our field trial has to be considered representative for intensive management as opposed to smallholder systems with minimal or no fertilization history.

Methane uptake by the soil in both seasons varied between 1.0 to 1.5 kg CH_4-C ha^{-1} without showing any significant treatment effect, even though maize-legume intercrops tended to take up less CH_4 than maize monocrops (Fig. S1). The observed trend might relate to competitive inhibition of CH_4 oxidation by higher NH_4^+ availability (Le Mer and Roger, 2001, Dunfield and Knowles, 1995) in the presence of legume intercrops, even though estimated total N inputs remained below 100 kg N ha^{-1}, which is considered a threshold for NH_4^+ inhibition (Aronson and Helliker, 2010). Alternatively, densely growing legumes may have lowered CH_4 uptake through impeding CH_4 and/or O_2 diffusion into the soil (Ball et al., 1997). We did not observe stimulation of CH_4 uptake by legume intercropping, which we attribute to the absence of N and P deficiency in this fertile soil. Methane uptake rates varied from 20 to 140 µg CH_4-C m^{-2} h^{-1} which is in the range of rates reported previously for SSA upland soils (Pelster et al., 2017). Seasonal CH_4 uptake in our experiment ~~offset~~offsets between 22 and 69% of the CO_2 equivalents associated with N_2O~~-GWP~~ emissions without revealing any significant treatment effect (Fig. S1a~~ and S1b~~, b), but the offset was relatively largest in the unfertilized maize monocrop and smallest in lablab intercropping. Hence, CH_4 uptake ~~appears to be~~is an important component of the non-CO_2 climate footprint of SSA crop production.

4.3 Legume intercropping and climate smart agriculture

Legumes are an important N source in smallholder farming systems, where mineral fertilizers are unaffordable or unavailable. Legume intercrops maximize resource use efficiency as total productivity is often higher than in mono-cropping systems (Banik et al., 2006). Moreover, N fixed biologically by legume intercrops can partly replace synthetic N fertilizers, if the release is synchronized with the nutrient demand of the cereal crop. On the other hand, surplus N from legumes may result in N losses as NO_3^-, NH_3 and NO, N_2O or N_2. Mulching and incorporation of legume biomass has been found to increase N_2O emissions under temperate conditions (Baggs et al., 2000, Baggs et al., 2003) and under humid tropical conditions (Millar et al., 2004). Also under semi-arid, Mediterranean conditions, vetch (*V. villosa*) used as a winter catch crop and mulched in spring significantly increased N_2O emissions during the fallow period while rape did not (Sanz-Cobena et al., 2014). This was later confirmed by a ^{15}N study, highlighting the role of N mineralization from legumes as a source of N_2O (Guardia et al., 2016). None of the studies found an overall N_2O saving effect of catch crops when scaling up to the entire crop cycle, even though the latter study used reduced mineral N fertilization rates in treatments with catch crops. By contrast, reduced NO_3^- leaching and N_2O emission has been reported from maize intercropped with legumes in the semi-arid North China plain, which the authors attributed to enhanced N uptake by both the inter and main crop and reduced soil moisture in treatments with intercrops during the rainy season (Huang et al., 2017). This shows that legume intercrops have a potential to both increase or reduce N_2O emissions with consequences for the non-CO_2 footprint of cereal production and hence for the viability of intercropping as a central component of CSA (Thierfelder et al., 2017).

The legume intercrops used in our study ~~have~~had low C:N ratios (Table S1~~),~~) and can be expected to release a significant part of their N through decomposition of roots and nodules or root exudation as well as during decomposition of mulches (Fustec et al., 2010). The effect of mulching on N_2O emissions depends on the C:N ratio ~~of the residues~~ with increased emissions for low C:N ratio residues (Baggs et al., 2000, Shan and Yan, 2013). In line with this, N_2O emissions in intercrop treatments of our study exceeded those in fertilized maize monocrop on several sampling dates, both during active growth of legumes and after mulching. Another important aspect is the amount of legume N carried over between years which depends, among others, on amount and quality of the legume and the weather between the growing seasons. Abera et al. (2014) showed that surface-placed residues of haricot bean and pigeon pea decompose quickly despite relatively dry conditions during offseason. Vigorous rainfalls in the beginning of the growing season like in 2016 (Fig. 1) could lead to dissolved N losses, which ~~will~~could lead to indirect N_2O emissions elsewhere ~~or to elevated direct N_2O emissions~~, which should be taken into account when evaluating intercropping as ~~seen on the first sampling date in 2016.~~a CSA strategy.

5. Conclusion

While legume intercrops have the potential to improve cereal yields and diversify produces for smallholders in ~~SSA~~central Ethiopian rift valley, a risk of enhanced N_2O emissions remains, which became apparent as increased "N_2O intensity" of the main crop in a drought year (2015). At the same time, our study points at possibilities to ~~manage~~counteract this ~~risk~~trend by actively controlling legume biomass development and hence potential N input through "climate-smart" choices of legume species, sowing date and mulch amounts~~.~~ in response to prevailing environmental conditions. This approach, however, is complicated by the annual variability in growth conditions and requires active planning of sowing and mulching time by the farmer. Our study was conducted on a relatively nutrient-rich soil (as compared to typical smallholder farms) which supports high yields of both maize and leguminous intercrops. Under these conditions, intercropped legumes can potentially replace a considerable part of synthetic fertilizer, thus supporting common CSA goals. However, more studies are needed to fully explore intercropping options in the framework of CSA in the ~~East-African Rift Valley~~rift valley, particularly in nutrient-poor smallholder fields. Future studies on CSA approaches in ~~SSA~~the rift valley should address, in addition to~~ non-CO_2~~ greenhouse gas emissions, N-runoff and soil organic matter build up, ideally in long-term field trials with and without legume intercropping. Future studies should also attempt to combine flux measurements with inorganic N dynamics and BNF measurements. Given that seasonal N_2O emission factors and intensities in our study were in the lower range of published values for SSA, intercropping appears as a promising approach to sustainable intensification in the Ethiopian Rift Valley.

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References

Abera, G., Wolde-Meskel, E. & Bakken, L. R.: Unexpected high decomposition of legume residues in dry season soils from tropical coffee plantations and crop lands, Agronomy for Sustainable Development, 34**,** 667-676; 2014.

ALmaraz, J. J., Zhou, X., Mabood, F., Madramootoo, C., Rochette, P., MA, B.-L. & Smith, D. L.: Greenhouse gas fluxes associated with soybean production under two tillage systems in southwestern Quebec, Soil and Tillage Research, 104**,** 134-139, 2009.

Aronson, E. L. & Helliker, B. R.: Methane flux in non-wetland soils in response to nitrogen addition: a meta-analysis, Ecology, 91**,** 3242-3251, 2010.

Arslan, A., Mccarthy, N., Lipper, L., Asfaw, S., Cattaneo, A. & Kokwe, M.: Climate Smart Agriculture? Assessing the Adaptation Implications in Zambia, Journal of Agricultural Economics, 66**,** 753-780, 2015.

Baggs, E. M., Chebii, J. & Ndufa, J. K.: A short-term investigation of trace gas emissions following tillage and no-tillage of agroforestry residues in western Kenya, Soil and Tillage Research, 90**,** 69-76, 2006.

Baggs, E. M., Rees, R. M., Smith, K. A. & Vinten, A. J. A.: Nitrous oxide emission from soils after incorporating crop residues, Soil Use and Management, 16**,** 82-87, 2000.

Baggs, E. M., Stevenson, M., Pihlatie, M., Regar, A., Cook, H., Cadisch, G. J.: Nitrous oxide emissions following application of residues and fertiliser under zero and conventional tillage, Plant and Soil, 254**,** 361-370, 2003.

Bakken, L. R., Bergaust, L., Liu, B. & Frostegård, Å.: Regulation of denitrification at the cellular level: a clue to the understanding of N_2O emissions from soils, Philos Trans R Soc Lond B Biol Sci., 367(1593):1226–1234. doi:10.1098/rstb.2011.0321, 2012.

Ball, B. C., Smith, K. A., Klemedtsson, L., Brumme, R., Sitaula, B. K., Hansen, S., Prieme, A., Macdonald, J. & Horgan, G. W.: The influence of soil gas transport properties on methane oxidation in a selection of northern European soils, Journal of Geophysical Research, 102**,** 23309-23317, 1997.

Banik, P., Midya, A., Sarkar, B. K. & Ghose, S. S.: Wheat and chickpea intercropping systems in an additive series experiment: Advantages and weed smothering, European Journal of Agronomy, 24**,** 325-332, 2006.

Bédard, C., Knowles, R.: Physiology, biochemistry, and specific inhibitors of CH_4, NH_4^+, and CO oxidation by methanotrophs and nitrifiers, Microbiol. Rev., 53, 500 68–84, 1989.

Blanc E. & Strobl, E.: The impact of climate change on cropland productivity: evidence from satellite based products at the river basin scale in Africa, Climatic Change, 117**,** 873–890, 2013.

Campiglia, E., Mancinelli, R., Radicetti, E., Marinari, S.: Legume cover crops and mulches: effects on nitrate leaching and nitrogen input in a pepper crop (*Capsicum annuum* L.), Nutr. Cycl. Agroecosyst. 89, 399-412, 2011.

Carranca, C., Torres, M. O. & Madeira, M.: Underestimated role of legume roots for soil N fertility, Agronomy for Sustainable Development, 35**,** 1095-1102, 2015.

Carruthers, K., Prithiviraj, B., FE, Q., Cloutier, D., Martin, R. C. & Smith, D. L.: Intercropping corn with soybean, lupin and forages: yield component responses, European Journal of Agronomy, 12**,** 103-115, 2000.

~~Castro, M. S., Peterjohn, W. T., Melillo, J. M., Steudler, P. A., Gholz, H. L. & Lewis, D.: Effects of nitrogen fertilization on the fluxes of N_2O, CH_4, and CO_2 from soils in a Florida slash pine plantation, Canadian Journal of Forest Research, 24, 9-13, 1994.~~

Davidson, E. A., Keller, M., Erickson, H. E., Verchot, L. V. & Veldkamp, E.: Testing a Conceptual Model of Soil Emissions of Nitrous and Nitric Oxides: Using two functions based on soil nitrogen availability and soil water content, the hole-in-the-pipe model characterizes a large fraction of the observed variation of nitric oxide and nitrous oxide emissions from soils, BioScience, 50, 667-680, 2000.

Dick, J., Kaya, B., Soutoura, M., Skiba, U., Smith, R., Niang, A. & Tabo, R.: The contribution of agricultural practices to nitrous oxide emissions in semi- arid Mali, Soil Use and Management, 24, 292-301, 2008.

Drury, C. F., Mckenney, D. J. & Findlay, W. I.: Relationships between denitrification, microbial biomass and indigenous soil properties, Soil Biology and Biochemistry, 23**,** 751-755, 1991.

Dunfield, P. & Knowles, R.: Kinetics of inhibition of methane oxidation by nitrate, nitrite, and ammonium in a humisol, Applied and Environmental Microbiology, 61**,** 3129, 1995.

Ehrmann, J. & Ritz, K.: Plant soil interactions in temperate multi-cropping production systems, Plant and Soil, 376**,** 1-29, 2014.

Fageria, N. K., Moreira, A., Moraes, L. A. C. & Moraes, M. F.: Root growth, nutrient uptake, and nutrient-use efficiency by roots of tropical legume cover crops as influenced by phosphorus fertilization, Communications in Soil Science and Plant Analysis, 45**,** 555-569, 2014.

Flessa, H., Dörsch, P., Besse, F.: Seasonal variation of N_2O and CH_4 fluxes in differently managed arable soils in Southern Germany, Journal of Geophysical Research, 100(D11), 23115-23124, 1995.

Fustec, J., Lesuffleur, F., Mahieu, S. & Cliquet, J.-B. J. A. F. S. D.: Nitrogen rhizodeposition of legumes. A review, Agronomy for Sustainable Development, 30**,** 57-66, 2010.

Guardia, G., Abalos, D., Garcia-Marco, S., Quemada, M., Alonso-Ayuso, M., Cardenas, L. M., Dixon, E. R. & Vallejo, A.: Effect of cover crops on greenhouse gas emissions in an irrigated field under integrated soil fertility management, Biogeosciences, 13**,** 5245-5257, 2016.

Harrison-Kirk, T., Beare, M. H., Meenken, E. D. & Condron, L. M.: Soil organic matter and texture affect responses to dry/wet cycles: Effects on carbon dioxide and nitrous oxide emissions, Soil Biology and Biochemistry, 57**,** 43-55, 2013.

Hickman, J. E., Palm, C. A., Mutuo, P., Melillo, J. M. & Tang, J.: Nitrous oxide (N_2O) emissions in response to increasing fertilizer addition in maize (*Zea mays* L.) agriculture in western Kenya, Nutrient Cycling in Agroecosystems, 100**,** 177-187, 2014a.

Hickman, J. E., Scholes, R. J., Rosenstock, T. S., Perez Garcia-Pando, C. & Nyamangara, J.: Assessing non-CO_2 climate-forcing emissions and mitigation in sub-Saharan Africa, Current Opinion in Environmental Sustainability, 9-10**,** 65-72, 2014b.

Ho, A., Reim, A., Kim, S. Y., Meima-Franke, M., Termorshuizen, A., De Boer, W., Van der Putten, W. H. & Bodelier, P. L. E.: Unexpected stimulation of soil methane uptake as emergent property of agricultural soils following bio-based residue application, Global Change Biology, 21**,** 3864-3879, 2015.

Huang, J., Sui, P., Gao, W. & Chen, Y.: Effect of maize-soybean intercropping on soil nitrous oxide emissions in silt loam soil of the North China Plain, Pedosphere. *In Press.* 2017.

IPCC: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A.

Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.

Jensen, E. S. & Hauggaard-Nielsen, H.: How can increased use of biological N_2 fixation in agriculture benefit the environment?, Plant and Soil, 252**,** 177-186, 2003.

Khalil, K., Mary, B. & Renault, P.: Nitrous oxide production by nitrification and denitrification in soil aggregates as affected by O_2 concentration, Soil Biology and Biochemistry, 36**,** 687-699, 2004.

Kim, D. G., Thomas, A. D., Pelster, D., Rosenstock, T. S. & Sanz-Cobena, A.: Greenhouse gas emissions from natural ecosystems and agricultural lands in sub-Saharan Africa: synthesis of available data and suggestions for further research, Biogeosciences, 13**,** 4789-4809, 2016.

Laanbroek, H. J. & Bodelier, P. L. E.: Nitrogen as a regulatory factor of methane oxidation in soils and sediments, FEMS Microbiology Ecology, 47**,** 265-277, 2004.

Le Mer, J. & Roger, P.: Production, oxidation, emission and consumption of methane by soils: A review, European Journal of Soil Biology, 37**,** 25-50, 2001.

Li, X., Sørensen, P., Olesen, J. E. & Petersen, S. O.: Evidence for denitrification as main source of N_2O emission from residue-amended soil, Soil Biology and Biochemistry, 92**,** 153-160, 2016.

Millar, N., Ndufa, J. K., Cadisch, G. & Baggs, E. M.: Nitrous oxide emissions following incorporation of improved-fallow residues in the humid tropics, Global Biogeochemical Cycles, 18. DOI: 10.1029/2003GB002114, 2004.

Nadeem, S., Bakken, L. R., Frostegård, Å., Gaby, J. C. & Dörsch, P.: Liming enhances nitrification and increases its N_2O yield but reduces soil N_2O emissions from coupled nitrification-denitrification through increased N_2O reductase activity, Submitted to Soil Biology and Biochemistry, 2019.

Neufeldt, H., Jahn, M., Campbell, B. M., Beddington, J. R., Declerck, F., De Pinto, A., Gulledge, J., Hellin, J., Herrero, M., Jarvis, A., Lezaks, D., Meinke, H., Rosenstock, T., Scholes, M., Scholes, R., Vermeulen, S., Wollenberg, E. & Zougmore, R.: Beyond climate-smart agriculture: toward safe operating spaces for global food systems, Agriculture & Food Security, 2**,** 12, 2013.

Odhiambo, J. J. O.: Decomposition and nitrogen release by green manure legume residues in different soil types, African Journal of Agricultural Research, 5**,** 090-096, 2010.

Ojiem, J. O., Vanlauwe, B., De Ridder, N. & Giller, K. E.: Niche-based assessment of contributions of legumes to the nitrogen economy of Western Kenya smallholder farms, Plant and Soil, 292**,** 119-135, 2007.

Pappa, V. A., Rees, R. M., Walker, R. L., Baddeley, J. A. & Watson, C. A.: Nitrous oxide emissions and nitrate leaching in an arable rotation resulting from the presence of an intercrop, Agriculture, Ecosystems & Environment, 141**,** 153-161, 2011.

Pelster, D., Rufino, M., Rosenstock, T., Mango, J., Saiz, G., Diaz-Pines, E., Baldi, G. & Butterbach-Bahl, K.: Smallholder farms in eastern African tropical highlands have lowsoil greenhouse gas fluxes, Biogeosciences, 14**,** 187-202, 2017.

Raji, S. G., Tzanakakis, V., Dörsch, P.: Bradyrhizobial inoculation and P application effects on haricot and mung beans in the Ethiopian Rift Valley, Plant and Soil, DOI: 10.1007/s11104-019-04170-2, 2019.

~~Rochette, P., Angers, D. A., Chantigny, M. H. & Bertrand, N.: Nitrous oxide emissions respond differently to no-till in a loam and a heavy clay soil, Soil Science Society of America Journal, 72, 1363-1369, 2008.~~

Rochette, P., Eriksen-Hamel, N.S.: Chamber measurements of soil nitrous oxide flux: Are absolute values reliable? Soil Sci. Soc. Am. J., 72, 331-342, 2008.

Rochette, P. & Janzen, H. H.: Towards a revised coefficient for estimating N_2O emissions from legumes, Nutrient Cycling in Agroecosystems, 73, 171-179, 2005.

Russenes A.L., Korsaeth A., Bakken L.R. & Dörsch P.: Spatial variation in soil pH controls off-season N2O emission in an agricultural soil, Soil Biology and Biochemistry, 99, 36-46, 2016.

Sant'anna, S. A. C., Martins, M. R., Goulart, J. M., Araujo, S. N., Araujo, E. S., Zaman, M., Jantalia, C. P., Alves, B. J. R., Boddey, R. M. & Urquiaga, S.: Biological nitrogen fixation and soil N_2O emissions from legume residues in an Acrisol in SE Brazil, Geoderma Regional, 15, e00196, 2018.

Sanz-Cobena, A., Garcia-Marco, S., Quemada, M., Gabriel, J. L., Almendros, P. & Vallejo, A.: Do cover crops enhance N_2O, CO_2 or CH_4 emissions from soil in Mediterranean arable systems?, Science of The Total Environment, 466-467, 164-174, 2014.

Schaufler, G., Kitzler, B., Schindlbacher, A., Skiba, U., Sutton, M. A. & Zechmeister-Boltenstern, S.: Greenhouse gas emissions from European soils under different land use: effects of soil moisture and temperature, Eur. J. Soil Sci., 61, 683-696, 2010.

Schlüter, S., Zawallich, J., Vogel, H. J. & Dörsch, P.: Physical constraints for respiration in microbial hotspots in soil and their importance for denitrification, Biogeosciences ~~Discuss., 2019, 1-31.~~, 16, 3665-3678, 2019.

Schwenke, G. D., Herridge, D. F., Scheer, C., Rowlings, D. W., Haigh, B. M. & Mcmullen, K. G.: Greenhouse gas (N_2O and CH_4) fluxes under nitrogen-fertilised dryland wheat and barley on subtropical Vertosols: Risk, rainfall and alternatives, Soil Research, 54, 634-650, 2016.

Shan, J. & Yan, X.: Effects of crop residue returning on nitrous oxide emissions in agricultural soils, Atmospheric Environment, 71, 170-175, 2013.

Sime, G., Aune, J.B.: Sustainability of Improved Crop Varieties and Agricultural Practices: A Case Study in the Central Rift Valley of Ethiopia. Agriculture, 8, 177, 2018.

Tang, Y.-.L., Yu, L.-.L., Gaun, A.-.M., Zhou, X.-.Y., Wang, Z.-.G., Gou, Y.-.G. & Wang, J.-.W.: Soil mineral nitrogen and yield-scaled soil N_2O emissions lowered by reducing nitrogen application and intercropping with soybean for sweet maize production in southern China, Journal of Integrative Agriculture, 16, 2586-2596, 2017.

Thierfelder, C., Chivenge, P., Mupangwa, W., Rosenstock, T. S., Lamanna, C. & Eyre, J. X. J. F. S.: How climate-smart is conservation agriculture (CA)? – its potential to deliver on adaptation, mitigation and productivity on smallholder farms in southern Africa, Food Security, 9, 537-560, 2017.

Wanyama, I., Pelster, D. E., Butterbach-Bahl, K., Verchot, L. V., Martius, C. & Rufino, M. C.: Soil carbon dioxide and methane fluxes from forests and other land use types in an African tropical montane region, Biogeochemistry, 143, 171-190, 2019.

Weiler, D. A., Giacomini, S. J., Recous, S., Bastos, L. M., Pilecco, G. E., Dietrich, G. & Aita, C.: Trade-off between C and N recycling and N_2O emissions of soils with summer cover crops in subtropical agrosystems, Plant and Soil, 433, 213-225, 2018.

Wrage-Mönnig, N., Horn, M. A., Well, R., Müller, C., Velthof, G. & Oenema, O.: The role of nitrifier denitrification in the production of nitrous oxide revisited, Soil Biology and Biochemistry, 123**,** A3-A16, 2018.

Wu, D., Wei, Z., Well, R., Shan, J., Yan, X., Bol, R. & Senbayram, M.: Straw amendment with nitrate-N decreased $N_2O/(N_2O+N_2)$ ratio but increased soil N_2O emission: A case study of direct soil-born N_2 measurements, Soil Biology and Biochemistry, 127, 301-304, 2018.

Xie, B., Zheng, X., Zhou, Z., Gu, J., Zhu, B., Chen, X., Shi, Y., Wang, Y., Zhao, Z., Liu, C., Yao, Z. & Zhu, J.: Effects of nitrogen fertilizer on CH_4 emission from rice fields: Multi-site field observations, Plant and Soil, 326, 393-401, 2010.

Table 1: N inputs from forage legumes and fertilization per treatment~~ which was estimated as outlined in the Materials and Method section 3.4.~~. Shown are mean values (n=4 ± standard error)

Legume	DMY	Aboveground N yield[a]	Belowground N yield[b]	N from mulch[c]	Mineral N	Carryover[d]	Total N input
	kg N ha^{-1}						
	2015						
Crotalaria							
3w	1516±183	53.3±6.4	17.7±2.1	26.6±3.2	64		75.8
6w	345±65	12.1±2.3	4.0±0.8	6.1±1.1	64		66.4
Lablab							
3w	2221±340	96.8±14.8	32.3±4.9	48.4±7.4	64		82.9
6w	467±137	20.3±6.0	6.8±2.0	10.2±3.0	64		67.7
	2016						
Crotalaria							
3w	468±85	16.4±3.0	5.47±1.0	8.21±1.5	32	11.1±1.3	56.8
6w	65±44	2.3±1.5	0.75±0.5	1.13±0.8	32	2.5±0.5	36.4
Lablab							
3w	1256±221	54.7±9.6	18.25±3.2	27.4±4.8	32	20.2±3.1	97.8
6w	186±60	8.1±2.6	2.70±0.9	4.06±1.3	32	4.2±1.2	43.0

[a] N content of crotalaria and lablab was 3.51 and 4.36%, respectively, measured in 2 representative samples, DMY=Dry matter yield

[b] assuming a shoot-to-root ratio of 2 and an average belowground N input from the standing legumes of 50% during the growing season

[c] returning half of the aboveground yield as mulch; assuming an average N release of 50% and 30% for 3-week and 6-week treatments, respectively, during the growing season

[d] assuming that 50% of the remaining N becomes available in the following cropping season

Table 2: Grain ~~yield~~yields, growing-season N_2O emission factors and non-CO_2 GHG emission associated with N_2O and CH_4 and N_2O emission intensities for ~~107 and 123 days in 2015 and 2016, respectively and combined global warming potential (GWP) of N_2O emission and CH_4 uptake for~~ fertilized treatments with and without legume intercropping during 107 and 123 days in 2015 and 2016, respectively. N input was estimated as outlined in Table 1. Shown are mean values (n=4 ± standard error). Different letters indicate statistical difference at $p < 0.05$.

	2015				2016			
Treatment	Maize Grain yield (kg ha^{-1})	N_2O emission factor (%)	~~*GWP~~Non-CO_2 GHG emission (kg CO_2 eq. ha^{-1} ~~107d^{-1}~~))*	N_2O emission intensity (g N_2O-N ton^{-1} grain^{-1})	Maize Grain yield (kg ha^{-1})	N_2O Emission factor (%)	~~*GWP~~Non-CO_2 GHG emission (kg CO_2 eq. ha^{-1} ~~123d^{-1}~~))*	N_2O emission intensity (g N_2O -N ton^{-1} grain^{-1})
~~Maize~~M-F	4313±235[a]		17.4±12[a]	29.7±4.2[ab]	6558±217[a]		29.7±18[a]	26.3±4.0[a]
~~Maize~~M+F	5022±133[ab]	0.07±0.07[ab]	38.4±25[a]	34.4±8.8[ab]	8403±342[b]	0.20±0.03[a]	91.4±16[ab]	37.0±4.0[a]
~~Maize~~M+Cr3w	5882±249[ab]	0.17±0.05[ab]	78.0±12[ab]	42.2±5.5[b]	8276±236[b]	0.16±0.08[a]	78.3±19[ab]	33.6±4.7[a]
~~Maize~~M+Cr6w	5316±316[ab]	0.07±0.06[ab]	47.0±15[ab]	34.8±5.4[ab]	8283±148[b]	0.16±0.05[a]	69.0±12[ab]	27.8±2.0[a]
~~Maize~~M+Lb3w	5989±528[b]	0.25±0.06[b]	120.5±27[b]	54.3±6.1[ab]	8557±262[b]	0.15±0.03[a]	111.7±9[b]	36.8±2.1[a]
M+Lb6w	5541±492[ab]	0.02±0.01[a]	21.2±7[a]	24.6±1.5[a]	8306±501[b]	0.11±0.07[a]	62.3±25[ab]	26.8±3.9[a]

* N_2O: 300 CO_2 eq; CH_4: 25 CO_2 eq

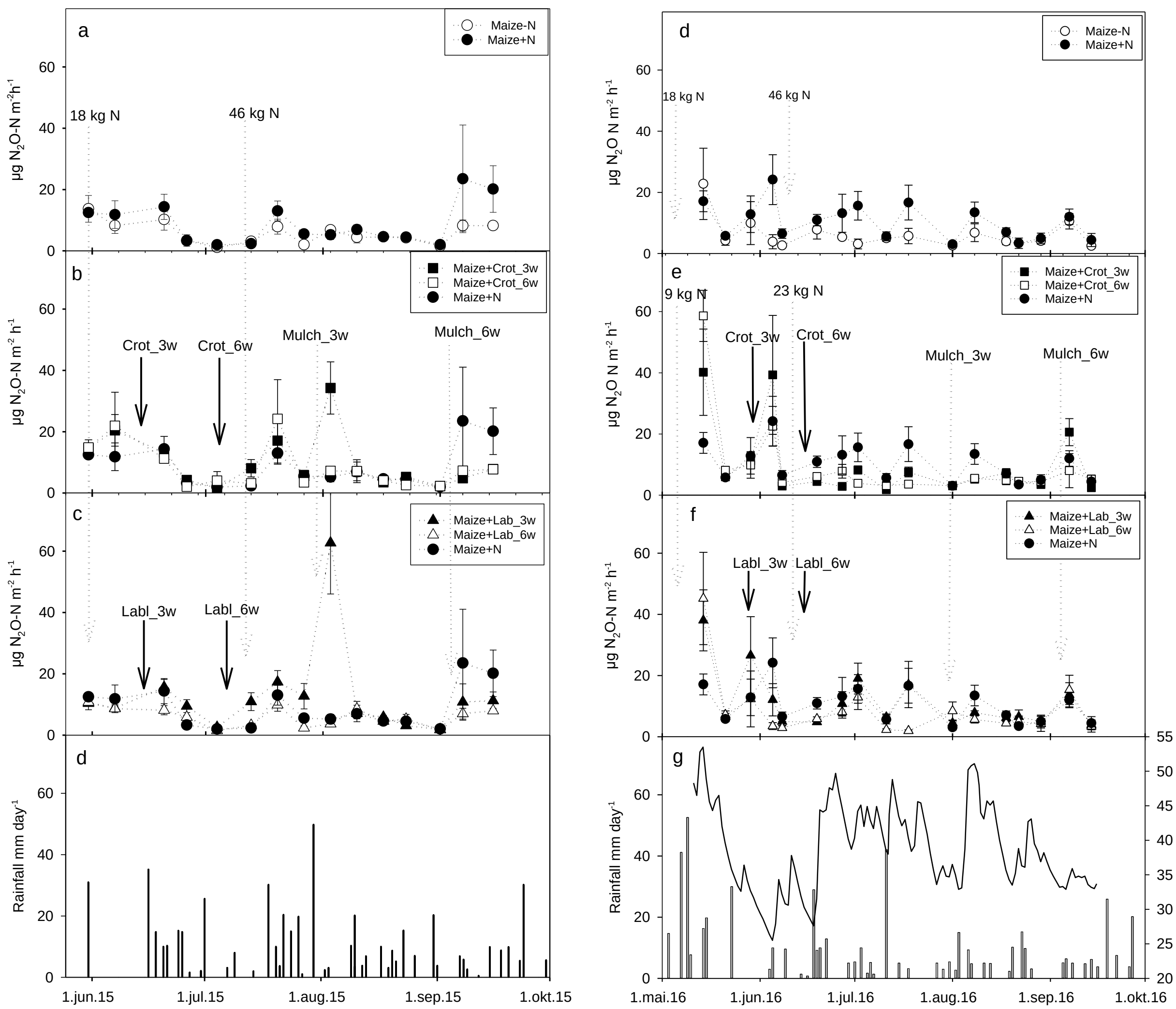

Figure 1: Mean N_2O emission rates (n=4; error bars = SEM) in 2015 (left panel) and 2016 (right panel) and daily rain fall and water-filled pore space (in 2016 only). Figures a and d show emission rates in the absence of intercrops, b and e with crotalaria and c and f with lablab intercrops.

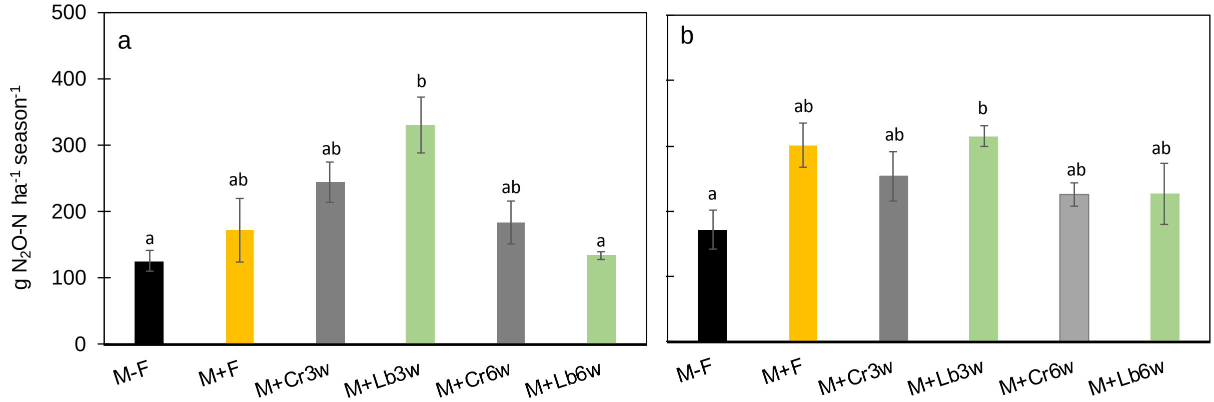

Figure 2: Cumulative seasonal N_2O-N (g N ha^{-1} $season^{-1}$) in 2015 (a) and 2016 (b) throughout 107 and 123 days, respectively, in treatments with and without legume intercropping. Error bars denote SEM (n=4). Different letters indicate significant differences at $p < 0.05$. M+F: fertilized maize; M+Cr3w: fertilized maize with crotalaria sown 3 weeks after maize; M+Cr6w: fertilized maize with crotalaria sown 6 weeks after maize; M+Lb3w: fertilized maize with lablab sown 3 weeks after maize; M+Lb6w: fertilized maize with lablab sown 6 weeks after maize

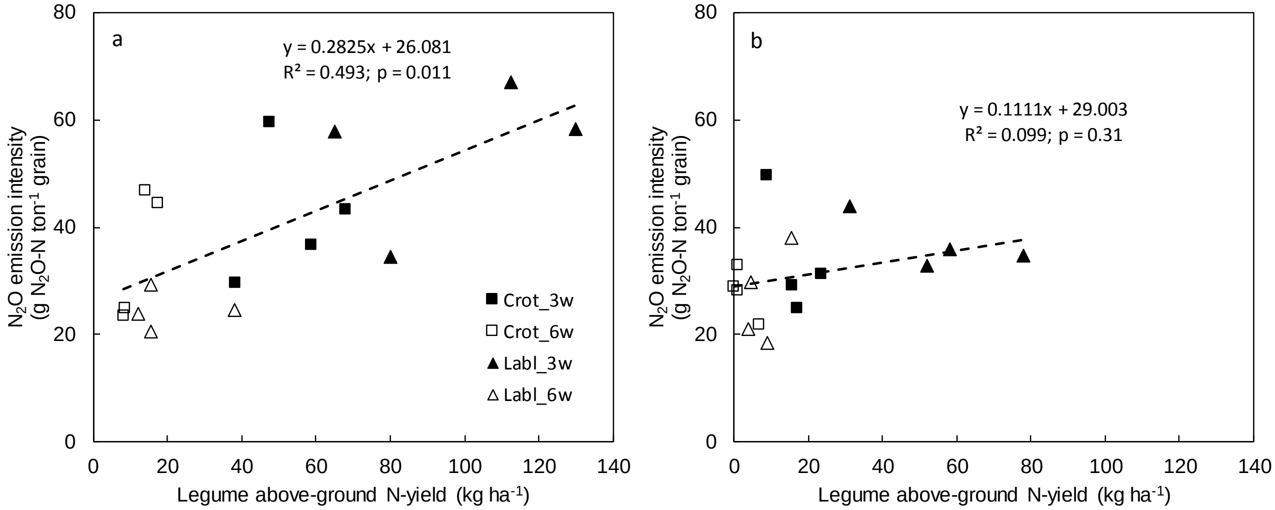

Figure 3: Relationship between N_2O emission intensity and aboveground intercrop legume ~~biomass~~N yield in intercrop treatments in 2015 (a) and 2016 (b). Shown are single-plot values for each treatment (n=4).

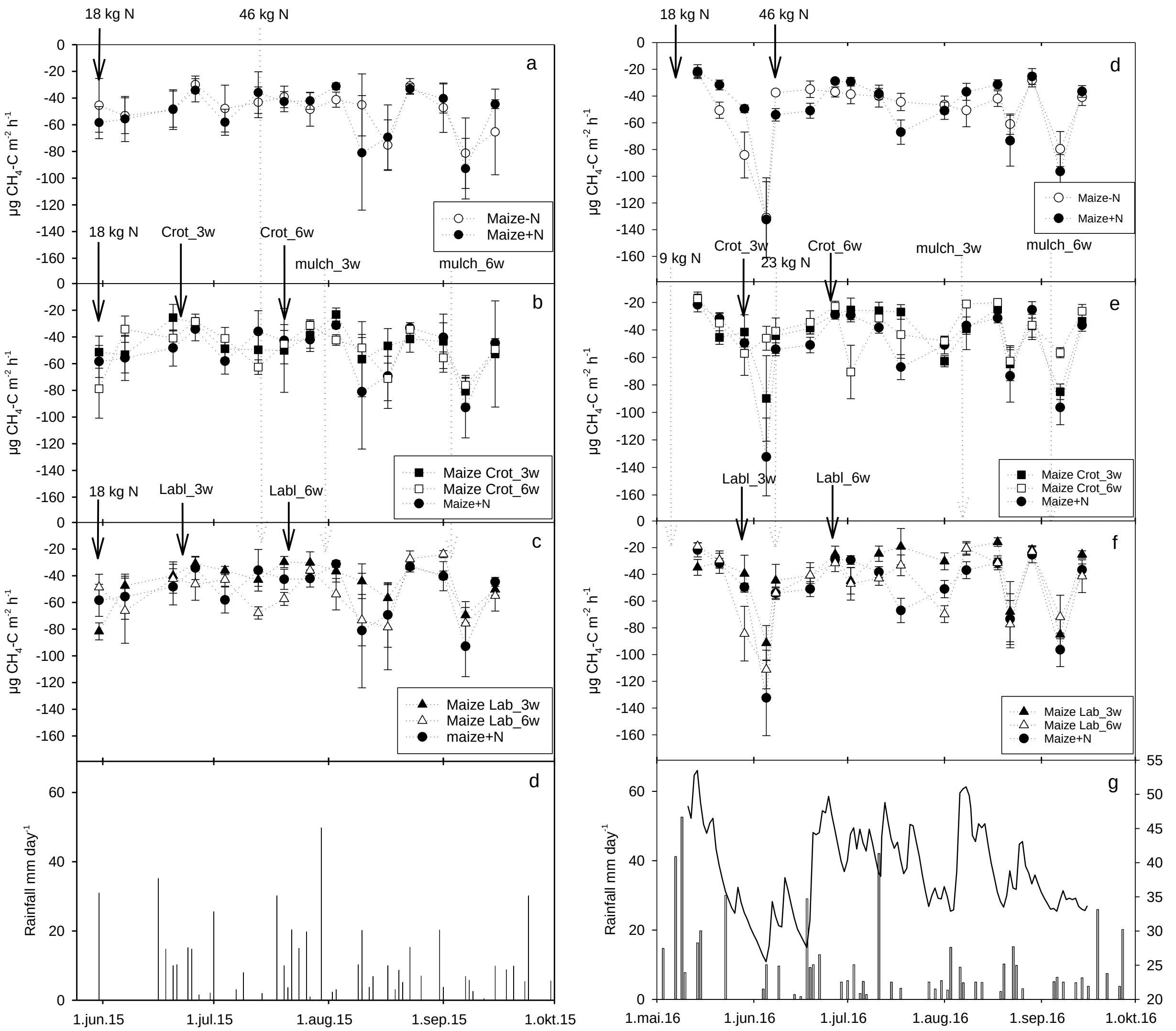

Figure 4: Mean CH_4 flux in 2015 (left panel) and 2016 (right panel) and daily rainfall and water-filled pore space (in 2016 only). Error bars show standard error of the mean (n=4). Figures a and d show emission rates in the absence of intercrops, b and e with crotalaria and c and f with lablab intercropping.

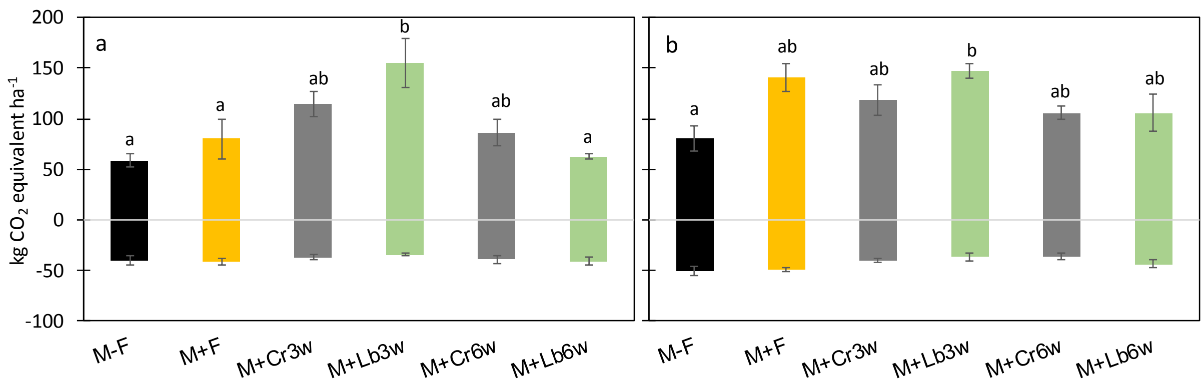

Figure 5: Relative contribution of CH_4 uptake and N_2O emission to seasonal ~~GWP~~total non-CO_2 GHG emissions in mono- and intercropping treatments in 2015 (a) and 2016 (b). Error bars indicate standard deviation (n=4). ~~For treatment names, see Fig. 2.~~