Dear Editor Professor Michael Weintraub,

Please receive our revised version of manuscript bg-2015-458 “Greenhouse gas emissions in natural and agricultural lands in sub-Saharan Africa: synthesis of available data and suggestions for further studies”. We thank you and the reviewers for constructive suggestions on the manuscript. We have addressed each of the comments as outlined below.

Anonymous Referee #1

This article is an interesting, novel review of greenhouse gas (GHG) emissions from natural and agricultural ecosystems in 22 countries in sub-Saharan Africa, compiling published data on CO2, CH4, and N2O emissions. The authors summarize knowledge of the baseline (current) emissions from this region. They report measured emissions from a range of different ecosystem and land use types, and management practices. The variability in measured emissions is large, and the authors highlight important research gaps and the need for further studies to elucidate environmental and management drivers of emissions at multiple spatial and temporal scales. This paper fills an important knowledge gap. However, I think the authors could improve upon several aspects of their review.

Both the results and summary sections might be improved by including a framework that organizes or summarizes the suite of complex direct (e.g., oxygen and carbon availability) and indirect (e.g., root and microbial respiration, soil texture, temperature) controls on emissions across the studies and how those controls are affected by management (e.g., tillage, fertility inputs) and ecosystem state factors (e.g., parent material, climate, vegetation).

Related to this, the review should also include more synthesis, if possible, such as quantitatively summarizing findings regarding controls across studies.

As currently written, the results read as an inventory or list of emissions rates and key findings from individual studies (rather than a “synthesis,” which is in the title), depending on which factors individual studies addressed (e.g., temperature, moisture, vegetation type, pH, dynamics of C and N availability, etc.). The current presentation of results makes it difficult to discern

– on average or in aggregate for different ecosystem types or management systems
– the state of knowledge regarding relative importance of different drivers of variation.

Statistical analysis was performed on agricultural studies to fit models for emissions as a function of N inputs. I wonder what additional statistics might be performed on these data to understand the aggregate effect of controls on emissions rates across multiple studies or ecosystem types (i.e., how emissions vary with these different factors)? Are there consistent effects of soil texture across the studies? Such information (if available) would better direct future research efforts. For example, the authors could highlight whether more is known about some controls than others, or if there is a lack of information about interactions between different controls, etc. It seems that a key point from the findings is that there is a need for more studies that address questions about how interactions between management (fertility practices, tillage) and environment (soil texture and type, etc.) drive GHG emissions, but this discussion could be strengthened.

Response:
There are fundamental challenges to address the comments due to lack of data in general and poor data quality specifically. For instance, few studies report GHG fluxes with respect to the research questions described above (e.g., mechanistic controls), or with suitable experimental designs (e.g., adequate replication). Therefore, it was difficult to synthesize beyond describing their findings relevant to key topical areas. Furthermore, available data was not a large enough to conduct valid statistical analysis. With the only exception of soil CO_2 fluxes, with which we were able to provide new statistical results as described below. Despite the difficulties, we have made significant efforts throughout the manuscript to improve the synthetic contribution of our effort to better describe and understand GHG emissions, mitigation potential and future challenges in SSA. Major changes were summarized as below:

1) New statistical results were added (see 3. 1. 1 CO_2 emissions) to show that observed annual soil CO_2 emissions in African natural terrestrial systems and agricultural lands had significant correlations with annual mean air temperature, annual rainfall, soil organic carbon and total nitrogen contents. Accordingly, Table 2 and relevant discussion were added.

2) We altered the previous descriptive list to a more thematically synthesized approach throughout Results and Discussion sections: the sub-title of the second section changed to 'Sources and drivers of greenhouse gas emissions in Africa' accordingly.

3) Summary of GHG emissions section (newly named as '3.1. Summary of greenhouse gas emissions in Africa') was revised and is now located right up front, first in Results and Discussion.

Second, more attention should be given to the disparate methods within the studies. The authors are clear that they selected only in situ studies, but then note that a wide range of methods was used in the studies they synthesize. Could this be accounted for in some way in the analysis (e.g., analyze emissions by measurement method)? Are some of the results presented likely more robust than others? More information could be added to the supplementary tables; for example, duration of the study (whether emissions were measured for one year, one growing season, multiple years, etc.), frequency of sampling events within a year, capturing major weather events, etc. Were any of the measurements for agricultural systems on actual farms, or were they in experiment stations? A methods column could also potentially list chamber type or other relevant information.

Response:
We newly assessed data quality of the cited studies using the criteria suggested by Rochette and Eriksen-Hamel (2008) and Barton et al. (2015). We categorized the studies as three different groups: the methods are 1) *poor to very poor*, 2) *marginal*

and 3) *good*. We newly added detail procedure of the assessment (see 2.1. Data collection), results (see 3.1.5 Data quality assessment) and discussion (see 3.3 Suggested future research) in the manuscript. We have recorded the assessment results in Supplementary Information Table S1 and S2.

If a paper provided detailed information on the method of gas collection, study periods and frequency, weather characteristics, and other environmental factors (soil, vegetation, management) then the information was recorded in the supplementary database (see Appendix A). However, few studies report detailed information, so it was not possible to analyze available data by measurement methods, frequency or periods as the reviewer suggested.

Third, the overall coherence would be improved by stronger links to theory, and by including broader discussion/interpretation of the summarized findings. For example, the authors could draw upon N saturation theory from N deposition studies in forest ecosystems (N surplus is mentioned in the discussion on page 16496, but might be better mentioned up front as a guiding framework for understanding a key driver of losses in systems with N inputs, and then woven throughout). For example, the finding that N2O emissions increased exponentially when fertilizer applications exceed plant uptake (for the very high rates) is in line with N saturation theory. Another option is to link findings to an ecological nutrient management framework in the agriculture section, which aims to couple C and N cycles (e.g., by adding a C source such as a cover crop together with an N source, or using organic N sources) to reduce N surplus and balance N inputs with harvested exports.

Response:

To link collected data to relevant theories,

1. We newly conducted correlation analysis and found observed annual soil CO_2 emissions had significant correlations with annual mean air temperature, annual rainfall, soil organic carbon and total nitrogen contents. We found an unexpected result showing negative relation between annual soil CO_2 emissions and annual mean air temperature. We discussed the results based on theories on drought and water stress effects on carbon balance and ecosystem production as stated below (see 3. 1. 1 CO_2 emissions):

"We speculate that the generally high temperatures, and poor quality, of many African soils mean that air temperature increases frequently result in vegetation stress and/or soil aridity, hindering root and soil microbial activities (root and microbial respiration) and subsequent soil CO_2 flux (e.g., Thomas et al., 2011)"

2. We have provided two new insights in the paper related to N saturation as pointed out in the following lines:

First, we found relationship between nitrogen (N) input and nitrous oxide (N_2O) emissions observed in Africa (Figure 3.). Second, we found relationship between nitrogen (N) input and yield scaled nitrous oxide (N_2O) emissions (Figure 4).

3. To link ecological nutrient management framework in the agriculture section, we newly added the below text (see Agroforestry in 3.2.2. Greenhouse gas emissions from agricultural lands).

"Therefore, there may be potential to reduce N_2O emissions in the agroforestry practice, but it may require ecological nutrient management (i.e., reduced inorganic fertilizer N inputs accounting N input from the legume trees; adding a C source such as a cover crop together with an N source) and rotation planning."

Finally, the paper would improve with brief discussion throughout regarding why and how reported emissions for the different ecosystems might matter for current sustainability concerns, particularly regarding land use change. Linking emissions rates to crop productivity (the yield-scaled results) is an important start, but what other trade-offs are there? Vegetable systems with high emissions, for example, are likely a small proportion of total land use, and may contribute high nutritional value per area. Table 2 with the impacts of different management practices gets at this, but it would be useful to identify some potential tradeoffs more generally and better synthesize across studies.

Response:

We recognized the importance of this synthesis to speak to sustainability concerns, especially land use changes issues, we discuss sustainability issues in '3.2.3 Greenhouse gas emissions from land use change; and '3.3 Suggested future research'. We also added the below sentences in '3.3 Suggested future research'.

"Throughout the study, we identified various trade-offs including increased CO_2 emission following forest thinning management, increased GHG emissions in land-use changes, very high N_2O emissions in vegetable gardens due to excessive N input to get high yields, increased CO_2 and N_2O emission in incorporation of crop residues to the soil and agroforestry practices, and exponential increased of N_2O emission and yield-scaled N_2O emissions in excessive N input. Further studies are needed to assess and manage potential trade-offs and drivers."

Specific Comments

Page 16483, lines 7-13: How do these numbers compare to countries or regions with highly industrialized agricultural systems and higher average N fertilizer rates? This would help to place these figures in a broader context.

Response:
We revised the mentioned sentences accordingly:

"According to Lassaletta et al. (2014), mean N application rates in Africa were 34 kg N ha^{-1} in 2009 and only 16 kg N ha^{-1} in sub-Saharan African countries while the rate was 169.1 kg N ha^{-1} in 2009 in the USA. Only Mauritius, Botswana and South Africa had average N application rates exceeding100 kg N ha^{-1}. Even with the low fertilizer rates used across the continent, agricultural GHG emissions in Africa are substantial; amounting to 26% of the continent's total GHG emissions (Valentini et al., 2014) while agricultural GHG emissions were responsible for 8.4% of total GHG emissions in the USA (US EPA, 2016)."

Page 16484, line 9: How many total papers did the initial search yield (from which the authors distilled the papers that met the criteria for inclusion)?

Response:
Over 300 peer-reviewed papers were acquired initially. We revised the sentence as below:

"Data were acquired by searching existing peer-reviewed literature (304 peer-reviewed papers) using the names of the sub-Saharan countries and the GHGs (i.e. CO_2, CH_4 and N_2O) as search terms (using Web of Science and Google Scholar; 1960 – 2015)."

Page 16485, line 6-11: Is there any reason to narrow your selection criteria? Can the authors analyze the results for different ecosystems by measurement method or frequency? Adding more information to the supplementary table on methods would help.

Response:
The paragraph was intended to note that the overall figures on GHG emissions shown are based on results achieved by different measurement techniques with inherent and contrasting sources of error.

If a paper provided detail information on gas collecting method, study periods and frequency, weather characteristics, and other environmental factors (soil, vegetation, management) we recorded the information in the supplementary database (see Appendix A). However, too few studies report sufficient descriptions and details of methodology to enable us to analyze available data by measurement methods, frequency or periods.

Page 16486, lines 7-10: Can the authors analyze the effect of soil moisture and temperature across the forest studies (e.g., more of a meta-analysis approach)? Or find ways to lump studies that measured or reported data on similar categories of controls?

Response:
We added new statistical analyses and discussion in section 3.1.1 as stated below:

"Observed annual soil CO_2 emissions in African natural terrestrial systems and agricultural lands showed significant correlations with annual mean air temperature (r=-0.322, P=0.01), annual rainfall (r=0.518, P <0.001), and SOC (r=0.626, P<0.001) and soil total N contents (r= 0.849, P <0.001) (Table 2). It was unexpected to find negative relation between annual soil CO_2 emissions and annual mean air temperature in this study since positive relation between soil CO_2 flux and temperature has been well known (e.g., Bond-Lamberty and Thomson, 2010). We speculate that the generally high temperatures, and poor quality, of many African soils mean that air temperature increases frequently result in vegetation stress and/or soil aridity, hindering root and soil microbial activities (root and microbial respiration) and subsequent soil CO_2 flux. This would account for the negative relationship we observed between annual mean air temperature and annual soil CO_2 emissions, but is an unproven hypothesis that deserves further exploration."

Page16487, lines 8-25: A mass balance, or C budget, perspective would help frame this paragraph. How do emissions relate to above- and belowground C inputs?

Response:
We newly conducted a correlation analysis for soil CO_2 flux with soil and environmental factors. We found an unexpected result showing negative relation between annual soil CO_2 emissions and annual mean air temperature. We discussed the results based on theories on drought and water stress on carbon balance and ecosystem production (see 3.1.1. CO_2 emissions). However, due to the dearth of data for above- and belowground C inputs, it was not feasible to test the relationship between soil CO_2 flux and above- and belowground C inputs as the reviewer suggested.

Page 16492, lines 7-27, Page 16493, lines 20-29; Page 16494, lines 7-9: Here are examples of where drawing on a mass balance perspective (and N saturation) would help provide a framework within which to interpret this list of results from individual studies. For example, in the case of the green beans, which did not increase emissions, much of the fixed N is harvested and exported from the system. There is also a need to understand relationships between management, N surplus, and emissions, which will depend on how loss pathways are partitioned (leaching v. gaseous losses).

Response:
We added the discussion in section 3.2.2 as below:

"Therefore, there may be potential to reduce N_2O emissions in the agroforestry practice, but it may require better management (i.e., reduced N inputs or adding a C source such as a cover crop together with an N source) and rotation planning."

Page 16493, line 3: I thought the review didn't include incubation studies. Or was this in situ?

Response:

For quantitative summary of GHG emissions, we only selected studies that reported *in situ* annual GHG emissions or those that provided enough information to estimate annual GHG emissions. So incubation studies were not included in the quantitative summary of GHG emissions (section 3. 1 Summary of greenhouse gas emissions in Africa). However, results from incubation studies were included in the synthesis of results from greenhouse gas emissions studies (section 3.2 Sources and drivers of greenhouse gas emissions in Africa).

To clarify it, we revised a sentence in section '2.1. Data collection' as below:

"To produce the quantitative summary of GHG emissions, we selected studies that reported *in situ* annual GHG emissions or those that provided enough information to estimate annual GHG emissions through unit conversion and/or extrapolation of given data."

Page 16495, lines 22-24: The C isotope result comes a bit out of context here. Briefly explain why this was measured/objective of the study.

Response:
We revise the sentence as below:

In Kenya, CH_4 fluxes did not show any seasonal trend and did not indicate appreciable variability among two different strains of rice (Tyler et al., 1988).

Page 16497, line 6: What is meant by output here? Harvest, leaching, or gaseous losses?

Response:
The sentence was removed.

Page 16497, lines 12-21: In the agroforestry/maize systems, were fertilizer rates adjusted (reduced or eliminated) based on the N input from the legume trees? It seems that for some of these studies the N balance perspective would allow the authors to say whether there may be potential to reduce emissions (in line with theory, if N surplus is reduced), but may require better management (i.e., reduced inputs) and rotation planning.

Response:
We did not find fertilizer rates were adjusted based on the N input from the legume trees. We added the below sentence in the paragraph (see Agroforestry in 3.2.2. Greenhouse gas emissions from agricultural lands):

"Therefore, there may be potential to reduce N_2O emissions in the agroforestry practice, but it may require ecological nutrient management (i.e., reduced inorganic fertilizer N inputs accounting N input from the legume trees; adding a C source such as a cover crop together with an N source) and rotation planning."

Page 16498, line 5: Again, the discussion of incubation experiments is a bit confusing. Were these included in the selection criteria? Are they in situ rather than lab incubations? Perhaps clarify in the methods.

Response:
For quantitative summary of GHG emissions, we only selected studies that reported *in situ* annual GHG emissions or those that provided enough information to estimate annual GHG emissions. So incubation studies were not included in the quantitative summary of GHG emissions (section 3. 1 Summary of greenhouse gas emissions in Africa). However, results from incubation studies were included in the synthesis of results from greenhouse gas emissions studies (section 3.2 Sources and drivers of greenhouse gas emissions in Africa).

To clarify it, we revised a sentence in section '2.1. Data collection' as below:

"To produce the quantitative summary of GHG emissions, we selected studies that reported *in situ* annual GHG emissions or those that provided enough information to estimate annual GHG emissions through unit conversion and/or extrapolation of given data."

Page 16499, line 8: Could place results in a broader sustainability context: soil CO2 emissions are only one component of emissions from agricultural systems, which also have all of the CO2 emissions from tillage, fuel use, and embodied emissions in chemical inputs, etc. (if used).

Response:
We added the prospective in '3.3 Suggested future studies' as below:

"Future research should consider the wider GHG budget of agriculture and include all the various (non-soil) components such as fuel use, and embodied emissions in chemical inputs."

Page 16500, lines 10-24 and Figure 5: Part (a) Can the authors separate the total N input by emissions graph by N source (e.g., manure, fertilizer, legume, or some combination of these)? It would be most interesting for part a, which is in a more realistic range of N input rates. For parts (b) and (c) it might be helpful to explain why these studies used such unrealistically high N rates, far outside of what would make economic sense for any farmer. What was the context of these studies?

Response:
In Fig. 5, we added N source information (control, organic fertilizer, inorganic fertilizer and mixture of organic and inorganic fertilizers) through showing different symbols for different N sources. The Fig. 5 (b) clearly indicated that very high N inputs came from mixture of organic and inorganic fertilizers and they were observed in vegetable gardens.

Page 16502, line 6: And N source (whether organic or inorganic).

Response:
It was revised as suggested.

Page 16502, line 15: Yes, and link new knowledge of microbial communities (e.g., functional gene abundance) to emissions rates (when talking about importance of identifying mechanisms/driving processes).

Response:
We revised the sentence as below:

"Where possible studies should seek to identify and separate driving processes contributing to efflux of soil CO_2 (e.g., autotrophic and heterotrophic sources), CH_4 (e.g., methanogenesis and methanotrophy) and N_2O (e.g., nitrification, denitrification, nitrifier denitrification) and link new knowledge of microbial communities (e.g., functional gene abundance) to GHG emissions rates."

Technical corrections
Page 16484, line 4: spell out AFOLU the first time

Response:
Corrected in line 12 in page 16482.

Page 16488, line 11: typo "this mechanisms"

Response:
The sentence was removed.

Page 16503, lines 22-23: two typos (advanced and higher)

Response:
We revised as it was suggested.

Anonymous Referee #2

The authors have done a notable job of bringing a lot of data into one article; however the structure at present is not acceptable. Due to the structure of the 'results and discussion' section it reads very much like a literature review made up of a list of examples which seem tediously linked. There has not been much actual synthesis, more just reporting on what individual studies have done. It would be far more informative to see more instances of '90% papers reviewed showed that: : :" as opposed to "x found Y, but Z found A". I would suggest starting this section with the summary of GHG emissions section then go on to discuss individual findings with more actual synthesis.

Response:
We want to address that lack of studies and low data quality in the existing studies for this region made hard to synthesize information beyond reviewing their findings. There are fundamental challenges to address the comments due to lack of data in general and poor data quality specifically. For instance, few studies report GHG fluxes with respect to the research questions described above, e.g., mechanistic controls, or with suitable experimental designs, e.g., adequate replication. Therefore, it was difficult to synthesize beyond describing their findings relevant to key topical areas. Furthermore, the data available were not a large enough sample to conduct valid statistical analysis, except for soil CO_2 fluxes, with which we were able to provide new statistical results as described below. Despite the difficulties, we have made significant efforts throughout the manuscript to improve the synthetic contribution of our effort and to improve the MS in order to better describe and understand GHG emissions, mitigation potential and future challenges in SSA.

Major changes were summarized as below:

1) New statistical results were added (see 3. 1. 1 CO_2 emissions) to show that observed annual soil CO_2 emissions in African natural terrestrial systems and agricultural lands had significant correlations with annual mean air temperature, annual rainfall, and soil organic carbon and total nitrogen contents. Accordingly, Table 2 and relevant discussion were added.

2) We altered the previous descriptive list to a more thematically synthesized approach throughout Results and Discussion: the sub-title of the second section changed to ' Sources and drivers of greenhouse gas emissions in Africa' accordingly.

3) Summary of GHG emissions section (newly named as '3. 1 Summary of greenhouse gas emissions in Africa') was revised and is now located right up front, first in Results and Discussion.

4) We newly assessed data quality of the cited studies using the criteria suggested by Rochette and Eriksen-Hamel (2008) and Barton et al. (2015). We categorized the studies as three different groups: the methods are 1) *poor to very poor*, 2) *marginal* and 3) *good*. We newly added detail procedure of the assessment (see 2.1. Data collection), results (see 3.1.5 Data quality assessment) and discussion (see 3.3 Suggested future research) in the manuscript. We have recorded the assessment

results in Supplementary Information Table S1 and S2.

The authors also make the error of not addressing the massive elephant in the room as to WHY there is so little data from Africa. It’s not simply a matter of scientific priorities but a massive socio-economic challenge! Mass poverty, extreme droughts, civil unrest, political instability, scientific funding/priorities etc. etc. are the main reason these data gaps exist. The authors seem to ignore this fact and suggest that it is as simple as someone deploying some cheap technologies such as chambers and IRGAS – noting that IRGAs are NOT a cheap technology! Unfortunately it is not that simple. There is certainly a point to be made that static chambers can be very cheap and require little know how to use but what about the analysis – where and how much will this cost?

Response:
We agree the current data gap is not only matter of research and science in the field but caused by long-lasting socio-economic issues in sub-Saharan Africa as well. We added the sentence below at the end of section 3.4.

"Beside, data acquisition will not be only determined by technical but also by socio-political (and economic) barriers in sub-Saharan Africa. These problems are not only affecting this process but are also driving forces for GHG emissions due to (e.g.) land-use change events. Therefore, the implication of social scientists on this kind of studies would be also needed."

Depending on countries in sub-Saharan Africa, different level of technology is applicable and approach and cost are very diverse. So we focused on providing a strategic plan for acquisition of soil GHG emission data such as prioritizing research topics and utilizing appropriate technology depending on level of scientific advance.

Specific comments

1. You need to establish some consistency with your units throughout the manuscript. It is confusing how you keep jumping from Pg to Gt to Kg etc… Pick one and stick with it through the manuscript using x10x where necessary. As it is it is very confusing and one must constantly be going back to check which unit you were in. It is best practice in science to use SI, in which case you should use kg and make use of x10x.

Response:
We modified the unit for CO_2 emissions. All CO_2 emissions were expressed as unit of Mg CO_2 throughout the text. In case of N_2O and CH_4 gases, some values were not large enough to apply 'Mg' unit so they were expressed as 'kg'.

2. Results/Discussion: Start this section with data from 3.4 so that it does not read like an introduction.

Response:

The summary of GHG emissions section (newly named as '3. 1 Summary of greenhouse gas emissions in Africa') is now located at the first section in Results and Discussion

Page 16481
Line 8: I would consider reporting these data in CO2-eq. At present these GHG data are not comparable to each other.

Response:
Reporting CH_4 and N_2O emissions in CO_2 eq may have advantage and disadvantage at the same time so it can be applied depending on context. Providing CO_2 eq for CH_4 and N_2O gases would be convenient to compare them with CO_2 gas. However, it may cause unavoidable confusion to someone who wants to know the range of CH_4 and N_2O emissions. Considering the context in the referred line, we thought providing the values in both original units and CO_2 eq would be better since the sentence was intended to provide the range of GHG emissions as well as the comparisons of source by source. Therefore, we revised the sentences and provide both original units and CO_2 eq.

Line 11: Make use of abbreviation GHG

Response:
Changed to GHG

Line 16-18: How were they different?

Response:
Incorporation of crop residues or manure with inorganic fertilizers resulted in various change in CO_2 and N_2O- showing increase or decrease in CO_2 and N_2O depending on the studies. We revised the sentence as below:

"Incorporation of crop residues or manure with inorganic fertilizers resulted in significant changes in GHG emissions but these were different for CO_2 and N_2O either increasing or decreasing depending on studies."

Line 22: “croplands and type and…” does not read well. Please restructure

Response:
We revised the sentence as below:

"Improving fallow with nitrogen (N)-fixing trees increased CO_2 and N_2O emissions compared to conventional croplands. Type and quality of plant residue in the improving fallow is likely to be an important control factor affecting CO_2 and N_2O emissions."

Page 16482
Line 2: Change: “~~and~~ WITH natural and agricultural lands ~~contributed~~ CONTRIBUTING 76.3…”

Response:
We revised the sentence as below:

"Overall, total CO_2 eq emissions from African natural ecosystems and agricultural lands were 56.9 ± 12.7 x 10^9 Mg CO_2 eq yr^{-1} with natural ecosystems and agricultural lands contributing 76.3% and 23.7%, respectively."

Line 3: Change ‘Africa’ to ‘African’

Response:
Changed.

Line 5: Change: “options on emissions.” To “options for emissions”

Response:
Changed.

Line 8: Remove ‘and’ and change to ‘involving international’

Response:
We revised the sentence as below:

"There is also a need to develop a common strategy for addressing this data gap that may include identifying priorities for data acquisition, utilizing appropriate technologies, and involving international networks and collaboration."

Line 10: Redefine greenhouse gas as ‘GHG’

Response:
Changed.

Line 12: ‘land use’ to ‘land uses’

Response:
'agricultural, forestry and other land use (AFOLU)' has been commonly used in IPCC reports and other documents.

Line 20: Place comma after ‘wetland’

Response:
Changed.

Page 16482
Line 2: “For example, CO2 eq emissions from…” Are you talking just about CO2 or about all the GHGs? You need to be clear. Using the terminology you have is not standard scientific practice and is confusing for the reader. CO2-eq is a unit for standardising non-CO2 GHGs for comparison to CO2 and should not be used to describe the sum of all 3 GHG emissions. Additional confusion comes when you have stated ‘CO2 eq emissions’ then report in terms of carbon! This section needs to be reworked to make it clear!

Response:
In the cited study (Borges et al., 2015), CO_2 eq emission was calculated by adopting 100-year global warming potentials (GWPs) of 28 and 265 for CH_4 and N_2O, respectively and then summing CO_2 emissions and GWPs of CH_4 and N_2O emissions. The method has been used in many other studies including a recent study (Tian et al., 2016, Nature).

We provided a modified unit (CO_2 eq per year) by multiplying 44/12 as below:

0.9 Pg C per year x (44/12) = 3.3 Pg CO_2 eq per year

Reference
Tian et al., 2016. The terrestrial biosphere as a net source of greenhouse gases to the atmosphere. Nature. 531, 225-228.

Line 17: I don't think fig 2 and 3 are particularly informative as you have stated all the information here in the text. Consider removing as they do not really add anything to your point.

Response
Removed.

Page: 16485
Line 19-23: Split this into 2 sentences.

Response:
We revised the sentence as below:

“Separate t-tests were used to assess significance of regression coefficients and intercepts in the fitted parametric models. Adjusted coefficients of determination (adjusted R^2) of fitted parametric models were used as criteria for model selection: the model with the higher adjusted R^2 was selected.”

Line 24: Remove ‘These’ and start sentence with ‘Statistical…’

Response:
We removed it.

Page 16487
Line 1-7: There is no original hypoth testing or statistical analysis here. Merely a list of examples where other authors have found causes of fluxes. It seems the authors have not been systematic in their approach and are picking and choosing data to write about. It would be much more informative for a review such as this to say “70% of papers found temp affected CO2 flux in natural lands…”

Line 8 onwards: Much smarter analyses could have been done to summarise the data in the literature than just reporting a range of values

Line 8 onwards: None of this seems suitable to be called results or discussion…it reads like an intro. Where is your analysis?

Response:
We want to reiterated that lack of studies and low data quality in the existing studies for this region made hard to synthesize information beyond reviewing their findings. There are fundamental challenges to address the comments due to lack of data in general and poor data quality specifically. For instance, few studies report GHG fluxes with respect to the research questions described above, e.g., mechanistic controls, or with suitable experimental designs, e.g., adequate replication. Therefore, it was difficult to synthesize beyond describing their findings relevant to key topical areas. Furthermore, the data available were not a large enough sample to conduct valid statistical analysis, except for soil CO_2 fluxes, with which we were able to provide new statistical results as described below. Despite the difficulties, we have made efforts to improve the MS in order to better describe and understand GHG emissions, mitigation potential and future challenges in SSA.

Major changes were summarized as below:

1) New statistical results were added (see 3. 1. 1 CO_2 emissions) to show that observed annual soil CO_2 emissions in African natural terrestrial systems and agricultural lands had significant correlations with annual mean air temperature, annual rainfall, and soil organic carbon and total nitrogen contents. Accordingly, Table 2 and relevant discussion were added.

2) We altered the previous descriptive list to a more thematically synthesized approach throughout Results and Discussion: the sub-title of the second section changed to ' Sources and drivers of greenhouse gas emissions in Africa' accordingly.

3) Summary of GHG emissions section (newly named as '3. 1 Summary of greenhouse gas emissions in Africa') was revised and is now located right up front, first in Results and Discussion.

4) We newly assessed data quality of the cited studies using the criteria suggested by Rochette and Eriksen-Hamel (2008) and Barton et al. (2015). We categorized the studies as three different groups: the methods are 1) *poor to very poor*, 2) *marginal* and 3) *good*. We newly added detail procedure of the assessment (see 2.1. Data collection), results (see 3.1.5 Data quality assessment) and discussion (see 3.3 Suggested future research) in the manuscript. We have recorded the assessment results in Supplementary Information Table S1 and S2.

Page 16495
Line 3 and 10: Throughout MS you have used the American spelling of 'fertilizer' but on line 10 you use the British spelling. Be consistent through manuscript with you use of 'z' and 's'.

Response:
We changed to 'fertilized'.

Line 13-18: I would be VERY cautious to make these statements as you are reporting on 1 study. This tells us very little…it tells us about one place at one time and certainly no generalisations should be made about other grazing grasslands across Africa!! Acknowledge this as a limitation!

Response:
We revised the sentence as below:

"Only one study measured GHG emissions in grazing grasslands and there is a serious limitation in understanding GHG emissions in grazing grassland."

Page 16496
Line 1: Why have you suddenly switched to using kg CO2 when everywhere else you have used Mg?! I have identified 4 different units being used through the MS (Mg, kg, Gt, Pg) when it should be 1! Do not be lazy and copy units from papers – make the conversions and the paper would be much easier to read.

Response:
We modified the unit for CO_2 emissions. All CO_2 emissions were expressed as unit of Mg CO_2 throughout the text. In case of N_2O and CH_4 gases, some values were not large enough to apply 'Mg' unit so they were expressed as 'kg'.

Line 10-15: I don’t think you can make generalisations and draw conclusions from just 2 studies!

Response:
We revised to sentence to prevent over generalization as below:

"Greenhouse gas emissions from soils in vegetable gardens in peri-urban areas of Burkina Faso (Lompo et al., 2012) and Niger (Predotova et al., 2010) ranged from 73.3 to 132.0 Mg CO_2 ha^{-1} y^{-1} and 53.4 to 177.6 kg N_2O ha^{-1} y^{-1} (Table 1 and SI Table 1)."

Page 16499
This section needs to come first in the results/discussion section. This is your results, lead with this

Response:
The summary of GHG emissions section (newly named as '3. 1 Summary of greenhouse gas emissions in Africa') is now located at the first section in Results and Discussion

Page 16500
Line 5-9: I would be cautious about making these bold claims when gardens only used 2 studies!!!!

Response:
We recognize the limitation and revised them as below:

"The largest N_2O source in agricultural lands was vegetable gardens followed by agroforestry, cropland and rice fields (Table 1). The N_2O EF was 0.5 ± 0.2% and 3.5 ± 0.5% for cropland and vegetable gardens, respectively (Table 1 and SI Table 1). The N_2O EF of cropland is lower and the N_2O EF of vegetable gardens is higher than IPCC default N_2O EF (1%, IPCC, 2006). It is noticed that the results were made by limited number of studies and more research is needed to verify and update the results."

Page 16501
Line 9: Stop switching units!!

Response:
We modified the unit for CO_2 emissions. All CO_2 emissions were expressed as unit of Mg CO_2 through the text. In case of N_2O and CH_4 gases, some values were not large enough to apply 'Mg' unit so they were expressed as 'kg'.

Page: 16503
Line 3 onwards: But why is Africa studies less? Because it comes with more challenges…you need to acknowledge this!!

Response:

We surely understood the reviewer's concerns and also recognized the current data gap is not only matter of research and science in the field but caused by long-lasting socio-economic issues in sub-Saharan Africa as well. So we added the below sentence at the end of section 3.4.

"Beside, data acquisition will not be only determined by technical but also by socio-political (and economic) barriers in sub-Saharan Africa. These problems are not only affecting this process but are also driving forces for GHG emissions due to (e.g.) land-use change events. Therefore, the implication of social scientists on this kind of studies would be also needed."

Drs. Alberto Borges & Steven Bouillon' s comments

Kim and co-authors report an important data compilation of soil-atmosphere fluxes of greenhouse gases (GHGs) from the African continent that is probably the least studied on the globe despite the vital importance of the corresponding ecosystems such as the second largest evergreen tropical forest in the World. We would like to comment the way the river/stream data are classified per country in Table S1. The unit that matters for hydrology and river biogeochemisty (including ex-change of GHG with the atmosphere) is the river basin and not the country where the measurements were made. For instance, for the Congo River, the river basin comprises ten African countries (Angola, Burundi, Cameroon, Central African Republic, Democratic Republic of the Congo, Republic of the Congo, Rwanda, South Sudan, Tanzania, and Zambia). In Table S1, the data for Congo River are attributed to the Republic of the Congo although the data reported by Borges et al. (2015) were in fact acquired in the Democratic Republic of the Congo, a country that has the largest share of the Congo basin (60%). Similarly, the data on the Zambezi basin reported by Teodoru et al. (2015) were acquired in both Zambia and Mozambique, although the Zambezi basin comprises eight African countries (Angola, Namibia, Botswana, Zimbabwe, Zambia, Tanzania, Malawi, and Mozambique).

We would like to also highlight that lakes are important features of the African landscapes (in addition to rivers/streams) since these are among the largest in the world (Tanganyika, Victoria, Malawi, Kivu, Edward, Albert, etc: : :), and deserve further investigation with regards to GHG exchange. Some data are available for Lake Kivu (Borges et al. 2011; 2014). Data from Lake Kariba (Delsontro et al. 2011) and CH4 from Ivory Coast lagoons (Koné et al. 2010) could also be included in the synthesis of aquatic fluxes.

References

Borges A.V., G. Abril, B. Delille, J.-P. Descy & F. Darchambeau (2011) Diffusive methane emissions to the atmosphere from Lake Kivu (Eastern Africa), Journal of Geophysical Research - Biogeosciences, 116, G03032, doi:10.1029/2011JG001673

Borges A.V., C. Morana, S. Bouillon, P. Servais, J.-P. Descy, F. Darchambeau (2014) Carbon cycling of Lake Kivu (East Africa): net autotrophy in the epilimnion and emission of CO2 to the atmosphere sustained by geogenic inputs, PLoS ONE 9(10): e109500. doi:10.1371/journal.pone.0109500

Borges AV, Darchambeau F, Teodoru CR, Marwick TR, Tamooh F, Geeraert N, Omengo FO, Guérin F, Lambert T, Morana C, Okuku E & Bouillon S (2015) Globally significant greenhouse gas emissions from African inland waters, Nature Geoscience, 8, 637-642, doi:10.1038/NGEO2486

Delsontro T et al. (2011) Spatial Heterogeneity of Methane Ebullition in a Large Tropical Reservoir, Environmental Science & Technology (Impact Factor: 5.33). 12/2011; 45(23):9866-73.

Koné Y.J.M., G. Abril, B. Delille & A.V. Borges (2010) Seasonal variability of methane in the rivers and lagoons of Ivory Coast (West Africa), Biogeochemistry, 100, 21–37

Teodoru C. R., F. C. Nyoni, A. V. Borges, F. Darchambeau, I. Nyambe & S. Bouillon (2015) Dynamics of greenhouse gases (CO2, CH4, N2O) along the Zambezi River and major tributaries, and their importance in the riverine carbon budget, Biogeosciences, 12, 2431–2453

Response:
We classified river and stream data per the river basin in Table S1. We newly added lake data (Lake Kivu (Borges et al. 2011; 2014), Lake Kariba (Delsontro et al. 2011), and Ivory Coast lagoons (Koné et al. 2010) in text and Table S1.

Title

Greenhouse gas emissions ~~in~~from natural ecosystems and agricultural lands in sub-Saharan Africa: synthesis of available data and suggestions for further ~~studies~~research

Authors

Dong-Gill Kim[a *], Andrew D. Thomas[b], David Pelster[c], Todd S. Rosenstock[d], Alberto Sanz-Cobena[e]

[a]Wondo Genet Collage of Forestry and Natural Resources, Hawassa University, PO Box 128, Shashemene, Ethiopia
[b]Department of Geography and Earth Sciences, Aberystwyth University, Aberystwyth SY23 3DB, UK
[c]International Livestock Research Institute, PO Box 30709, Nairobi, Kenya
[d]World Agroforestry Centre (ICRAF), PO Box 30677-00100, United Nations Avenue, Nairobi, Kenya
[e]Technical University of Madrid, School of Agriculture, Avd. Complutense s/n, 28040 Madrid, Spain

[*]Corresponding author
Dong-Gill Kim
Wondo Genet Collage of Forestry and Natural Resources, Hawassa University, PO. Box 128, Shashemene, Ethiopia, Tel: 251 928 768480,
E-mail: donggillkim@gmail.com

Formatted: Font color: Auto

Formatted: Font color: Auto

Formatted: Font color: Auto

Formatted: Font color: Auto

Formatted: Font color: Auto

Formatted: Font: Bold, Font color: Auto

Formatted: Line spacing: Double

Abstract

This paper summarizes currently available data on greenhouse gas (GHG) emissions from African natural ecosystems and agricultural lands, outlines the knowledge gaps and suggests future directions and strategies for GHG emission ~~studies~~research. GHG emission data were collected from 73 studies conducted in 22 countries in sub-Saharan Africa (SSA). Soil carbon dioxide (CO_2) emissions were by far the largest contributor to GHG emissions ~~from~~and global warming potential (GWP) in African natural terrestrial systems. CO_2 emissions ranged from 3.3 to 57.0 Mg ~~carbon dioxide (~~CO_2~~)~~ ha^{-1} yr^{-1}, methane (CH_4) emissions ranged from -4.8 to 3.5 kg ~~methane (CH_4)~~ ha^{-1} yr^{-1} ~~and -0.1 to 13.7 kg~~ (-0.16 to 0.12 Mg CO_2 equivalent (eq) ha^{-1} yr^{-1}) and nitrous oxide (N_2O) ~~ha^{-1} yr^{-1}.~~emissions ranged from -0.1 to 13.7 kg ha^{-1} yr^{-1} (-0.03 to 4.1 Mg CO_2 eq ha^{-1} yr^{-1}). Soil physical and chemical properties, rewetting, vegetation type, forest management and land-use changes were all found to be important factors affecting soil GHG emissions~~. Greenhouse gas emissions~~ from natural terrestrial systems. In African aquatic systems~~ ranged~~, CO_2 was the largest contributor to total GHG emissions, ranging from 5.7 to 232.0 Mg CO_2 ha^{-1} yr^{-1}, followed by -26.3 to 2741.9 kg CH_4 ha^{-1} yr^{-1} (-0.89 to 93.2 Mg CO_2 eq ha^{-1} yr^{-1}) and 0.2 to 3.5 kg N_2O ha^{-1} yr^{-1} ~~and~~(0.06 to 1.0 Mg CO_2 eq ha^{-1} yr^{-1}). Rates of all GHG emissions from aquatic systems were all strongly affected by discharge. ~~Soil GHG emissions from African~~In croplands~~ ranged~~, soil GHG emissions were dominated by CO_2, ranging from 1.7 to 141.2 Mg CO_2 ha^{-1} yr^{-1}, with -1.3 to 66.7 kg CH_4 ha^{-1} yr^{-1} (-0.04 to 2.3 Mg CO_2 eq ha^{-1} yr^{-1}) and 0.05 to 112.0 kg N_2O ha^{-1} yr^{-1} ~~and the~~ (0.015 to 33.4 Mg CO_2 eq ha^{-1} yr^{-1}). N_2O emission ~~factor~~factors (EF) ranged from 0.01 to 4.1%. Incorporation of crop residues or manure with inorganic fertilizers invariably resulted in significant changes in GHG emissions but ~~these~~the magnitude and direction of changes were different for CO_2 and N_2O~~.~~ as well as location. Soil GHG emissions ~~in~~from vegetable gardens ranged from 73.3 to 132.0 Mg CO_2 ha^{-1} ~~y~~yr^{-1} and 53.4 to 177.6 kg N_2O ha^{-1} ~~y^{-1}~~yr^{-1} (15.9 to 52.9 Mg CO_2 eq ha^{-1} yr^{-1})

Formatted: Font color: Auto
Formatted: Space Before: 12 pt
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto, English (U.S.)
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto, English (U.S.)
Formatted: Font color: Auto
Formatted: Font color: Auto, Not Superscript/ Subscript
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto, English (U.K.)
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto, English (U.K.)
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto

and N_2O EFs ranged from 3 to 4%. Soil CO_2 and N_2O emissions from agroforestry were 38.6 Mg CO_2 ha^{-1} y^{-1} and 0.2 to 26.7 kg N_2O ha^{-1} yr^{-1}~~,~~ (0.06 to 8.0 Mg CO_2 eq ha^{-1} yr^{-1}), respectively. Improving fallow with nitrogen (N)-fixing trees led to increased CO_2 and N_2O emissions compared to conventional croplands~~ and~~. The type and quality of plant residue in the fallow is ~~likely to be~~ an important control ~~factor affecting~~ on how CO_2 and N_2O emissions are affected. Throughout agricultural lands, N_2O emissions slowly increased with N inputs below 150 kg N ha^{-1} yr^{-1} and increased exponentially with N application rates up to 300 kg N ha^{-1} yr^{-1}. The lowest yield-scaled N_2O emissions were reported with N application rates ranging between 100 and 150 kg N ha^{-1}. Overall, total CO_2 ~~equivalent (~~eq~~)~~ emissions from African natural ecosystems and agricultural lands were 56.9 ± 12.7 ~~Pg~~x 10^9 Mg CO_2 eq~~,~~ yr^{-1} ~~and~~with natural ecosystems and agricultural lands ~~contributed~~contributing 76.3% and 23.7%, respectively. Additional GHG emission measurements throughout ~~Africa~~African agricultural and natural lands are urgently required to reduce uncertainty on annual GHG emissions from the different land uses and identify major control factors and mitigation options ~~on~~for emissions. There is also a need to develop a common strategy for addressing this data gap that may ~~involve~~include identifying priorities for data acquisition, utilizing appropriate technologies, and ~~establishing~~involving international networks and collaboration.

Key words: Africa, greenhouse gas, carbon dioxide, methane, nitrous oxide, natural lands, agricultural lands

1. Introduction

Global greenhouse gas (GHG) emissions were estimated to be 49 (± 4.5) ~~Gt~~x 10^9 Mg CO_2 eq in 2010 (IPCC, 2014), with approximately 21.2 – 24% (10.3 – 12 ~~Gt~~x 10^9 Mg CO_2 eq) of emissions originating from soils in agricultural, forestry and other land use (AFOLU) (Tubiello et al., 2015; IPCC, 2014). Annual non-CO_2 GHG emissions (primarily CH_4 and N_2O) from agriculture were estimated to be 5.2 – 5.8 ~~Gt~~x 10^9 Mg CO_2 eq yr^{-1} in 2010 (FAOSTAT, 2014; Tubiello et al., 2013),

Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman
Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman
Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman
Formatted: Font color: Auto
Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman
Formatted: Font color: Auto
Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman
Formatted: Font color: Auto
Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman
Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman
Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman
Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman
Formatted ...
Formatted ...
Formatted ...
Formatted ...

with approximately 4.3 – 5.5 ~~Gt~~x 10^{9} Mg CO_2 eq yr^{-1} attributable to land~~-use and land~~-use change ~~activities~~ (IPCC, 2014).

Greenhouse gas fluxes in Africa play an important role in the global GHG budget (Thompson et al., 2014; Hickman et al., 2014; Valentini et al., 2014; Ciais et al., 2011; Bombelli et al., 2009). In recent years, conversion rates of African natural lands, including forest, grassland and wetland, to agricultural lands have increased (Gibbs et al., 2010; FAO, 2010). The dominant type of land use change has been the conversion of forest to agriculture with average deforestation rates of 3.4 million ha per year (FAOSTAT, 2014) (Fig. 1). This land-use conversion results in an estimated additional release of 0.32 ± 0.05 ~~Pg~~x 10^{9} Mg C yr^{-1} (Valentini et al., 2014) or 157.9 ± 23.9 ~~Gt~~x 10^{9} Mg CO_2 eq in 1765 to 2005 (Kim and Kirschbaum, 2015), higher than fossil fuel emissions for ~~the continent~~Africa (Valentini et al., 2014).

Soil emissions of all the major GHGs from Africa can be potentially significant at global scales. For example, ~~-~~CO_2 eq emissions from 12 river channels in SSA and wetlands of the Congo River were ~~about 0.9 Pg C~~3.3 x 10^{9} Mg CO_2 eq per year, equivalent to ~~about~~c. 25% of the global terrestrial and ocean carbon sink (Borges et al., 2015). Nitrous oxide emissions in Africa contribute between 6 – 19% of the global total, and changes in soil N_2O fluxes in Africa drive large inter-annual variations in tropical and subtropical N_2O sources (Thompson et al., 2014; Hickman et al., 2011). Nitrous oxide emissions from biogenic sources and fires in natural lands were estimated to contribute to 34% of total N_2O emissions in the region (Valentini et al., 2014). According to Lassaletta et al. (2014), mean N application rates in Africa were 34 kg N ha^{-1} in 2009 (16 kg N ha^{-1} in sub-Saharan Africa) compared to 169.1 kg N ha^{-1} in 2009 in the USA. Only Mauritius, Botswana and South Africa had average N application rates exceeding100 kg N ha^{-1}. Even with the low fertilizer rates used across the continent, agricultural GHG emissions in Africa are substantial; amounting to 26% of the continent's total GHG emissions (Valentini et al., ~~2014).~~ 2014) while agricultural GHG emissions were responsible for 8.4% of total GHG emissions in the USA (US EPA, 2016). Use~~According to Lassaletta et al. (2014), mean N application rates in Africa were 34~~

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman, English (U.K.)

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted ...

~~kg N ha^{-1} in 2009 and only 16 kg N ha^{-1} in sub-Saharan African countries. Only Mauritius, Botswana and South Africa had average N application rates exceeding100 kg N ha^{-1}. However, use~~ of synthetic fertilizers such as urea has increased in the last four decades as well as the number of livestock (and their manure and urine products) in Africa (Bouwman et al., 2009 and 2013~~) (Figs.2 and 3~~). The increasing trend in N application rates is expected to cause a twofold increase in agricultural N_2O emissions in Africa by 2050 (from 2000) (Hickman et al., 2011). In the case of CH_4 emissions, there are important differences between ecosystems. Tropical humid forest, wetlands, rice paddy fields and termite mounds are likely sources of CH_4, while seasonally dry forests and savannahs are typically CH_4 sinks (Valentini et al., 2014).

Our current understanding of GHG emissions in Africa is particularly limited when compared to the potential the continent has as both a GHG sink and source. This lack of data on GHG emissions from African natural and agricultural lands and the lack of a comprehensive analysis of existing data hinder the progress of our understanding of GHG emissions on the continent (Hickman et al., 2014; Valentini et al., 2014; Ciais et al., 2011; Bombelli et al., 2009). In order to identify mitigation measures and other climate smart interventions for the region it is important to quantify baseline GHG emissions, as well as understand the impacts of different land-use management strategies on GHG emissions (e.g., Palm et al., 2010).

In this study our objectives are to synthesize currently available data on GHG emissions from African AFOLU; create an inventory of information from studies on emissions; and select priority topics for future GHG emission studies in natural and agricultural lands in SSA.

~~2. Methodology~~

~~2.1. Data collection~~

2. Methodology

2.1. Data collection

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: Bold, Font color: Auto

Formatted: Line spacing: Double

Formatted: Font: (Asian) +Body Asian, Bold, Font color: Auto, (Intl) Times New Roman

Formatted: Font: Bold, Font color: Auto

Formatted: Font: (Asian) +Body Asian, Bold, Font color: Auto, (Intl) Times New Roman

Formatted: Font: Bold, Font color: Auto

Data were acquired by searching existing peer-reviewed literature (304 peer-reviewed papers) using the names of the sub-Saharan countries and the GHGs (i.e. CO_2, CH_4 and N_2O) as search terms (using Web of Science and Google Scholar; 1960 – 2015). ~~We~~ To produce the quantitative summary of GHG emissions, we selected studies that reported *in situ* annual GHG emissions or those that provided enough information to estimate annual GHG emissions through unit conversion and/or extrapolation of given data. Data from ~~73~~76 studies, conducted in 22 countries (n=244) in SSA were used and were further categorized as GHG emission in natural ~~lands~~ecosystems [n=117; Supplementary Information (SI) Table 1] and agricultural lands (n=127; SI Table 2) (Fig. ~~4~~2). The category of GHG emissions in natural ~~lands~~ecosystems were further divided into emissions from natural terrestrial systems [forest/ plantation/woodland (n=55), savannah/grassland (n=31), termite mounds (n=5), and salt pans (n=1)] and aquatic systems [streams/rivers (n=14), wetlands/ floodplains /lagoons/ reservoirs/lakes (n=11~~), termite mounds (n=5), and salt pans (n=1))~~] (Table 1). The category of GHG emission in agricultural lands, were subdivided into emissions from cropland (n=105), rice ~~paddy~~paddies (n=1), vegetable garden (n=5), and agroforestry (n=16) (Table 1). Across all categories there were 174 CO_2, 201 CH_4 and 184 N_2O emissions measurements. To allow comparison between different GHG emissions CH_4 and N_2O emissions were converted to CO_2 eq assuming a 100 year global warming potential and values of 34 and 298 kg CO_2 eq for CH_4 and N_2O, respectively (IPCC, 2013). Where N_2O emission studies included experimental data from control plots with no N fertilizer additions (i.e. for background N_2O emissions) and from plots with different levels of applied N, a N_2O emission factor (EF) was calculated following the IPCC (2006) Tier I methodology as follows:

$$N_2O\ EF(\%) = \frac{N_2O\ emission_{N\,treatment} - N_2O\ emission_{control}}{N\,input} \times 100 \qquad [1]$$

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

where, $N_2O\ EF\ (\%)$ is N_2O emission factor, $N_2O\ emission_{\ N\ treatment}$ is N_2O emission in N input, $N_2O\ emission_{control}$ is control treatments with no N fertilizer additions, and $N_{\ input}$ is the amount of added N.

It should be noted that our data compilation includes a wide variety of studies that were conducted under diverse biophysical conditions using a range of methodologies for quantifying GHG emissions (e.g., different sampling protocols, chamber design, and emission rate calculations), soil properties, and climatic factors. Therefore, the overall figures on GHG emissions shown are based on results achieved by different measurement techniques with inherent and contrasting sources of error. To assess data quality of the cited studies we used the criteria (rank from “very poor” to “very good") suggested by Rochette and Eriksen-Hamel (2008). We went through the methods of the papers used in the study (only those for terrestrial emissions, since these criteria do not work for aquatic systems) where there was sufficient detail in the methods section. We categorized the studies as three different groups: the methods are 1) *poor to very poor*, 2) *marginal* and 3) *good*. Studies that were ranked “poor” on 3 or more criteria, or “very poor” on 2 or more criteria were categorized as the methods were *poor to very poor*. In addition, we took into account the importance of sampling frequency (Barton et al., 2015) and sampling periods. Studies estimating annual GHG emissions with a sampling frequency lower than biweekly (i.e., less than 2 times per month) and sampling periods of less than 6 months (i.e., covering both rainy and dry seasons) were categorized as the methods were *poor to very poor*. Studies that were ranked as "poor" on 2 criteria, or "very poor" on 1 criterion, or with insufficient details on the methods were ranked as *marginal*. The *good* studies were those with only 1 "poor" ranking, sufficient detail and a sampling frequency of every 2 weeks or more frequent.

2.2. Statistical analyses

To determine the relationship between annual soil CO_2 emissions and edaphic and climatic factors (e.g., soil pH, soil bulk density, soil organic carbon (SOC), total N, and annual average air

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto, English (U.K.)

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

temperature and rainfall) in African natural terrestrial systems and agricultural lands, we used a Pearson correlation analysis. The compiled datasets were used to examine the best model fit ~~and to derive the corresponding model parameters~~selection for N_2O emissions and yield-scaled N_2O emissions as a function of the respective N input levels. Different data fitting models (linear, nonlinear, natural log, logarithm and sigmoidal) were tested for each dataset. The regression models were checked for violation of assumptions of normal distribution (Shapiro–Wilk test), homoscedasticity (Breusch–Pagan test), and constant variance (Durbin–Watson statistic) (Motulsky and Christopoulos, 2004). Separate t-tests were used to assess significance of regression coefficients and intercepts in the fitted parametric models~~ and adjusted~~. Adjusted coefficients of determination (adjusted R^2) of fitted parametric models were used as criteria for model selection: the model with the higher adjusted R^2 was selected. Statistical significance was considered at the critical level of 5%. ~~These statistical~~Statistical analyses were conducted using SAS® ver. 9.2 (SAS Institute, Cary, NC, USA) and SigmaPlot® ver. 11.0 (Systat Software Inc., San Jose, CA, USA).

3~~.~~ Results and ~~discussion~~Discussion

3. 1~~. Greenhouse~~ Summary of greenhouse gas emissions in ~~natural lands~~ Africa

3. 1. 1~~. Terrestrial systems~~ CO_2 emissions

~~Soil GHG emissions from African natural terrestrial systems such as natural forest, plantation, woodland, savannah, grassland, termite mounds and salt pans~~ Carbon dioxide emissions ranged from 3.3 to 130.9 Mg CO_2 ha^{-1} y^{-1}~~, 4.8~~ in natural terrestrial systems and from -11.9 to ~~3.5 kg CH_4~~232.0 Mg CO_2 ha^{-1} ~~y^{-1}and -0.~~yr^{-1} ~~to 13.7 kg N_2O~~in aquatic systems. The area weighted average was 27.6 ± 17.2 Mg CO_2 ha^{-1} ~~y~~yr^{-1} (Table 1 and SI Table 1). Aquatic systems such as water bodies or water submerged lands were the largest source of CO_2 followed by forest, savannah, termite mounds and salt pans (Table 1). Soil CO_2 emissions in agricultural lands were similar to emissions from natural lands and ranged from 6.5 to 141.2 Mg CO_2 ha^{-1} ~~The high variability in~~yr^{-1} with an area weighted average of 23.0 ± 8.5 Mg CO_2 ha^{-1} yr^{-1} (Table 1 and SI

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: Not Bold, Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman, English (U.S.), Superscript

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Table 2). Vegetable gardens were the largest sources of CO_2 emission ~~rates was likely related to differences in~~ largely due to the large C inputs, followed by agroforestry, cropland and rice fields (Table 1 and SI Table 2).

Observed annual soil CO_2 emissions in African natural terrestrial systems and agricultural lands showed significant correlations with annual mean air temperature~~, moisture~~ (r=-0.322, P=0.01), annual rainfall (r=0.518, P <0.001), and SOC (r=0.626, P<0.001) and soil total N content ~~and physical-chemical properties as~~(r= 0.849, P <0.001) (Table 2). The negative relationship between annual soil CO_2 emissions and annual mean air temperature was unexpected since positive correlations between soil CO_2 flux and temperature are well ~~as the type of natural~~ established (e.g., Bond-Lamberty and Thomson, 2010). We speculate that the generally high temperatures, and poor quality, of many African soils mean that air temperature increases frequently result in vegetation ~~present. Within~~stress and/or soil aridity, hindering root and soil microbial activities (root and microbial respiration) and subsequent soil CO_2 flux (e.g., Thomas et al., 2011). This would account for the negative relationship we observed between annual mean air temperature and annual soil CO_2 emissions, but is an unproven hypothesis that deserves further exploration.

3. 1. 2 CH_4 emissions

Forest/plantation/woodland were sinks of CH_4 (-1.5 ± 0.6 kg CH_4 ha^{-1} yr^{-1}) and savannah/grassland, crop lands, termite mounds, and rice fields were low to moderate CH_4 sources (0.5 – 30.5 kg CH_4 ha^{-1} yr^{-1}). Stream/river and wetland/floodplain/lagoon/reservoir were high CH_4 sources (766.0 – 950.4 kg CH_4 ha^{-1} yr^{-1}) (Table 1 and Table 1 in supplementary material). The area weighted averages of CH_4 emissions from natural and agricultural lands were 43.0 ± 5.8 and 19.5 ± 5.6 kg CH_4 ha^{-1} yr^{-1}, respectively.

3. 1. 3 N_2O emissions and emission factor (EF)

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman, Subscript

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Nitrous oxide emissions in natural ecosystems ranged from -0.1 to 13.7 kg N_2O ha^{-1} yr^{-1} and the area weighted average was 2.5 ± 0.8 kg N_2O ha^{-1} yr^{-1} (Table 1 and SI Table 1). Our study reveals that forest, plantation and woodland were the largest source of N_2O followed by rivers and wetlands, savannah and termite mounds in natural ecosystems (Table 1). Soil N_2O emissions in agricultural lands ranged from 0.051 to 177.6 kg N_2O ha^{-1} yr^{-1} and the area weighted average was 4.5 ± 2.2 kg N_2O ha^{-1} yr^{-1} (Table 1 and SI Table 2). The largest N_2O source in agricultural lands was vegetable gardens followed by agroforestry, cropland and rice fields (Table 1). The N_2O EF was 0.5 ± 0.2% and 3.5 ± 0.5% for cropland and vegetable gardens, respectively (Table 1 and SI Table 1). The N_2O EF of cropland is lower and the N_2O EF of vegetable gardens is higher than IPCC default N_2O EF (1%, IPCC, 2006). The number of studies on N_2O emissions in Africa is, however, particularly low (n=14) and there are significant regional gaps leading to uncertainties in the conclusions that can be currently drawn.

N_2O emissions were significantly affected by N input levels (Fig. 3). N_2O emissions increase slowly up to 150 kg N ha^{-1} yr^{-1}, after which emissions increase exponentially up to 300 kg N ha^{-1} yr^{-1} (Fig. 3 (A)). Consistent with earlier work by van Groenigen (2010) N inputs of over 300 kg N ha^{-1} yr^{-1} resulted in an exponential increase in emission (Fig. 3 (B)), slowing to a steady state with N inputs of 3000 kg N ha^{-1} yr^{-1}. Overall, the relationship between N input and N_2O emissions shows a sigmoidal pattern (Fig. 3 (C)). The observed relationship is consistent with the proposed hypothetical conceptualization of N_2O emission by Kim et al. (2013) showing a sigmoidal response of N_2O emissions to N input increases. The results suggest that N inputs over 150 kg N ha^{-1} yr^{-1} may cause an abnormal increase of N_2O emissions in Africa. The relationship between N input and N_2O emissions show that the lowest yield-scaled N_2O emissions were reported for N application rates ranging from 100 to 150 kg N ha^{-1} (Fig. 4). The results are in line with the global meta-analysis of Philiber et al. (2012) who showed that from an N application rate ~150 kg N ha^{-1} the increase in N_2O emissions is not linear but exponential.

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman, English (U.S.)

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

3. 1. 4 CO_2 eq emission

Carbon dioxide eq emission (including CO_2, CH_4 and N_2O) in natural lands ranged from 11.7 to 121.3 Mg CO_2 eq ha^{-1} yr^{-1} and the area weighted average of CO_2 eq. emissions (excluding salt pans) was 29.9 ± 22.5 Mg CO_2 eq ha^{-1} yr^{-1} (Table 1). Water bodies or water submerged lands such as rivers and wetlands were the largest source of CO_2 eq. emissions followed by forest/ plantation/ woodland, savannah/ grassland and termite mounds (Table 1). Carbon dioxide eq. emissions in agricultural lands ranged from 7.3 to 26.1 Mg CO_2 eq ha^{-1} yr^{-1} and had an area weighted average of CO_2 eq. emissions (excluding vegetable gardens and agroforestry due to lack of data) of 25.6 ± 12.4 Mg CO_2 eq ha^{-1} yr^{-1} (Table 1).

Total CO_2 eq. emissions in natural lands (excluding salt pans) were 43.4 ± 9.3 x 10^9 Mg CO_2 eq yr^{-1} with forest/ plantation/ woodland the largest source followed by savannah/grassland, stream/river, wetlands/floodplains/lagoons/reservoir, and termite mounds (Table 1). Total CO_2 eq. emissions in agricultural lands (excluding vegetable gardens and agroforestry) were 13.5 ± 3.4 x 10^9 Mg CO_2 eq yr^{-1} with crop land the largest source followed by rice fields (Table 1). Overall, total CO_2 eq emissions in natural ecosystems and agricultural lands were 56.9 ± 12.7 x 10^9 Mg CO_2 eq yr^{-1} with natural and agricultural lands contributing 76.3% and 23.7%, respectively.

3.1.5 Data quality assessment

Twenty third of the 76 studies cited in the study were categorized as methods were *poor to very poor*, 19 studies were *marginal* and 14 studies were *good* (Table S1 and S2). Major reasons the studies were ranked as *poor to very poor* were because sampling periods were too short for calculating annual emissions (i.e., less than or only one season of data), sampling frequency was too low (i.e., monthly or less), or a combination of poor methods with the sample collection, primarily insufficient samples per gas collecting chamber and very long chamber deployment times.

3.2 Sources and drivers of greenhouse gas emissions in Africa

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

3.2.1 Greenhouse gas emissions in natural ecosystems

Natural terrestrial systems~~,~~

A range of factors affect direct emissions of soil CO_2 in African natural terrestrial systems such as natural forest, plantation, woodland, savannah, grassland, termite mounds and salt pans. These factors can be grouped into i) climatic, ii) edaphic, iii) vegetation and iv) human interventions via land management. Data on the effects of these variables on GHG emissions are variable, with some much less well understood than others. In almost all cases data are limited to a few studies, and there are large areas where there has been no research. This hinders our ability to estimate the contribution of African landscapes to global GHG emissions.

Soil CO_2 emissions were strongly related to both soil moisture and temperature in forest systems. For example, soil moisture explained about 50% of the seasonal variability in soil CO_2 efflux in a *Croton macrostachys*, *Podocarpus falcatus* and *Prunus africana* forest in Ethiopia (Yohannes et al., 2011), as well as much of the seasonal variation in soil CO_2 efflux in a 3-year-old *Eucalyptus* plantation in Republic of Congo (Epron et al., 2004). Thomas et al. (2011) found that the Q_{10} of soil CO_2 efflux (a measure of the temperature sensitivity of efflux, where a Q_{10} of 2 represents a doubling of efflux given a 10℃ increase in temperature) was dependent on soil moisture at sites across the Kalahari in Botswana, ranging from 1.1 in dry soils, to 1.5 after a 2mm rainfall event and 1.95 after a 50mm event. Similarly, in a Zambian woodland, the main driving factor controlling CO_2 emissions at a seasonal time scale was a combination of soil water content and temperature (Merbold et al., 2011).

Increased GHG emissions following soil rewetting were observed in various regions in Africa. Soil rewetting has a significant and well documented impact on GHG emissions (e.g., Kim et al., 2012b). Two broad mechanisms responsible for changed soil GHG flux following rewetting have been hypothesized: (1) enhanced microbial metabolism by an increase in available substrate

Formatted: Font: (Asian) +Body Asian, Bold, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Indent: First line: 1.27 cm, Don't adjust right indent when grid is defined, Don't adjust space between Latin and Asian text, Don't adjust space between Asian text and numbers

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

due to microbial death and/or destruction of soil aggregates (i.e. commonly known as the Birch effect (Birch, 1964)), and (2) physical mechanisms that can influence gas flux, including infiltration, reduced diffusivity, and gas displacement in the soil (e.g., Kim et al., 2012b). Soil CO_2 efflux increased immediately after rainfall in a sub-tropical palm woodland in northern Botswana, however the increase was short-lived (Thomas et al., 2014). Large pulses of CO_2 and N_2O, followed by a steady decline were also observed after the first rainfall event of the wet season in a Kenyan rainforest (Werner et al., 2007). Soil CO_2 efflux was strongly stimulated by addition of rainfall in a South African savannah (Fan et al., 2015; Zepp et al., 1996). In Zimbabwe, the release of N_2O from dryland savannahs was shown to constitute an important pathway of release for N, and emissions were strongly linked to patterns of rainfall (Rees et al., 2006).

Soil physical (e.g., bulk density, porosity and soil texture) and chemical properties (e.g., pH, C and N) also affected soil GHG emissions (e.g., Saggar et al., 2013; Smith, 2010; Snyder et al., 2009). Soil CO_2 efflux was positively related to total soil C content in undisturbed *miombo* woodland in Zambia, although not in an adjacent disturbed woodland (Merbold et al., 2011). In a Kenyan rainforest, CO_2 emissions were negatively correlated with subsoil C and positively correlated with subsoil N concentrations, while N_2O emissions were negatively correlated with clay content and topsoil C:N ratios (Werner et al., 2007). However, soil bulk density and pH were the most influential factors driving spatial variation of *in situ* N_2O emissions in a tropical highland rainforest in Rwanda (Gharahi Ghehi et al., 2014). Similarly, a laboratory-based experiment using soils from 31 locations in a tropical mountain forest in Rwanda showed that N_2O emissions were negatively correlated with soil pH, and positively correlated with soil moisture, soil C and soil N (Gharahi Ghehi et al., 2012).

In many temperate systems, vegetation type also affects soil GHG emissions, likely because of differences in litter quality and production rate, amount of below-ground biomass, the structure of root systems as well as plant-mediated effects on soil microclimate (e.g., Díaz-Pinés et al., 2014; Masaka et al., 2014; Kim et al., 2010). This is consistent with findings from African systems where

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

annual soil CO_2 efflux also varied with vegetation types. For example, annual soil CO_2 emissions were significantly lower in N-fixing acacia monocultures than in eucalypt monocultures and mixed-species stands in Republic of Congo (Epron et al., 2013). The differences were attributed to leaf area index in another study from the Republic of Congo where they found 71% of seasonal soil CO_2 efflux variability was explained by the quantity of photosynthetically active radiation absorbed by the grass canopy (Caquet et al., 2012). Also in the Republic of Congo, it was found that litterfall accounted for most of the age-related trends after the first year of growth, and litter decomposition produced 44% of soil CO_2 flux in the oldest stand (Nouvellon et al., 2012), strongly suggesting that the amount and quality of litter plays a major role in determining soil CO_2 flux. However, the effect of vegetation type can also interact with soil physical-chemical properties. For example in Benin, root respiration contributed to 30% of total soil CO_2 efflux in oil palms when the soil was at field capacity and 80% when soil was dry (Lamade et al., 1996).

Formatted: Font color: Auto

~~Forest soils predominantly act as sinks for CH_4 (Werner et al., 2007). In Cameroon, the largest CH_4 oxidation rates were observed from relatively undisturbed near-primary forest sites (−14.7 to −15.2 ng m^{-2} s^{-1}) compared to disturbed forests (−10.5 to 0.6 ng m^{-2} s^{-1}) (Macdonald et al., 1998). Savannah and grassland were found to be both a sink and source of CH_4. In Mali, CH_4 uptake was observed in dry sandy savannah (Delmas et al., 1991), while a savannah in Burkina Faso was found to be both a CH_4 sink and source during the rainy season, although overall it was a net CH_4 source (Brümmer et al., 2009).~~

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

~~Soil rewetting typically has a large impact on GHG emissions. Two broad mechanisms responsible for changed soil GHG flux following rewetting have been hypothesized: (1) enhanced microbial metabolism by an increase in available substrate due to microbial death and/or destruction of soil aggregates (i.e. commonly known as the Birch effect (Birch, 1964)), and (2) physical mechanisms that can influence gas flux, including infiltration, reduced diffusivity, and gas displacement in the soil (e.g., Kim et al., 2012b). Consistent with this mechanisms of re-wetting effects in soils of other continents (e.g., Kim et al., 2012b), soil CO_2 efflux increased immediately~~

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

~~after rainfall in a sub-tropical palm woodland in northern Botswana, however the increase was short-lived (Thomas et al., 2014), while large pulses of CO_2 and N_2O, followed by a steady decline were also observed after the first rainfall event of the wet season in a Kenyan rainforest (Werner et al., 2007). Soil CO_2 efflux in a South African savannah was strongly stimulated by addition of rainfall (Fan et al., 2015; Zepp et al., 1996) and soil N_2O concentrations increased markedly 30 minutes after wetting and peaked between 2 and 5 hours after rainfall in a semi-arid savannah (Scholes et al., 1997). In Zimbabwe, the release of N_2O from dryland savannahs was shown to constitute an important pathway of release for N, and emissions were strongly linked to patterns of rainfall (Rees et al., 2006). In Botswana, Thomas and Hoon (2010) reported large and short-lived pulses of soil CO_2 efflux after artificial wetting of dry soils: soil CO_2 efflux on dry soils was between 2.8 – 14.8 mg C m^{-2} h^{-1} but increased to 65.6 mg C m^{-2} h^{-1} in the hour after light wetting and 339.2 mg C m^{-2} h^{-1} in the hour after heavy wetting.~~

Forest management such as burning, which is a common practice in SSA, and thinning, affects GHG emissions (Table ~~2~~3). The IPCC Tier 1 methodology only calculates the amount of GHG emissions as a percentage of the carbon that is released through the burning; however it may also increase forest soil GHG emissions once the fire has passed. For example, soil CO_2 efflux immediately increased after burning of woodland in Ethiopia (Andersson et al., 2004); also, five days after burning rainfall resulted in a 2-fold increase in soil CO_2 efflux from the burned plots compared to the unburned plots. In contrast, 12 days after burning soil CO_2 efflux was 21% lower in the burned plots (Andersson et al., 2004). However, contrasting impacts of fire on soil GHG emission were observed in a savannah/grassland in the Republic of Congo where fire did not change soil CO_2, CH_4 and N_2O fluxes (Castaldi et al., 2010, Delmas et al., 1991). Similarly, in South Africa, soil CH_4 efflux was not significantly affected by burning (Zepp et al., 1996). In contrast, annual fires decreased soil CH_4 oxidation rates in a Ghanaian savannah (Prieme and Christensen, 1999). These case studies demonstrate that fire impacts are not always consistent and this is likely the result of different fire characteristics (e.g., intensity or frequency), soil type (e.g.,

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Indent: First line: 0 cm

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Kulmala et al., 2014; Kim et al., 2011) and post-fire weather conditions. Thinning forest cover can also ~~can~~ increase soil CO$_2$ efflux. Yohannes et al. (2013) reported 24% and 14% increases in soil CO$_2$ efflux in the first and second years following thinning of a 6 year old *Cupressus lusitanica* plantation in Ethiopia.

There is a particular paucity of data on sources and sinks of CH$_4$ in African natural terrestrial systems. In Cameroon, the largest CH$_4$ oxidation rates were observed from relatively undisturbed near-primary forest sites (–14.7 to –15.2 ng m^{-2} s^{-1}) compared to disturbed forests (–10.5 to 0.6 ng m^{-2} s^{-1}) (Macdonald et al., 1998). Savannah and grassland were found to be both a sink and source of CH$_4$. ~~Termite mounds are known sources of CH$_4$ and CO$_2$, and a~~ In Mali, CH$_4$ uptake was observed in dry sandy savannah (Delmas et al., 1991), while a savannah in Burkina Faso was found to be both a CH$_4$ sink and source during the rainy season, although overall it was a net CH$_4$ source (Brümmer et al., 2009). Termite mounds are known sources of CH$_4$ and CO$_2$ (References). A study in a Burkina Faso savannah found that CH$_4$ and CO$_2$ released by termites (*Cubitermes fungifaber)* contributed 8.8% and 0.4% of total soil CH$_4$ and CO$_2$ emissions, respectively (Brümmer et al., 2009). In Cameroon, the mounds of soil-feeding termites (*Thoracotermes macrothorax* and *Cubitermes fungifaber*) were point sources of CH$_4$ ranging 53.4 to 636 ng s^{-1} mound^{-1}, which at the landscape scale may exceed the general sink capacity of the soil (Macdonald et al., 1998). In Zimbabwe, it was found that *Odontotermes transvaalensis* termite mounds located in dambos (seasonal wetlands) were an important source of GHGs, and emissions varied with catena position for CO$_2$ and CH$_4$ (Nyamadzawo et al., 2012).

Compared to the other environments covered in this review there are very few studies from salt pans. Thomas et al. (2014) however, found soil CO$_2$ efflux increased with temperature and also increased for a few hours after flooding of the surface of the Makgadikgadi salt pan in Botswana. Annual CO$_2$ emissions in salt pan were estimated as 0.7 Mg CO$_2$ ha^{-1} ~~y~~yr^{-1} (Thomas et al., 2014).

~~3. 1. 2.~~ **Aquatic systems**

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

~~Greenhouse gas emissions from~~ African aquatic systems such as streams, rivers, wetlands, floodplains, ~~reservoir, and~~ reservoirs, lagoons ~~ranged from 5.7 to 232.0 Mg CO_2 ha^{-1} y^{-1}, 26.3 to 2741.9 kg CH_4 ha^{-1} y^{-1} and 0.2 to 4.5 kg N_2O ha^{-1} y^{-1}~~, and lakes can be significant sources of GHG (Table 1 and SI Table 1). ~~In~~Differences in regional setting and hydrology mean that emissions are highly spatially and temporally variable and when combined with the ~~Nyong River (Cameroon), CO_2~~paucity of studies, it is challenging to identify clear control factors.

Studies found African aquatic systems can be significant sources of GHG emissions ~~(5.5 kg CO_2 m^{-2} y^{-1}) were four times greater than the flux of dissolved inorganic carbon (Brunet et al., 2009).~~. In Ivory Coast, three out of five lagoons were oversaturated in CO_2 during all seasons and all were CO_2 sources (3.1 – 16.2 g CO_2 m^{-2} d^{-1}) due to net ecosystem heterotrophy and inputs of riverine CO_2 rich waters (Koné et al., 2009). In the flooded forest zone of the Congo River basin (Republic of Congo) and the Niger River floodplain (Mali), high CH_4 emissions (5.16 ×10^{20} – 6.35 ×10^{22} g CH_4 m^{-2} d^{-1}) were recorded on flooded soils (Tathy et al., 1992; Delmas et al., 1991). In ~~Zimbabwe, dambos can be major or minor sources of GHGs depending on catena position. Upland dambos were important sources of N_2O and CO_2, and a sink for CH_4; while those in a mid-slope position were a major source of CH_4, but a weak source of CO_2 and N_2O; and those at~~ the ~~bottom were a weak source for all GHGs (Nyamadzawo et al., 2014a). In the Congo Basin (Republic of Congo), streams and rivers in savannah regions had higher~~Nyong River (Cameroon), CO_2 emissions (~~46.8 – 56.4 g~~5.5 kg CO_2 m^{-2} ~~d~~ yr^{-1}) were four times greater than ~~swamps (13.7 – 16.3 g CO_2 m^{-2} d^{-1}) and tropical forest catchments (37.9 – 62.9 g CO_2 m^{-2} d^{-1}) (Mann et al.,~~the ~~2014). In the Okavango Delta (Botswana), the average CH_4~~ flux ~~in river channels (0.75 g CH_4 m^{-2} d^{-1}) was higher than that in floodplains and lagoons (0.41 – 0.49 g CH_4 m^{-2} d^{-1}) (Gondwe and Masamba, 2014~~of dissolved inorganic carbon (Brunet et al., 2009). In the Zambezi River (Zambia), ~~while CO_2 and CH_4 concentrations in the main channel were highest downstream of the floodplains, N_2O concentrations were lowest downstream of the floodplains (Teodoru et al., 2015). Overall,~~ 38% of the total C in the ~~Zambezi~~ River is emitted into the atmosphere, mostly as CO_2 (98 %) (Teodoru et

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

al., 2015). The source of CH_4 to the atmosphere from Lake Kivu corresponded to ~60% of the terrestrial sink of atmospheric CH_4 over the lake's catchment (Borges et al., 2011). A recent study of 10 river systems in SSA estimated water-air CO_2, CH_4 and N_2O fluxes to be 8.2 to 66.9 g CO_2 m^{-2} d^{-1}, 0.008 to 0.46 g CH_4 m^{-2} d^{-1}, and 0.09 to 1.23 mg N_2O m^{-2} d^{-1}, respectively (Borges et al., 2015). The authors suggested that lateral inputs of CO_2 from soils, groundwater and wetlands were the largest contributors of the CO_2 emitted from the river systems (Borges et al., 2015).

The magnitude of GHG emissions from African aquatic systems varied with type and location. Streams and rivers in savannah regions had higher CO_2 emissions (46.8 – 56.4 g CO_2 m^{-2} d^{-1}) than swamps (13.7 – 16.3 g CO_2 m^{-2} d^{-1}) and tropical forest catchments (37.9 – 62.9 g CO_2 m^{-2} d^{-1}) in the Congo Basin (Mann et al., 2014). ~~The~~ The average CH_4 flux in river channels (0.75 g CH_4 m^{-2} d^{-1}) was higher than that in floodplains and lagoons (0.41 –0.49 g CH_4 m^{-2} d^{-1}) in the Okavango Delta (Botswana) (Gondwe and Masamba, 2014). Methane emissions from river deltas were substantially higher (~103 mg CH_4 m^{-2} d^{-1}) than these from non-river bays (<100 mg CH_4 m^{-2} d^{-1}) in Lake Kariba (Zambia/Zimbabwe). It was found substantially higher CH_4 fluxes in river deltas (~103 mg CH_4 m^{-2} d^{-1}) compared to non-river bays (<100 mg CH_4 m^{-2} d^{-1}) in Lake Kariba (Zambia/Zimbabwe) (DelSontro et al., 2011). While CO_2 and CH_4 concentrations in the main channel were highest downstream of the floodplains, N_2O concentrations were lowest downstream of the floodplains in the Zambezi River (Zambia and Mozambique) (Teodoru et al., 2015). Dambos in Zimbabwe can be major or minor sources of GHGs depending on catena position. Upland dambos were important sources of N_2O and CO_2, and a sink for CH_4; while those in a mid-slope position were a major source of CH_4, but a weak source of CO_2 and N_2O; and those at the bottom were a weak source of all GHGs (Nyamadzawo et al., 2014a).

Studies were conducted to identify control factors for concentration and flux of GHGs in African aquatic systems. Studies found the concentration and flux of GHGs are strongly linked to ~~stream~~hydrological characteristics such as discharge, but clear patterns have not yet been identified. ~~In the Congo River, surface~~ Surface CO_2 flux was positively correlated with discharge in the Congo

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

River (Wang et al., 2013), while in Ivory Coast, rivers were often oversaturated with CO_2 and the seasonal variability of partial pressure of CO_2 (pCO_2) was due to dilution during the flooding period (Koné et al., 2009). Similarly, CO_2 fluxes show a very pronounced seasonal pattern strongly linked to hydrological conditions in the Oubangui River in the Central African Republic (Bouillon et al., 2012). Although higher CH_4 concentrations were found during low-discharge conditions, N_2O concentrations were lowest during low-discharge conditions (Bouillon et al., 2012). ~~In the Zambezi River (Zambia~~In Lake Kivu, seasonal variations of CH_4 in the main basin were driven by deepening of the mixolimnion and mixing of surface waters with deeper waters rich in CH_4 (Borges et al., 2011). In the Zambezi River (Zambia and Mozambique), inter-annual variability was relatively large for CO_2 and CH_4 and significantly higher concentrations were measured during wet seasons (Teodoru et al., 2015). However, inter-annual variability of N_2O was less pronounced and generally higher values were found during the dry season (Teodoru et al., 2015).

~~The relationship between GHG fluxes from aquatic systems~~Studies found the concentration and flux of GHGs are strongly linked to and water ~~temperature is~~environment or quality but clear patterns have not ~~clear.~~yet been identified. In the Okavango Delta (Botswana), CH_4 emissions were highest during the warmer, ~~summerrainy~~summer rainy season and lowest during cooler winter season suggesting the emissions were probably regulated by water temperature (Gondwe and Masamba, 2014). However, Borges et al., (2015) found no significant correlation between water temperature and pCO_2 and dissolved CH_4 and N_2O in 11 SSA river systems, ~~although~~but there was a positive relationship between pCO_2 and dissolved organic C in six of the rivers. They also found the lowest N_2O values were observed at the highest pCO_2 and lowest % O_2 levels, suggesting the removal of N_2O by denitrification (Borges et al., 2015). In Lake Kivu (East Africa), the magnitude of CO_2 emissions to the atmosphere seems to depend mainly on inputs of dissolved inorganic carbon from deep geothermal springs rather than on the lake metabolism (Borges et al., 2014).

3.~~-~~2.2. Greenhouse gas emissions from agricultural lands

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Normal

Formatted: Font: Bold, Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

~~3. 2. 1. Croplands~~

~~Soil GHG emissions reported from African croplands ranged from 1.7 to 141.2 Mg CO_2 ha^{-1} y^{-1}, 1.3 to 66.7 kg CH_4 ha^{-1} y^{-1} and 0.05 to 112.0 kg N_2O ha^{-1} y^{-1} (Table 1 and SI Table 1). The N_2O EF ranged from 0.01 to 4.1% (Table 1 and SI Table 1).~~

Identifying controls on the emission of GHG from African agricultural land is even more challenging because in addition to natural variations associated with climate and soil type, land management (particularly fertilization) and crop type have a dominant influence on GHG emissions.

Croplands

The effects of the amount and type of N input on N_2O emissions in croplands have been studied in several locations (Table ~~2~~3). In western Kenya, the rate of N fertilizer application (0 to 200 kg N ha^{-1}) had no significant effect on N_2O emissions (620 to 710 g N_2O–N ha^{-1} for 99 days) (Hickman et al., 2014~~), however~~). However another study from western Kenya, found a relationship between N input and N_2O emissions that was best described by an exponential model with the largest impact on N_2O emissions occurring when N inputs increased from 100 to150 kg N ha^{-1} (Hickman et al., 2015). An incubation study in Madagascar demonstrated that application of mixed urea and di-ammonium -phosphate resulted in lower N_2O emissions (28 vs. 55 ng N_2O–N g^{-1} h^{-1} for 28 days, respectively) than a mixed application of urea and NPK fertilizer (Rabenarivo et al., 2014).

Incorporation of crop residues to the soil has frequently been proposed to increase soil fertility (Malhi et al., 2011), however incorporation of crop residues also affects CO_2 and N_2O emissions (Table ~~2~~3). In Tanzania, incorporation of plant residue into soil increased annual CO_2 fluxes substantially (emissions rose from 2.5 to 4.0 and 2.4 to 3.4 Mg C ha^{-1} ~~y~~yr^{-1} for clay and sand soils, respectively) (Sugihara et al., 2012), although a study in Madagascar showed that rice-straw residue application resulted in larger fluxes of CO_2 but reduced N_2O emissions due to N immobilization (Rabenarivo et al., 2014). In contrast, application of *Tithonia diversifolia* (tithonia) leaves led to greater N_2O emissions compared to urea application in maize fields in Kenya (Sommer

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

et al., 2015; Kimetu et al., 2007). The higher N_2O emissions after application of *Tithonia diversifolia* were attributed to high levels of nitrate and available carbon in the soil caused by the application that subsequently enhanced denitrification rates. In incubation studies with cultivated soil from Ghana, N_2O emissions were significantly higher from soils amended with low C:N ratio clover residues compared to high C:N ratio barley residues (Frimpong et al., 2012~~) and increasing~~). Increasing the proportion of maize in a cowpea-maize residue significantly decreased N_2O emissions compared to cowpea residue incorporation alone (Frimpong et al., 2011), again likely due to the higher C:N ratio of the maize residue compared with the cowpea. Another incubation study with cultivated soil from Ghana showed that N_2O emissions increased after addition of residues of three tropical plant species (*Vigna unguiculata*, *Mucuna pruriens* and *Leucaena leucocephala*) and emissions were positively correlated with the ~~residue~~ C:N ratio of the residue, and negatively correlated with residue polyphenol content, polyphenol:N ratio and (lignin + polyphenol):N ratio (Frimpong and Baggs, 2010). It is rare for N_2O emissions to be positively correlated to C:N ratio and the authors of the study suggest that it was either because soil C was limiting denitrification rates or that release of N from the residues was slow (Frimpong and Baggs, 2010). The results demonstrate that the quality of residues (e.g., C:N ratio, N, lignin and soluble polyphenol contents) affect GHG emissions and further studies are needed to clearly identify the relationship between them (Snyder et al. 2009; Mafongoya et al., 1997).

Adding an additional ~~source of~~ N (mineral or organic) when crop residues are incorporated into the soil could stimulate mineralization of crop residues, increase N-use efficiency and produce higher yields (e.g., Garcia-Ruiz and Baggs, 2007) (Table ~~2~~3). It was found that application of mixed crop residue or manure and inorganic fertilizers resulted in different response of CO_2 and N_2O emissions. In maize (*Zea mays* L.) and winter wheat (*Triticum aestivum* L.) fields in Zimbabwe, application of inorganic fertilizer (ammonium nitrate, NH_4NO_3-N) with manure increased CO_2 emissions (26 to 73%), compared to sole application of manure (Nyamadzawo et al., 2014a). However, the mixed application resulted in lower N_2O emissions per yield (1.6–4.6 g N_2O kg^{-1}

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

yield), compared to sole application of inorganic fertilizer (6−14 g N_2O kg^{-1} yield) (Nyamadzawo et al., 2014a). Similarly, in a maize field in Zimbabwe, N_2O emissions were lower after the application of composted manure and inorganic fertilizer (NH_4NO_3-N) compared to sole application of inorganic fertilizer. The same treatments, however, led to the opposite results for CO_2 emissions (Mapanda et al., 2011). In Mali, pearl millet (*Pennisetum glaucum*) fields treated with both manure and inorganic fertilizer urea emitted significantly less N_2O than plots receiving only urea fertilizer (Dick et al., 2008). The lower N_2O emissions in soils amended with manure were attributed to the initial slow release and immobilisation of mineral N and the consequently diminished pool of N available to be lost as N_2O (Nyamadzawo et al., 2014a, b; Mapanda et al., 2011; Dick et al., 2008). In an incubation study with cultivated soils from Zimbabwe, Ghana and Kenya, combining organic residue (maize, calliandra, and tithonia) and urea fertilizers decreased N_2O emissions in coarse-textured soils but it increased N_2O emissions in fine-textured soils due to the higher level of available N (Gentile et al., 2008).

The effects of crop type and management on GHG emissions have also been studied by several groups (Table ~~2~~3). In Uganda, there were no significant differences in soil CO_2 effluxes from different crops (lettuces, cabbages, beans) (Koerber et al., 2009). However, in Zimbabwe, rape production resulted in greater N_2O emissions (0.64 – 0.93% of applied N was lost as N_2O) than tomatoes (0.40 – 0.51% of applied N was lost as N_2O) (Masaka et al., 2014). ~~The results suggest that the effect of crop type on GHG emissions is difficult to predict and more research is needed to elucidate the relationship between crops, crop management and GHG emissions.~~

~~In Mali, growing N-fixing haricot beans in rotation did not significantly increase N_2O emissions (Dick et al., 2008).~~ In Madagascar, N_2O emissions were not significantly affected by management practices such as direct seeding mulch-based cropping and traditional hand-ploughing after harvesting (Chapuis-Lardy et al., 2009). However, the authors admitted the lack of difference between treatments may be partially due to the short duration of the experiment and suggested more complete monitoring to validate the observation. In highland Tanzanian maize fields, GHG fluxes

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

were similar from soils under conventional and various conservation agriculture practices (Kimaro et al., 2015). However, when fluxes were yield-scaled the global warming potential (Mg CO$_2$ eq Mg grain^{-1}) was lower from fields with reduced tillage plus mulch and leguminous trees (2.1–3.1 Mg CO$_2$ eq Mg grain^{-1}) and from fields with reduced tillage plus mulch and nitrogen fertilizer (1.9–2.3 Mg CO$_2$ eq Mg grain^{-1}) compared to fields under -conventional agriculture (1.9–8.3 Mg CO$_2$ eq Mg grain^{-1}) (Kimaro et al., 2015). The results suggest that the effect of crop type and management on GHG emissions is difficult to predict and more research is needed to elucidate the relationship between crops, crop management and GHG emissions.

Croplands were found to be both a sink and a source of CH$_4$. In Burkina Faso, CH$_4$ flux rates from croplands ranged from -0.67 to 0.70 kg CH$_4$–C ha^{-1} ~~y~~yr^{-1} (Brümmer et al., 2009), while in Republic of Congo, CH$_4$ uptake was observed in cassava and peanut fields and a recently ploughed field (Delmas et al., 1991). However, cropped and ~~fertilised~~fertilized dambos in Zimbabwe were consistently sources of CH$_4$ (13.4 to 66.7 kg CH$_4$ ha^{-1} ~~y~~yr^{-1}) (Nyamadzawo et al., 2014b).

~~3. 2. 2.~~ Grazing grassland

Only one study measured GHG emissions in grazing grasslands and there is a serious limitation in understanding GHG emissions in grazing grassland. Thomas (2012) found that soil CO$_2$ efflux from a Botswana grazing land was significantly higher in sandy soils where the biological soil crust (BSC) was removed and on calcrete where the BSC was buried under sand. The results indicated the importance of BSCs for C cycling in drylands and ~~indicate that~~ intensive grazing, which destroys BSCs through trampling and burial, will adversely affect C sequestration and storage (Thomas, 2012).

~~3. 2. 3.~~ Rice paddies

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Default) Times New Roman, (Asian) +Body Asian, English (U.K.)

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: No widow/orphan control

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Rice paddies are well known~~ to be~~ sources of CH_4 (e.g., Linquist et al., 2012). Experiments measuring GHG emissions in rice paddies were conducted in Kenya (Tyler et al., 1988) and Zimbabwe (Nyamadzawo et al., 2013). In Kenya, ~~the range of δ^{13}C in~~ CH_4 ~~for rice paddies was from −57 to −63‰ and δ^{13} CH_4~~fluxes did not show any seasonal trend and did not indicate appreciable variability among two different strains of rice (Tyler et al., 1988). In Zimbabwe, intermittently saturated dambo rice paddies were a source of GHG and annual emissions from these rice paddies (150 day growing season and 126 kg of applied N ha^{-1}) were estimated as ~~2680 kg~~2.7 Mg CO_2 ha^{-1} ~~y~~yr^{-1}, 12.5 kg CH_4 ha^{-1}, and 0.12 kg N_2O ha^{-1} (Nyamadzawo et al., 2013). The IPCC (2006) use a CH_4 emission factor of 1.30 kg CH_4 ha^{-1} day^{-1} for rice cultivation. The CH_4 emissions in the dambo rice paddies referred to here are much lower than the IPCC estimate (195 kg CH_4 ha^{-1}=1.3 kg CH_4 ha^{-1} day^{-1} × 150 days). The corresponding IPCC (2006) N_2O EF is 0.3% for rice cultivation and thus the N_2O emissions in the dambo rice paddies are also much lower than the IPCC estimate (0.40 kg N_2O−N ha^{-1} = 126 kg N ha^{-1} × 0.003; 0.63 kg N_2O ha^{-1}).

~~3. 2. 4.~~ Vegetable gardens

Greenhouse gas emissions from soils in vegetable gardens in peri-urban areas of Burkina Faso (Lompo et al., 2012) and Niger (Predotova et al., 2010) ~~were much higher than all other land uses, ranging~~ranged from 73.3 to 132.0 Mg CO_2 ha^{-1} ~~y~~yr^{-1} and 53.4 to 177.6 kg N_2O ha^{-1} ~~y~~yr^{-1} (Table 1 and SI Table 1).

In Burkina Faso, annual CO_2 and N_2O emissions from the garden soils were 68 to 85% and 3 to 4% of total C and N input, respectively (Lompo et al., 2012). The N_2O EFs (3 to 4%) were higher than the IPCC default value of 1.0% for all cropping systems (IPCC, 2006) and the global N_2O EF of vegetable fields (0.94%) (Rezaei Rashti et al., 2015). The high N_2O EFs may be attributed to the large amount of applied N in vegetable gardens (2700 – 2800 kg N ha^{-1} ~~y~~yr^{-1}) since surplus N will stimulate N_2O production and also indirectly promote N_2O production by inhibiting biochemical N_2O reduction (e.g., Shcherbak et al., 2014; Kim et al., 2013). In vegetable gardens of

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Niger, a simple plastic sheet roofing and addition of ground rock phosphate to stored ruminant manure decreased N_2O gaseous losses by 50% in comparison to dung directly exposed to the sun (Predotova et al. 2010). The authors argued that a decreased evaporation rate was behind this abating effect.

~~3. 2. 5.~~ Agroforestry

Soil CO_2 and N_2O emissions from African agroforestry were 38.6 Mg CO_2 ha^{-1} ~~yr~~$^{-1}$ and 0.2 to 26.7 kg N_2O ha^{-1} ~~yr~~$^{-1}$, respectively (Table 1 and SI Table 1). ~~In agroforestry homegardens in Sudan, CO_2 (16.6 Mg CO_2 ha^{-1} from June to December) and N_2O emissions (17.3 kg N_2O ha^{-1} from June to December) accounted for two-thirds of total C output and one-third of total N output, respectively and the CO_2 and N_2O fluxes were positively correlated with soil moisture (Goenster et al., 2015).~~

Improving fallow with N-fixing trees is a common agroforestry practice in several areas of Africa since it provides additional N to the soil that can be utilised by the subsequent cash crop (e.g., Makumba et al., 2007; Chikowo et al., 2004; Dick et al., 2001). However, the practice is also thought to increase CO_2 and N_2O emissions compared to conventional croplands (Table ~~2). In an intercropping system with a N-fixing tree (*Gliricidia*) and maize in southern Malawi, soil C was depleted as a result of enhanced CO_2 emissions, with over 67% of soil C lost over the first 7 years of intercropping (Kim, 2012a). In Zimbabwe, N_2O emissions in improved-fallow agroforestry systems were 7 times higher than emissions in maize monoculture (Chikowo et al., 2004). In Senegal, soil collected under the N-fixing tree (*Acacia raddiana*) emitted significantly more N_2O than soil collected under the N-fixing crop (*Arachis hypogaea*) and non-N fixing tree (*Eucalyptus camaldulensis*) (Dick et al.,~~ 3). Nitrous oxide~~2006). In western Kenya, N_2O~~ emissions increased after incorporation of fallow residues and emissions were higher after incorporation of improved-fallow legume residues than natural-fallow residues (Baggs et al., 2006; Millar and Baggs, 2004; Millar et al., 2004). It was found that N_2O emissions were positively correlated with residue N

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

content (Baggs et al., 2006; Millar et al., 2004) and negatively correlated with polyphenol content and their protein binding capacity (Millar and Baggs, 2004), soluble C-to-N ratio (Millar and Baggs, 2005) and lignin content (Baggs et al., 2006). While high residue N content likely leads to more available soil N and consequently increased N_2O production (Baggs et al., 2006; Millar and Baggs, 2005; Millar et al., 2004), polyphenols and lignins are both resistant to decomposition and could result in N immobilization resulting in less labile soil N and less N_2O production (Baggs et al., 2006; Millar and Baggs, 2004). ~~The type and quality of plant residue is likely to be an important control factor affecting N_2O emissions~~Therefore, there may be potential to reduce N_2O emissions in the agroforestry practice, but it may require ecological nutrient management (i.e., reduced inorganic fertilizer N inputs accounting N input from the legume trees; adding a C source such as a cover crop together with an N source) and rotation planning.

As in natural systems, ~~improved fallow with N-fixing trees~~agroforestry also results in increased N_2O emissions following rainfall events. In an incubation experiment in Uganda, N_2O emissions following simulated rainfall were ~~a~~at least 4 times larger for soils from under N-fixing trees (*Calliandra calothyrsus*) compared to soils with non-N fixing trees (*Grevillea robusta*) (Dick et al., 2001). Similarly, in Mali, N_2O emissions were around six times higher from improved fallow with N-fixing trees (*Gliricidia sepium* and *Acacia colei*) following a simulated rainfall event, compared with the emissions from soil under traditional fallow and continuous cultivation (Hall et al., 2006).~~ Replacing traditional natural fallow with improved-fallow systems in the humid tropics of Kenya also increased N_2O emissions by up to 3.9 kg N_2O–N ha^{-1} over a 122-day maize cropping season (Millar et al., 2004).~~ In agroforestry homegardens in Sudan, CO_2 and N_2O fluxes were positively correlated with soil moisture (Goenster et al., 2015).

3.2.3. Greenhouse gas emissions from land use change

Land-use change affects soil GHG emissions due to changes in vegetation, soil, hydrology and nutrient management (e.g., Kim and Kirschbaum, 2015) and the effects of land-use change on

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman, English (U.K.)

Formatted: Font color: Auto, English (U.K.)

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

soil GHG emissions have been observed in African woodlands and savannah.~~ In Zimbabwe, clearing~~ Clearing and converting woodlands to croplands increased soil emissions of CO_2, CH_4 and N_2O (Mapanda et al., 2012) and soil CO_2 emissions from the converted croplands were higher than *Eucalyptus* plantations established in former natural woodlands (Mapanda et al., 2010).~~ In Republic of Congo, early-rotation changes~~ Changes in soil CO_2 efflux after afforestation of a tropical savannah with *Eucalyptus* were mostly driven by the rapid decomposition of savannah residues and the increase in *Eucalyptus* rhizospheric respiration (Nouvellon et al., 2012).

3.~~ 4. Summary of greenhouse gas emissions in natural and agricultural lands in Africa~~

3~~. 4. 1. CO_2 emissions~~

~~Carbon dioxide emissions ranged from 3.3 to 130.9 Mg CO_2 ha^{-1} y^{-1} in natural terrestrial systems and from -11.9 to 232.0 Mg CO_2 ha^{-1} y^{-1} in aquatic systems. The area weighted average was 27.6 ± 17.2 Mg CO_2 ha^{-1} y^{-1} (Table 1 and SI Table 1). Aquatic systems such as water bodies or water submerged lands were the largest source of CO_2 followed by forest, savannah, termite mounds and salt pans (Table 1). Soil CO_2 emissions in agricultural lands were similar to emissions from natural lands and ranged from 6.5 to 141.2 Mg CO_2 ha^{-1} y^{-1} with an area weighted average of 23.0 ± 8.5 Mg CO_2 ha^{-1} y^{-1} (Table 1 and SI Table 2). Vegetable gardens were the largest sources of CO_2 emission largely due to the large C inputs, followed by agroforestry, cropland and rice fields (Table 1 and SI Table 2).~~

~~3. 4. 2. CH_4 emissions~~

~~Forest/plantation/woodland were sinks of CH_4 (-1.5 ± 0.6 kg CH_4 ha^{-1} y^{-1}) and savannah/ grassland, crop lands, termite mounds, and rice fields were low to moderate CH_4 sources (0.5 – 30.5 kg CH_4 ha^{-1} y^{-1}). Stream/river and wetland/floodplain/lagoon/reservoir were high CH_4 sources (766.0 – 950.4 kg CH_4 ha^{-1} y^{-1}) (Table 1 and SI Table 1). The area weighted averages of CH_4~~

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

~~emissions from natural and agricultural lands were 43.0 ± 5.8 and 19.5 ± 5.6 kg CH_4 ha^{-1} y^{-1}, respectively.~~

~~3. 4. 3. N_2O emissions and emission factor (EF)~~

~~Nitrous oxide emissions in natural lands ranged from -0.1 to 13.7 kg N_2O ha^{-1} y^{-1} and the area weighted average was 2.5 ± 0.8 kg N_2O ha^{-1} y^{-1} (Table 1 and SI Table 1). Our study reveals that forest, plantation and woodland were the largest source of N_2O followed by rivers and wetlands, savannah and termite mounds (Table 1). Soil N_2O emissions in agricultural lands ranged from 0.051 to 177.6 kg N_2O ha^{-1} y^{-1} and the area weighted average was 4.5 ± 2.2 kg N_2O ha^{-1} y^{-1} (Table 1 and SI Table 2). The largest N_2O source in agricultural lands was vegetable gardens followed by agroforestry, cropland and rice fields (Table 1). The N_2O EF was 0.5 ± 0.2% and 3.5 ± 0.5% for cropland and vegetable gardens, respectively (Table 1 and SI Table 1). The results indicate that the N_2O EF of African cropland is lower and the N_2O EF of African vegetable gardens is higher than IPCC default N_2O EF (1%, IPCC, 2006).~~

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

~~The relationship between N input and N_2O emissions varied depending on N input level (Fig. 4). N_2O emissions increase slowly up to 150 kg N ha^{-1} y^{-1}, after which emissions increase exponentially up to 300 kg N ha^{-1} y^{-1} (Fig. 5 (A)). Consistent with van Groenigen (2010) N inputs of over 300 kg N ha^{-1} y^{-1} resulted in an exponential increase in emission (Fig. 5 (B)), slowing to a steady state with N inputs of 3000 kg N ha^{-1} y^{-1}. Overall, the relationship between N input and N_2O emissions shows a sigmoidal pattern (Fig. 5 (C)). The observed relationship is consistent with the proposed hypothetical conceptualization of N_2O emission by Kim et al. (2013) showing a sigmoidal response of N_2O emissions to N input increases. The results suggest that N inputs over 150 kg N ha^{-1} y^{-1} may cause an abnormal increase of N_2O emissions in Africa. The relationship between N input and N_2O emissions show that the lowest yield-scaled N_2O emissions were reported for N application rates ranging from 100 to 150 kg N ha^{-1} (Fig.6). The results are in line with the global~~

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

~~meta-analysis of Philiber et al. (2012) who showed that from an N application rate ~150 kg N ha^{-1} the increase in N_2O emissions is not linear but exponential.~~

~~3. 4. 4. CO_2 eq emission~~

~~Carbon dioxide eq emission (including CO_2, CH_4 and N_2O) in natural lands ranged from 11.7 to 121.3 Mg CO_2 eq. ha^{-1} y^{-1} and the area weighted average of CO_2 eq. emissions (excluding salt pans) was 29.9 ± 22.5 Mg CO_2 eq. ha^{-1} y^{-1} (Table 1). Water bodies or water submerged lands such as rivers and wetlands were the largest source of CO_2 eq. emissions followed by forest/ plantation/ woodland, savannah/ grassland and termite mounds (Table 1). Carbon dioxide eq. emissions in agricultural lands ranged from 7.3 to 26.1 Mg CO_2 eq. ha^{-1} y^{-1} and had an area weighted average of CO_2 eq. emissions (excluding vegetable gardens and agroforestry) of 25.6 ± 12.4 Mg CO_2 eq. ha^{-1} y^{-1} (Table 1).~~

~~Total CO_2 eq. emissions in natural lands (excluding salt pans) were 43.4 ± 9.3 Pg CO_2 eq. y^{-1} with forest/ plantation/ woodland the largest source followed by savannah/grassland, stream/river, wetlands/floodplains/lagoons/reservoir, and termite mounds (Table 1). Total CO_2 eq. emissions in agricultural lands (excluding vegetable gardens and agroforestry) were 13.5 ± 3.4 Pg CO_2 eq y^{-1} with crop land the largest source followed by rice fields (Table 1). Overall, total CO_2 eq. emissions in natural and agricultural lands were 56.9 ± 12.7 Pg CO_2 eq y^{-1} with natural and agricultural lands contributing 76.3% and 23.7%, respectively.~~

~~3. 5.~~ Suggested future ~~studies~~research

Despite an increasing number of published estimates of GHG emissions in the last decade, there remains a high degree of uncertainty about the contribution of AFOLU to emissions in SSA~~.~~ due to lack of studies and uncertainty in the limited number of existing studies. To address this and reduce the uncertainty surrounding the estimates, additional GHG emission measurements across agricultural and natural lands throughout Africa are urgently required. Identifying controlling

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font color: Auto

factors and their effects on GHG fluxes is a pre-requisite to enhancing our understanding of efflux mechanisms and a necessary step towards scaling up the field-scale data to landscape, national and continental scales. It is important to know how GHG fluxes can be affected by management practices and natural events such as logging (e.g., Yashiro et al., 2008), thinning (e.g., Yohannes et al., 2013), storms (e.g., Vargas, 2012), pest outbreaks (e.g., Reed et al., 2014), fires (e.g., Andersson et al., 2004), and wood encroachment (e.g., Smith and Johnson, 2004) in natural terrestrial systems and changing discharge (e.g., Wang et al., 2013) and water table (e.g., Yang et al., 2013) in aquatic systems. It is also important in agricultural lands to know how GHG fluxes are affected by management factors such as soil compaction (e.g., Ball et al., 1999), tillage (e.g., Sheehy et al., 2013), removal of crop residues (Jin et al., 2014), incorporation of crop residues and synthetic fertilizer (e.g., Nyamadzawo et al., 2014a), N input (whether organic or inorganic) (e.g., Hickman et al., 2015) and crop type (e.g., Masaka et al., 2014). However, because management and soil physical/chemical interactions cause different responses in soil GHG emissions (e.g. Pelster et al., 2012), it is critical to measure these interaction effects in the African context. The effect of predicted climatic change in Africa such as increased temperature (e.g., Dijkstra et al., 2012), changing rainfall patterns (e.g., Hall et al., 2006), increase in droughts incidence (e.g., Berger et al., 2013), rewetting effects (e.g., Kim et al., 2012b) and increased atmospheric CO_2 concentration (e.g., Lane et al., 2013) also require further testing using laboratory and field experiments. Future research should consider the wider GHG budget of agriculture and include all the various (non-soil) components such as fuel use, and embodied emissions in chemical inputs.

Where possible studies should seek to identify and separate driving processes contributing to efflux of soil CO_2 (e.g., autotrophic and heterotrophic sources), CH_4 (e.g., methanogenesis and methanotrophy) and N_2O (e.g., nitrification, denitrification, nitrifier denitrification~~).~~) and link new knowledge of microbial communities (e.g., functional gene abundance) to GHG emissions rates. This is important because the consequences of increasing GHG emissions depend on the mechanism responsible. For example, if greater soil CO_2 efflux is primarily due to autotrophic

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font color: Auto

Formatted: Font color: Auto, English (U.S.)

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

respiration from plant roots, then it simply reflects greater plant growth. If however, it is due to heterotrophic microbial respiration of soil organic carbon then it represents a depletion of soil organic matter and a net transfer of C from soil to the atmosphere. Currently there are very few studies that differentiate these sources making it impossible to truly determine the consequences and implications on changes in soil GHG efflux.

Land-use change has been recognized as the largest source of GHG emission in Africa (Valentini et al., 2014). Hence, various types of conversion from natural lands to different land-use types should be assessed to know how these changes may affect the GHG budget (e.g., Kim and Kirschbaum, 2015). The focus of the assessment should be on deforestation and wetland drainage, followed by a conversion to agricultural lands, since they are dominant types of land-use change in Africa (Valentini et al., 2014).

Throughout the study, we identified various trade-offs including increased CO_2 emission following forest thinning management, increased GHG emissions in land-use changes, very high N_2O emissions in vegetable gardens due to excessive N input to get high yields, increased CO_2 and N_2O emission in incorporation of crop residues to the soil and agroforestry practices, and exponential increased of N_2O emission and yield-scaled N_2O emissions in excessive N input. Further studies are needed to assess and manage potential trade-offs and drivers.

3.~~6.~~4 Strategic approaches for data acquisition

A strategic plan for acquisition of soil GHG emission data in sub-Saharan Africa is required. The success of any plan is dependent on long-term investment, stakeholder involvement, technical skill and supporting industries, which have not always been available in the region (Olander et al., 2013; Franks et al., 2012). A major challenge is to address the lack of consistency in the various methodologies used to quantify GHG emissions (Rosenstock et al. 2013). Relatively low cost and simple techniques can be used to determine GHG emission estimates in the first instance. Soil CO_2 fluxes can be quantified with a soda lime method (Tufekcioglu et al., 2001; Cropper et al., 1985;

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font color: Auto, English (U.S.)

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Edwards, 1982) or an infra-red gas analyzer (Bastviken et al., 2015; Verchot et al., 2008; Lee and Jose, 2003) and these do not require advanced technology or high levels of resource to undertake. Later, other GHG such as N_2O and CH_4 fluxes in addition to CO_2 flux can be measured with more advanced technology (e.g., gas chromatography, photo-acoustic spectroscopy, or laser gas analyzers). Initially, the measurement can be conducted using manual gas chambers with periodical sampling frequencies. The sampling interval can be designed so that it is appropriate to the particular type of land-use or ecosystem, management practices and/or for capturing the effects of episodic events (e.g., Parkin, 2008). For example, GHG measurement should be more during potentially high GHG emission periods following tillage and fertilizer applications and rewetting by natural rainfalls or irrigation. With more ~~advance~~advanced technology and utilisation of automatic chamber systems measurements can be conducted at a much ~~high~~higher frequency with relative ease.

In order for the challenges associated with improving our understanding of GHG emissions from African soils it is critical to establish networks of scientists and scientific bodies both within Africa and across the world. Good communication and collaboration between field researchers and the modelling community should also be established during the initial stages of research, so results obtained from field scientists can be effectively used for model development and to generate hypotheses to be tested in the field and laboratory (de Bruijn et al., 2009).

Furthermore, lessons learned from scientific experiments can only really be successfully implemented by farmers if local stakeholders are involved from the start and throughout (see for example Stringer et al., 2012). Interviews, focus-groups, on-site or farm demonstrations, local capacity building training, local farmers and extension staff can all improve dialogue and understanding between local communities and scientists, ultimately improving the likelihood of successful GHG emission and mitigation strategies. These will equip local researchers and stakeholders (including farmers and extension staff) with state of art methodologies and help motivate them to develop their GHG mitigation measures and assist them in understand their roles

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

and contributions to global environmental issues. Beside, data acquisition will not be only determined by technical but also by socio-political (and economic) barriers in sub-Saharan Africa. These problems are not only affecting this process but are also driving forces for GHG emissions due to (e.g.) land-use change events. Therefore, the implication of social scientists on this kind of studies would be also needed.

Formatted: Font color: Auto

4. Conclusions

This paper synthesizes the available data on GHG emissions from African agricultural and natural lands. Emissions of CO_2, CH_4 and N_2O in a variety of environments (forests, savannahs, termite mounds, salt pans, agricultural areas and water bodies) were considered. Two broad conclusions can be drawn from the work. The first one is that African natural and agricultural lands may be a significant source of GHG and that the emissions may increase through land-use change and management strategies. Secondly, there are huge research gaps. Africa is a vast continent, with a multitude of land uses, climates, soils and ecosystems. Field-based data on soil GHG emissions from many areas, soil types and environments are extremely sparse and as a result our understanding of Africa’s contribution to global GHG emissions remains incomplete and highly uncertain. There is an urgent need to develop and agree on a strategy for addressing this data gap. The strategy may involve identifying priorities for data acquisition, utilizing appropriate technologies, and establishing networks and collaboration.

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Appendix A

A Blog for open discussion and web based open databases

We have created a Blog entitled ‘Greenhouse gas emissions in Africa: study summary and database’ (http://ghginafrica.blogspot.com/) and an open-access database, which can be modified by the users, entitled ‘Soil greenhouse gas emissions in Africa database’ (linked in the Blog) based on this review. In the Blog, we have posted a technical summary of each section of this review, where

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

comments can be left under the posts. The database contains detailed information on the studies reported on GHG emissions, such as ecosystem and land use types, location, climate, vegetation type, crop type, fertilizer type, N input rate, soil properties, GHGs emission measurement periods, N_2O EF, and corresponding reference. The database is hosted in web based spreadsheets and is easily accessible and modified. The authors do not have any relationship with the companies currently being used to host the Blog and databases.

Acknowledgements

We are grateful for the numerous researchers and technicians who provided invaluable data. It is impossible to cite all the references due to limited space allowed and we apologize for the authors whose work has not been cited. We are also grateful to Benjamin Bond-Lamberty and Rodrigo Vargas for insightful comments, Luis Lassaletta for providing raw data of N application rates in Africa and Antony Smith for creating maps showing studies sites. A. S.-C. gratefully acknowledges to the Spanish Ministry of Science and Innovation and the Autonomous Community of Madrid for their economic support through the NEREA project (AGL2012-37815- C05-01, AGL2012-37815-C05-04), the Agrisost Project (S2013/ABI-2717) and the FACCE JPI MACSUR project. D.-G.K. acknowledges support from Research and Development Office, Wondo Genet College and IAEA Coordinated Research Project (CRP D1 50.16).

Reference

Andersson, M., Michelsen, A., Jensen, M., and Kjøller, A.: Tropical savannah woodland: Effects of experimental fire on soil microorganisms and soil emissions of carbon dioxide, Soil Biol. Biochem., 36, 849-858, 2004.

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

Ball, B.C., Scott, A., Parker, J.P.: Field N_2O, CO_2 and CH_4 fluxes in relation to tillage, compaction and soil quality in Scotland, Soil Tillage Res., 53, 29-39, 1999.

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Barton, L., Wolf, B., Rowlings, D., Scheer, C., Kiese, R., Grace, P., Stefanova, K., and Butterbach-Bahl, K.: Sampling frequency affects estimates of annual nitrous oxide fluxes, Sci. Rep., 5, 15912, doi: 10.1038/srep15912 2015.

Bastviken, D., Sundgren, I., Natchimuthu, S., Reyier, H., and Gålfalk, M.: Technical note: Cost-efficient approaches to measure carbon dioxide (CO$_2$) fluxes and concentrations in terrestrial and aquatic environments using mini loggers, Biogeosciences, 12, 3849-3859, 2015.

Berger, S., Jung, E., Köpp, J., Kang, H., Gebauer, G.: Monsoon rains, drought periods and soil texture as drivers of soil N$_2$O fluxes - Soil drought turns East Asian temperate deciduous forest soils into temporary and unexpectedly persistent N$_2$O sinks, Soil Biol. Biochem., 57, 273-281, 2013.

Birch, H.F.: Mineralisation of plant nitrogen following alternate wet and dry conditions, Plant Soil, 20, 43-49, 1964.

Bombelli, A., Henry, M., Castaldi, S., Adu-Bredu, S., Arneth, A., de Grandcourt, A., Grieco, E., Kutsch,W. L., Lehsten, V., Rasile, A., Reichstein, M., Tansey, K., Weber, U., and Valentini, R.: An Outlook on the Sub-Saharan Africa Carbon Balance, Biogeosciences, 6, 2193-2205, 2009.

Bond-Lamberty, B., and Thomson, A.M.: Temperature-associated increases in the global soil respiration record, Nature, 464, 579-582, 2010.

Borges, A.-V., Darchambeau, F., Teodoru, C. R., Marwick, T. R., Tamooh, F., Geeraert, N., Omengo, F. O., Guerin, F., Lambert, T., Morana, C., Okuku, E., and Bouillon, S.: Globally significant greenhouse-gas emissions from ~~african~~African inland waters, Nature Geosci., doi:10.1038/ngeo2486, 2015.

Borges, A.V., Morana, C., Bouillon. S., Servais, P., Descy, J.-P.., and Darchambeau, F..: Carbon cycling of Lake Kivu (East Africa): net autotrophy in the epilimnion and emission of CO$_2$ to the atmosphere sustained by geogenic inputs, PLoS one, 9(10), e109500, doi:10.1371/journal.pone.0109500, 2014.

Borges, A.V., Abril, G., Delille, B., Descy, J.P. and Darchambeau, F.: Diffusive methane emissions to the atmosphere from Lake Kivu (Eastern Africa), J. Geophys. Res, 116(G3), doi: 10.1029/2011JG001673, 2011.

Bouillon, S., Yambélé, A., Spencer, R. G. M., Gillikin, D. P., Hernes, P. J., Six, J., Merckx, R., and Borges, A.: Organic matter sources, fluxes and greenhouse gas exchange in the Oubangui river (Congo river basin), Biogeosciences, 9, 2045-2062, doi:10.5194/bg-9-2045-2012, 2012.

Bouwman, A.F., Beusen, A.H.W., and Billen, G.: Human alteration of the global nitrogen and phosphorus soil balances for the period 1970–2050, Global Biogeochem. Cycles, GB0A04, doi:10.1029/2009GB003576, 2009.

Bouwman, L., Goldewijk, K.K., Van Der Hoek, K.W., Beusen, A.H.W., Van Vuuren, D.P., Willems, J., Rufino, M.C., and Stehfest, E.: Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900-2050 period, Proc. Natl. Acad. Sci. U.S.A., 110, 20882-20887, doi: 10.1073/pnas.1012878108, 2013.

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Brümmer, C., Papen, H., Wassmann, R., and Brüggemann, N.: Fluxes of CH_4 and CO_2 from soil and termite mounds in south Sudanian savanna of Burkina Faso (West Africa), Global Biogeochem. Cycles, 23, GB1001, doi:10.1029/2008GB003237, 2009.

Brunet, F., Dubois, K., Veizer, J., Nkoue Ndondo, G. R., Ndam Ngoupayou, J. R., Boeglin, J. L., and Probst, J. L.: Terrestrial and fluvial carbon fluxes in a tropical watershed: Nyong basin, Cameroun, Chem. Geol., 2, 563-572, 2009.

Caquet, B., De Grandcourt, A., Thongo M'bou, A., Epron, D., Kinana, A., Saint André, L., and Nouvellon, Y.: Soil carbon balance in a tropical grassland: Estimation of soil respiration and its partitioning using a semi-empirical model, Agr. Forest. Meteorol., 158-159, 71-79, 2012.

Castaldi, S., de Grandcourt, A., Rasile, A., Skiba, U., and Valentini, R.: Fluxes of CO_2, CH_4 and N_2O from soil of burned grassland savannah of central Africa, Biogeosciences ~~Discuss., 7, 4089-4126~~, 7, 3459-3471, doi:10.5194/bg-7-3459-2010, 2010.

Chapuis-Lardy, L., Metay, A., Martinet, M., Rabenarivo, M., Toucet, J., Douzet, J. M., Razafimbelo, T., Rabeharisoa, L., and Rakotoarisoa, J.: Nitrous oxide fluxes from malagasy agricultural soils, Geoderma, 148, 421-427, 2009.

Chikowo, R., Mapfumo, P., Nyamugafata, P., and Giller, K. E.: Mineral n dynamics, leaching and nitrous oxide losses under maize following two-year improved fallows on a sandy loam soil in Zimbabwe, Plant Soil, 259, 315-330, 2004.

Ciais, P., Bombelli, A., Williams, M., Piao, S. L., Chave, J., Ryan, C. M., Henry, M., Brender, P., and Valentini, R.: The Carbon Balance of Africa: Synthesis of Recent Research Studies, Philos. T. R. Soc. A, 269, 2038-2057, 2011.

Cropper, Jr. W., Ewel, K.C., and Raich, J.: The measurement of soil CO_2 evolution in situ. Pedobiologia, 28, 35-40, 1985.

de Bruijn, A. M. G., Butterbach-Bahl, K., Blagodatsky, S., and Grote, R.: Model evaluation of different mechanisms driving freeze-thaw N_2O emissions, Agric. Ecosyst. Environ., 133, 196-207, 2009.

Delmas, R. A., Marenco, A., Tathy, J. P., Cros, B., and Baudet, J. G. R.: Sources and sinks of methane in African savanna. CH_4 emissions from biomass burning, J. Geophys. Res., 96, 7287-7299, 1991.

DelSontro et al., 2011 dx.doi.org/10.1021/es2005545 | Environ. Sci. Technol. 2011, 45, 9866–9873

Díaz-Pinés, E., Schindlbacher, A., Godino, M., Kitzler, B., Jandl, R., Zechmeister-Boltenstern, S., and Rubio, A.: Effects of tree species composition on the CO_2 and N_2O efflux of a Mediterranean mountain forest soil, Plant Soil, 384, 243-257, 2014.

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

Dick, J., Skiba, U., and Wilson J.: The effect of rainfall on NO and N_2O emissions from Ugandan agroforest soils, Phyton, 41, 73-80, 2001.

Dick, J., Skiba, U., Munro, R., and Deans, D.: Effect of N-fixing and non n-fixing trees and crops on NO and N_2O emissions from Senegalese soils, J. Biogeogr., 33, 416-423, 2006.

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted ...

Formatted: Font color: Auto

Formatted ...

Formatted ...

Formatted: Font color: Auto

Formatted ...

Formatted: Font color: Auto

Formatted ...

Formatted: Font color: Auto

Formatted ...

Formatted: Font color: Auto

Formatted ...

Formatted: Font color: Auto

Dijkstra, F.A., Prior, S.A., Runion, G.B., Torbert, H.A., Tian, H., Lu, C., and Venterea, R.T.: Effects of elevated carbon dioxide and increased temperature on methane and nitrous oxide fluxes: evidence from field experiments, Front. Ecol. Environ., 10, 520-527, 2012.

Edwards, N.: The use of soda-lime for measuring respiration rates in terrestrial systems, Pedobiologia, 23, 321-330, 1982.

Epron, D., Nouvellon, Y., Mareschal, L., e Moreira, R. M., Koutika, L.-S., Geneste, B., Delgado-Rojas, J. S., Laclau, J.-P., Sola, G., and de Moraes Goncalves, J. L.: Partitioning of net primary production in eucalyptus and acacia stands and in mixed-species plantations: Two case-studies in contrasting tropical environments, For. Ecol. Manage., 301, 102-111, 2013.

Epron, D., Nouvellon, Y., Roupsard, O., Mouvondy, W., Mabiala, A., Saint-André, L., Joffre, R., Jourdan, C., Bonnefond, J.-M., Berbigier, P., and Hamel, O.: Spatial and temporal variations of soil respiration in a eucalyptus plantation in Congo, For. Ecol. Manage., 202, 149-160, 2004.

Fan, Z., Neff, J.C., and Hanan, N.P.: Modeling pulsed soil respiration in an African savanna ecosystem, Agr. Forest. Meteorol., 200, 282-292, 2015.

FAO: Global Forest Resources Assessment 2010, FAO Forestry Paper 163, Food and Agriculture Organization of the United Nations, Rome, 340 pp., available at: http://www.fao.org/forestry/fra/fra2010/en/, access October 1, 2015, 2010.

FAOSTAT, http://faostat.fao.org/site/377/default.aspx#ancor, ~~2014~~ access October 1, 2015.

Franks, J. R. and Hadingham, B.: Reducing greenhouse gas emissions from agriculture: Avoiding trivial solutions to a global problem, Land Use Policy, 29, 727-736, 2012.

Frimpong, K.A., and Baggs, E.M.: Do combined applications of crop residues and inorganic fertilizer lower emission of N_2O from soil?, Soil Use Manage., 26, 412-424, 2010.

Frimpong, K.A., Yawson, D.O., Agyarko, K., and Baggs, E.M.: N_2O emission and mineral N release in a tropical acrisol incorporated with mixed cowpea and maize residues, Agron., 2, 167-186, 2012.

Frimpong, K.A., Yawson, D.O., Baggs, E.M., and Agyarko, K.: Does incorporation of cowpea-maize residue mixes influence nitrous oxide emission and mineral nitrogen release in a tropical luvisol?, Nutr. Cycl. Agroecosys., 91, 281-292, 2011.

Garcia-Ruiz, R., and Baggs, E.: N_2O emission from soil following combined application of fertiliser-N and ground weed residues, Plant Soil, 299, 263-274, 2007.

Gentile, R., Vanlauwe, B., Chivenge, P., and Six, J.: Interactive effects from combining fertilizer and organic residue inputs on nitrogen transformations, Soil Biol. Biochem., 40, 2375-2384, 2008.

Gharahi Ghehi, N., Werner, C., Cizungu Ntaboba, L., Mbonigaba Muhinda, J. J., Ranst, E. V., Butterbach-Bahl, K., Kiese, R., and Boeckx, P.: Spatial variations of nitrogen trace gas emissions from tropical mountain forests in Nyungwe, Rwanda, Biogeosciences, 9, 1451-1463, 2012.

Gharahi Ghehi, N., Werner, C., Hufkens, K., Kiese, R., Van Ranst, E., Nsabimana, D., Wallin, G., Klemedtsson, L., Butterbach-Bahl, K., and Boeckx, P.: N_2O and NO emission from the Nyungwe tropical highland rainforest in Rwanda. Geoderma Regional, 2-3, 41-49, 2014.

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font: (Asian) +Body Asian, Font color: Auto, (Intl) Times New Roman

Formatted: Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted ...

Formatted: Font color: Auto

Formatted ...

Formatted: Font color: Auto

Formatted ...

Formatted: Font color: Auto

Formatted ...

Formatted: Font color: Auto

Formatted ...

Formatted: Font color: Auto

Gibbs, H. K., Ruesch, A. S., Achard, F., Clayton, M. K., Holmgren, P., Ramankutty, N., and Foley, J. A.: Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s, P. Natl. Acad. Sci. USA, 107, 16732-16737, 2010.

Goenster, S., Wiehle, M., Predotova, M., Gebauer, J., Ali, A.M., and Buerkert, A.: Gaseous emissions and soil fertility of homegardens in the Nuba Mountains, Sudan. J. Plant Nutr. Soil Sci., 178, 413-424, 2015.

Gondwe, M. J., and Masamba, W. R.: Spatial and temporal dynamics of diffusive methane emissions in the Okavango delta, northern Botswana, Africa, Wetlands Ecol. Manage., 22, 63-78, 2014.

Hall, N. M., Kaya, B., Dick, J., Skiba, U., Niang, A., and Tabo, R.: Effect of improved fallow on crop productivity, soil fertility and climate-forcing gas emissions in semi-arid conditions, Biol. Fertility Soils, 42, 224-230, 2006.

Hickman, J. E., Tully, K. L., Groffman, P. M., Diru, W., and Palm, C. A. C. J. G.: A potential tipping point in tropical agriculture: Avoiding rapid increases in nitrous oxide fluxes from agricultural intensification in Kenya, J. Geophys. Res., ~~2015.~~12, 938-951, doi: 10.1002/2015JG002913, 2015.

Hickman, J. E., Palm, C., Mutuo, P., Melillo, J., and Tang, J.: Nitrous oxide (N_2O) emissions in response to increasing fertilizer addition in maize (Zea mays L.) agriculture in western Kenya, Nutr. Cycl. Agroecosys., 100, 177-187, 2014.

Hickman, J.E., Havlikova, M., Kroeze, C., Palm, C.A.: Current and future nitrous oxide emissions from African agriculture, Curr. Opin. Environ. Sustain., 3, 370-378, 2011.

Intergovernmental Panel on Climate Change (IPCC): Guidelines for national greenhouse gas inventories, Available at http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html [verified 27 March 2015]. Geneva, Switzerland, 2006.

IPCC: Summary for ~~Policymakers, In~~policymakers, in: Climate Change 2014, Mitigation of Climate Change~~. Contribution~~, contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change~~ [~~, edited by: Edenhofer, O., ~~R.~~ Pichs-Madruga, ~~Y.~~R., Sokona, ~~E.~~Y., Farahani, ~~S.~~E., Kadner, ~~K.~~S., Seyboth, ~~A.~~K., Adler, ~~I.~~A., Baum, ~~S.~~I., Brunner, ~~P.~~S., Eickemeier, ~~B.~~P., Kriemann, ~~J.~~B., Savolainen, ~~S.~~J., Schlomer, ~~C.~~S., von Stechow, ~~T.~~C., Zwickel, T., and ~~J.C.~~ Minx~~ (eds.)]~~, J. C., Cambridge University Press, Cambridge, ~~United Kingdom~~UK and New York, NY, USA, 1-30, 2014.

Jin, V. L., Baker, J. M., Johnson, J. M. F., Karlen, D. L., Lehman, R. M., Osborne, S. L., Sauer, T. J., Stott, D. E., Varvel, G. E., and Venterea, R. T.: Soil greenhouse gas emissions in response to corn stover removal and tillage management across the us corn belt, BioEnergy Research, 7, 517-527, 2014.

Kim, D.-G., and Kirschbaum, M. U.: The effect of land-use change on the net exchange rates of greenhouse gases: A compilation of estimates, Agr. Ecosyst. Environ., 208, 114-126, 2015.

Kim, D.-G., Hernandez-Ramirez, G., and Giltrap, D.: Linear and nonlinear dependency of direct nitrous oxide emissions on fertilizer nitrogen input: A meta-analysis, Agr. Ecosyst. Environ., 168, 53-65, 2013.

Kim, D.-G., Mu, S., Kang, S., and Lee, D.: Factors controlling soil CO_2 effluxes and the effects of rewetting on effluxes in adjacent deciduous, coniferous, and mixed forests in Korea, Soil Biol. Biochem., 42, 576-585, 2010.

Kim, D.-G., Vargas, R., Bond-Lamberty, B., and Turetsky, M.R.: Effects of soil rewetting and thawing on soil gas fluxes: a review of current literature and suggestions for future research, Biogeosciences, 9, 2459-2483, 2012b.

Kim, D.-G.: Estimation of net gain of soil carbon in a nitrogen-fixing tree and crop intercropping system in sub-Saharan Africa: Results from re-examining a study, Agroforest. Sys., 86, 175-184, 2012a.

Kim, Y. S., Makoto, K., Takakai, F., Shibata, H., Satomura, T., Takagi, K., Hatano, R., and Koike, T.: Greenhouse gas emissions after a prescribed fire in white birch-dwarf bamboo stands in northern Japan, focusing on the role of charcoal, Eur J. of For. Res., 130, 1031-1044, 2011.

Kimaro, A., Mpanda, M., Rioux, J., Aynekulu, E., Shaba, S., Thiong'o, M., Mutuo, P., Abwanda, S., Shepherd, K., Neufeldt, H., and Rosenstock, T.: Is conservation agriculture 'climate-smart' for maize farmers in the highlands of Tanzania?, Nutr. Cycl. Agroecosys., 10.1007/s10705-015-9711-8, 2015.

Kimetu, J., Mugendi, D., Bationo, A., Palm, C., Mutuo, P., Kihara, J., Nandwa, S., and Giller, K.: Partial balance of nitrogen in a maize cropping system in humic nitisol of Central Kenya, Nutr. Cycl. Agroecosys., 76, 261-270, 2007.

Koerber, G. R., Edwards-Jones, G., Hill, P. W., Nyeko, P., York, E. H., and Jones, D. L.: Geographical variation in carbon dioxide fluxes from soils in agro-ecosystems and its implications for life-cycle assessment, J. Appl. Ecol., 46, 306-314, 2009.

Koné, Y. J. M., Abril, G., Kouadio, K. N., Delille, B., and Borges, A. V.: Seasonal variability of carbon dioxide in the rivers and lagoons of Ivory Coast (West Africa), Estuaries Coast., 32, 246-260, 2009.

Kulmala, L., Aaltonen, H., Berninger, F., Kieloaho, A.-J., Levula, J., Bäck, J., Hari, P., Kolari, P., Korhonen, J. F. J., Kulmala, M., Nikinmaa, E., Pihlatie, M., Vesala, T., and Pumpanen, J.: Changes in biogeochemistry and carbon fluxes in a boreal forest after the clear-cutting and partial burning of slash, Agr. Forest. Meteorol., 188, 33-44, 2014.

Lamade, E., Djegui, N., and Leterme, P.: Estimation of carbon allocation to the roots from soil respiration measurements of oil palm, Plant Soil, 181, 329-339, 1996.

Lane, R. W., Menon, M., McQuaid, J. B., Adams, D. G., Thomas, A. D., Hoon, S. R., and Dougill, A. J.: Laboratory analysis of the effects of elevated atmospheric carbon dioxide on respiration in biological soil crusts, J. Arid Environ., 98, 52-59, 2013.

Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., and Garnier, J.: 50 year trends in nitrogen use efficiency of world cropping systems: The relationship between yield and nitrogen input to cropland, Environ. Res. Lett., 9, 105011, doi: 10.1088/1748-9326/9/10/105011, 2014.

Lee, K.-H., and Jose, S.: Soil respiration and microbial biomass in a pecan-cotton alley cropping system in southern USA, Agroforest. Syst., 58, 45-54, 2003.

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Linquist, B. A., Adviento-Borbe, M. A., Pittelkow, C. M., van Kessel, C., and van Groenigen, K. J.: Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis, Field Crops Res., 135, 10-21, 2012.

Lompo, D. J.-P., Sangaré, S. A. K., Compaoré, E., Papoada Sedogo, M., Predotova, M., Schlecht, E., and Buerkert, A.: Gaseous emissions of nitrogen and carbon from urban vegetable gardens in bobo-dioulasso, Burkina Faso, J. Plant Nutr. Soil Sci., 175, 846-853, 2012.

Macdonald, J. A., Eggleton, P., Bignell, D. E., Forzi, F., and Fowler, D.: Methane emission by termites and oxidation by soils, across a forest disturbance gradient in the mbalmayo forest reserve, Cameroon, Global Change Biol., 4, 409-418, 1998.

Mafongoya, P., Giller, K., and Palm, C.: Decomposition and nitrogen release patterns of tree prunings and litter, Agroforest. Syst., 38, 77-97, 1997.

Makumba, W., Akinnifesi, F. K., Janssen, B., and Oenema, O.: Long-term impact of a gliricidia-maize intercropping system on carbon sequestration in southern Malawi, Agr. Ecosyst. Environ., 118, 237-243, 2007.

Malhi, S., Nyborg, M., Solberg, E., Dyck, M., and Puurveen, D.: Improving crop yield and N uptake with long-term straw retention in two contrasting soil types, Field Crops Res., 124, 378-391, 2011.

Mann, P. J., Spencer, R. G., Dinga, B., Poulsen, J. R., Hernes, P., Fiske, G., Salter, M. E., Wang, Z. A., Hoering, K. A., and Six, J.: The biogeochemistry of carbon across a gradient of streams and rivers within the Congo basin, J. Geophys. Res: Biogeosciences, 119, 687-702, 2014.

Mapanda, F., Mupini, J., Wuta, M., Nyamangara, J., and Rees, R.: A cross-ecosystem assessment of the effects of land cover and land use on soil emission of selected greenhouse gases and related soil properties in Zimbabwe, Eur. J. Soil Sci., 61, 721-733, 2010.

Mapanda, F., Wuta, M., Nyamangara, J., and Rees, R. M.: Effects of organic and mineral fertilizer nitrogen on greenhouse gas emissions and plant-captured carbon under maize cropping in Zimbabwe, Plant Soil, 343, 67-81, 2011.

Mapanda, P., Wuta, M., Nyamangara, J., Rees, R., and Kitzler, B.: Greenhouse gas emissions from savanna (miombo) woodlands: Responses to clearing and cropping, Afr. Crop Sci. J., 20, 385-400, 2012.

Masaka, J., Nyamangara, J., and Wuta, M.: Nitrous oxide emissions from wetland soil amended with inorganic and organic fertilizers, Arch. Agron. Soil Sci., 60, 1363-1387, 2014.

Merbold, L., Ziegler, W., Mukelabai, M., and Kutsch, W.: Spatial and temporal variation of CO$_2$ efflux along a disturbance gradient in a miombo woodland in western Zambia, Biogeosciences, 8, 147-164, 2011.

Millar, N., and Baggs, E. M.: Chemical composition, or quality, of agroforestry residues influences N$_2$O emissions after their addition to soil, Soil Biol. Biochem., 36, 935-943, 2004.

Millar, N., and Baggs, E. M.: Relationships between N$_2$O emissions and water-soluble c and n contents of agroforestry residues after their addition to soil, Soil Biol. Biochem., 37, 605-608, 2005.

Millar, N., Ndufa, J., Cadisch, G., and Baggs, E.: Nitrous oxide emissions following incorporation of improved-fallow residues in the humid tropics, Global Biogeochem. Cycles, 18, 2004.

Motulsky, H.J., and Christopoulos, A.: Fitting models to biological data using linear and nonlinear regression: a practical guide to curve fitting, Oxford University Press, New York, 2004.

Formatted: No underline, Font color: Auto
Formatted: Font color: Auto
Formatted: No underline, Font color: Auto
Formatted: Font color: Auto
Formatted: No underline, Font color: Auto
Formatted: Font color: Auto
Formatted: No underline, Font color: Auto
Formatted: Font color: Auto
Formatted: No underline, Font color: Auto
Formatted: Font color: Auto
Formatted: No underline, Font color: Auto
Formatted: Font color: Auto
Formatted: No underline, Font color: Auto
Formatted: Font color: Auto
Formatted: No underline, Font color: Auto
Formatted: Font color: Auto
Formatted: No underline, Font color: Auto
Formatted: Font color: Auto
Formatted: No underline, Font color: Auto
Formatted: Font color: Auto
Formatted: No underline, Font color: Auto
Formatted: Font color: Auto
Formatted: No underline, Font color: Auto
Formatted: Font color: Auto
Formatted: No underline, Font color: Auto
Formatted: Font color: Auto
Formatted: No underline, Font color: Auto
Formatted: Font color: Auto
Formatted: No underline, Font color: Auto
Formatted: Font color: Auto
Formatted: No underline, Font color: Auto
Formatted: Font color: Auto

Nouvellon, Y., Epron, D., Marsden, C., Kinana, A., Le Maire, G., Deleporte, P., Saint-Andre´, L., Bouillet, J.-P., and Laclau, J.-P.: Age-related changes in litter inputs explain annual trends in soil CO_2 effluxes over a full eucalyptus rotation after afforestation of a tropical savannah, Biogeochemistry, 111, 515-533, 2012.

Nyamadzawo, G., Gotosa, J., Muvengwi, J., Wuta, M., Nyamangara, J., Nyamugafata, P., and Smith, J. L.: The effect of catena position on greenhouse gas emissions from dambo located termite (odontotermes transvaalensis) mounds from central Zimbabwe, Atmospheric and Climate Sciences, 2, 501-509, doi:10.4236/acs.2012.24044, 2012.

Nyamadzawo, G., Shi, Y., Chirinda, N., Olesen, J.r., Mapanda, F., Wuta, M., Wu, W., Meng, F., Oelofse, M., de Neergaard, A., and Smith, J.: Combining organic and inorganic nitrogen fertilisation reduces N_2O emissions from cereal crops: a comparative analysis of China and Zimbabwe, Mitig. Adapt. Strategies Glob. Chang., ~~DOI~~doi: 10.1007/s11027-11014-19560-11029, 2014b.

Nyamadzawo, G., Wuta, M., Chirinda, N., Mujuru, L., and Smith, J. L.: Greenhouse gas emissions from intermittently flooded (dambo) rice under different tillage practices in chiota smallholder farming area of Zimbabwe, Atmospheric and Climate Sciences, 3, 13-20, 2013.

Nyamadzawo, G., Wuta, M., Nyamangara, J., Smith, J.L., and Rees, R.M.: Nitrous oxide and methane emissions from cultivated seasonal wetland (dambo) soils with inorganic, organic and integrated nutrient management, Nutr. Cycl. Agroecosys., 100, 161-175, 2014a.

Olander, L., Wollenberg, E., Tubiello, F. and Herold, M.: Advancing agricultural greenhouse gas quantification, Environ. Res. Lett., 8, 011002, doi:10.1088/1748-9326/8/1/011002, 2013.

Palm, C. A., Smukler, S. M., Sullivan, C. C., Mutuo, P. K., Nyadzi, G. I., and Walsh, M. G.: Identifying potential synergies and trade-offs for meeting food security and climate change objectives in sub-Saharan Africa, Proc. Natl. Acad. Sci. U. S. A., 107, 19,661-19,666, 2010.

Parkin, T. B.: Effect of sampling frequency on estimates of cumulative nitrous oxide emissions, J. Environ. Qual., 37, 1390-1395, 2008.

Pelster, D.E., Chantigny, M.H., Rochette, P., Angers, D.A., Rieux, C., Vanasse, A.: Nitrous oxide emissions respond differently to mineral and organic N sources in contrasting soil types. J. Environ. Qual., 41, 427-435, 2012.

Predotova, M., Schlecht, E., and Buerkert, A.: Nitrogen and carbon losses from dung storage in urban gardens of Niamey, Niger, Nutr. Cycl. Agroecosys., 87, 103-114, 2010.

Priemé, A., and Christensen, S.: Methane uptake by a selection of soils in Ghana with different land use, J. Geophys. Res., 104, 23,617-23,622, 1999.

Rabenarivo, M., Wrage-Moennig, N., Chotte, J. L., Rabeharisoa, L., Razafimbelo, T. M., and Chapuis-Lardy, L.: Emissions of CO_2 and N_2O from a pasture soil from Madagascar-simulating conversion to direct-seeding mulch-based cropping in incubations with organic and inorganic inputs, J. Plant Nutr. Soil Sci., 177, 360-368, 2014.

Reed, D. E., Ewers, B. E., and Pendall, E.: Impact of mountain pine beetle induced mortality on forest carbon and water fluxes, Environ. Res. Lett., 9, 105004, doi:10.1088/1748-9326/9/10/105004, 2014.

Rees, R. M., Wuta, M., Furley, P. A., and Li, C.: Nitrous oxide fluxes from savanna (miombo) woodlands in Zimbabwe, J. Biogeogr., 33, 424-437, 2006.

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted ...

Formatted: Font color: Auto

Rezaei Rashti, M., Wang, W., Moody, P., Chen, C., and Ghadiri, H.: Fertiliser-induced nitrous oxide emissions from vegetable production in the world and the regulating factors: A review, Atmos. Environ., 112, 225-233, 2015.

Rochette, P., and Eriksen-Hamel, N. S.: Chamber measurements of soil nitrous oxide flux: Are absolute values reliable? , Soil Sci. So. Am. J., 72, 331-342, doi:10.2136/sssaj2007.0215, 2008.

Rosenstock, T., Rufino, M., Butterbach-Bahl, K., and Wollenberg, E.: Toward a protocol for quantifying the greenhouse gas balance and identifying mitigation options in smallholder farming systems, Environ. Res. Lett., 8, 021003, doi:10.1088/1748-9326/8/2/021003, 2013.

Saggar, S., Jha, N., Deslippe, J., Bolan, N. S., Luo, J., Giltrap, D. L., Kim, D. G., Zaman, M., and Tillman, R. W.: Denitrification and N_2O:N_2 production in temperate grasslands: Processes, measurements, modelling and mitigating negative impacts, Sci. Total Environ., 465, 173-195, 2013.

Scholes, M. C., Martin, R., Scholes, R. J., Parsons, D., and Winstead, E.: NO and N_2O emissions from savanna soils following the first simulated rains of the season, Nutr. Cycl. Agroecosys., 48, 115-122, 1997.

Shcherbak, I., Millar, N., and Robertson, G. P.: Global metaanalysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertilizer nitrogen, Proc. Natl. Acad. Sci., 111, 9199-9204, 2014.

Sheehy, J., Six, J., Alakukku, L., and Regina, K.: Fluxes of nitrous oxide in tilled and no-tilled boreal arable soils, Agr. Ecosyst. Environ., 164, 190-199, 2013.

Smith, D.L., and Johnson, L.: Vegetation-mediated changes in microclimate reduce soil respiration as woodlands expand into grasslands, Ecology, 85, 3348-3361, 2004.

Smith, K.: Nitrous Oxide and Climate Change, Earthscan, London, UK, 240 pp., 2010.

Snyder, C. S., Bruulsema, T. W., Jensen, T. L., and Fixen, P. E.: Review of greenhouse gas emissions from crop production systems and fertilizer management effects, Agr. Ecosyst. Environ., 133, 247-266, 2009.

Sommer, R., Mukalama, J., Kihara, J., Koala, S., Winowiecki, L., and Bossio, D.: Nitrogen dynamics and nitrous oxide emissions in a long-term trial on integrated soil fertility management in western Kenya, Nutr. Cycl. Agroecosys., 10.1007/s10705-015-9693-6, 2015.

Stringer, L., Dougill, A.J., Thomas, A.D., Spracklen, D., Chesterman, S., Speranza, C. I., Rueff, H., Riddell, M., Williams, M., and Beedy, T.: Challenges and opportunities in linking carbon sequestration, livelihoods and ecosystem service provision in drylands, Environ. Sci. Policy, 19, 121-135, 2012.

Sugihara, S., Funakawa, S., Kilasara, M., and Kosaki, T.: Effects of land management on CO_2 flux and soil C stock in two Tanzanian croplands with contrasting soil texture, Soil Biol. Biochem., 46, 1-9, 2012.

Tathy, J., Cros, B., Delmas, R., Marenco, A., Servant, J., and Labat, M.: Methane emission from flooded forest in central Africa, J. Geophys. Res., 97, 6159-6168, 1992.

Teodoru, C. R., Nyoni, F. C., Borges, A. V., Darchambeau, F., Nyambe, I., and Bouillon, S.: Dynamics of greenhouse gases (CO_2, CH_4, N_2O) along the zambezi river and major

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto

Formatted: Font color: Auto

Formatted: Font color: Auto

tributaries, and their importance in the riverine carbon budget, Biogeosciences, 12, 2431-2453, 2015.

Thomas, A. D., and Hoon, S. R.: Carbon dioxide fluxes from biologically-crusted Kalahari sands after simulated wetting, J. Arid Environ., 74, 131-139, 2010.

Thomas, A. D., Dougill, A. J., Elliott, D. R., and Mairs, H.: Seasonal differences in soil CO_2 efflux and carbon storage in Ntwetwe pan, Makgadikgadi Basin, Botswana, Geoderma, 219, 72-81, 2014.

Thomas, A. D., Hoon, S. R., and Dougill, A. J.: Soil respiration at five sites along the kalahari transect: Effects of temperature, precipitation pulses and biological soil crust cover, Geoderma, 167, 284-294, 2011.

Thomas, A. D.: Impact of grazing intensity on seasonal variations in soil organic carbon and soil CO_2 efflux in two semiarid grasslands in southern Botswana, Phil. Trans. R. Soc. B., 367, 3076-3086, 2012.

Thompson, R., Chevallier, F., Crotwell, A., Dutton, G., Langenfelds, R., Prnn, R., Weiss, R., Tohjima, Y., Nakazawa, T., and Krummel, P.: Nitrous oxide emissions 1999 to 2009 from a global atmospheric inversion. Atmos. Chem. Phys. 14, 1801-1817, 2014.

Tubiello, F. N., Salvatore, M., Ferrara, A. F., House, J., Federici, S., Rossi, S., Biancalani, R., Condor Golec, R. D., Jacobs, H., Flammini, A., Prosperi, P., Cardenas-Galindo, P., Schmidhuber, J., Sanz Sanchez, M. J., Srivastava, N., and Smith, P.: The contribution of agriculture, forestry and other land use activities to global warming, 1990–2012, Global Change Biol., 21, 2655-2660, 2015.

Tubiello, F. N., Salvatore, M., Rossi, S., Ferrara, A., Fitton, N., and Smith, P.: The FAOSTAT database of greenhouse gas emissions from agriculture, Environ. Res. Lett., 8, 015009, doi:10.1088/1748-9326/8/1/015009, 2013.

Formatted: Font color: Auto

Tufekcioglu, A., Raich, J., Isenhart, T., and Schultz, R.: Soil respiration within riparian buffers and adjacent crop fields, Plant Soil, 229, 117-124, 2001.

Tyler, S. C., Zimmerman, P. R., Cumberbatch, C., Greenberg, J. P., Westberg, C., and Darlington, J. P.: Measurements and interpretation of ^{d13}C of methane from termites, rice paddies, and wetlands in Kenya, Glob Biogeochem Cy, 2, 341-355, 1988.

US EPA. Draft U.S. Greenhouse Gas Inventory Report: 1990-2014. 2016. Available at https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport.html (Access April 10, 2016)

Valentini, R., Arneth, A., Bombelli, A., Castaldi, S., Cazzolla Gatti, R., Chevallier, F., Ciais, P., Grieco, E., Hartmann, J., and Henry, M.: A full greenhouse gases budget of africa: Synthesis, uncertainties, and vulnerabilities, Biogeosciences, 11, 381-407, 2014.

Formatted: Font color: Auto

Van Groenigen, J., Velthof, G., Oenema, O., Van Groenigen, K., and Van Kessel, C.: Towards an agronomic assessment of N_2O emissions: A case study for arable crops, Eur. J. Soil Sci., 61, 903-913, 2010.

Vargas, R.: How a hurricane disturbance influences extreme CO_2 fluxes and variance in a tropical forest, Environ. Res. Lett., 7, 035704, doi:10.1088/1748-9326/7/3/035704, 2012.

Formatted: Font color: Auto

Verchot, L. V., Brienza Junior, S., de Oliveira, V. C., Mutegi, J. K., Cattanio, J. H., and Davidson, E. A.: Fluxes of CH_4, CO_2, NO, and N_2O in an improved fallow agroforestry system in eastern Amazonia, Agr. Ecosyst. Environ., 126, 113-121, 2008.

Wang, Z.A., Bienvenu, D.J., Mann, P.J., Hoering, K.A., Poulsen, J.R., Spencer, R.G., and Holmes, R.M.: Inorganic carbon speciation and fluxes in the Congo River, Geophys. Res. Lett., 40, 511-516, 2013.

Werner, C., Kiese, R., and Butterbach-Bahl, K.: Soil-atmosphere exchange of N_2O, CH_4, and CO_2 and controlling environmental factors for tropical rain forest sites in western Kenya, J. Geophys. Res., 112, doi:10.1029/2006JD007388, 2007.

Yang, J., Liu, J., Hu, X., Li, X., Wang, Y., and Li, H.: Effect of water table level on CO_2, CH_4 and N_2O emissions in a freshwater marsh of Northeast China, Soil Biol. Biochem., 61, 52-60, 2013.

Yashiro, Y., Kadir, W.R., Okuda, T., and Koizumi, H.: The effects of logging on soil greenhouse gas (CO_2, CH_4, N_2O) flux in a tropical rain forest, Peninsular Malaysia, Agr. Forest. Meteorol., 148, 799-806, 2008.

Yohannes, Y., Shibistova, O., Abate, A., Fetene, M., and Guggenberger, G.: Soil CO_2 efflux in an afromontane forest of ethiopia as driven by seasonality and tree species, For. Ecol. Manage., 261, 1090-1098, doi: 10.4172/2168-9776.1000111, 2011.

Yohannes, Y., Shibistova, O., Asaye, Z., and Guggenberger, G.: Forest management influence on the carbon flux of cupressus lusitanica plantation in the Munessa forest, Ethiopia, Forest Res, 2, 2, 2013.

Zepp, R. G., Miller, W. L., Burke, R. A., Parsons, D. A. B., and Scholes, M. C.: Effects of moisture and burning on soil-atmosphere exchange of trace carbon gases in a southern African savanna, J. Geophys. Res., 101, 23,699-23,706, 1996.

Formatted: Font color: Auto

Formatted: Font color: Auto

Formatted: Font color: Auto

Table 1 Summary of greenhouse gas carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) emissions and CO_2 equivalents (CO_2 eq) in natural ecosystems and agricultural lands in sub-Saharan African countries. Mean ± standard error (number of data) are shown.

Type	Area (Mha)	CO_2 emission	CH_4 emission	N_2O emission	N_2O emission factor	CO_2 eq emission	Total CO_2 eq emission
		Mg CO_2 ha^{-1} yr^{-1}	kg CH_4 ha^{-1} yr^{-1}	kg N_2O ha^{-1} yr^{-1}	%	Mg CO_2 eq. ha^{-1} yr^{-1}	~~Pg~~ x 10^9 Mg CO_2 eq. yr^{-1}
Forest/ plantation/ woodland	740.6[#]	32.0 ± 5.0 (34)	-1.5 ± 0.6 (15)	4.2 ± 1.5 (10)	*	34.0 ± 5.7	25.2 ± 4.2
Savannah /grassland	638.9[#]	15.5 ± 3.8 (11)	0.5 ± 0.4 (18)	0.6 ± 0.1 (6)	*	15.8 ± 3.8	10.1 ± 2.4
Stream/river	28.2[#]	78.1 ± 13.2 (27)	436.3± 133.8 (24)	1.6 ± 0.3 (17)	*	93.4 ± 17.9	2.8 ± 1.0
Wetlands/floodplains/lagoons/reservoir	43.8[#]	96.6 ± 31.0 (7)	950.4 ± 350.4 (5)	2.0 ± 1.5 (2)	*	121.3 ± 39.7	5.3 ± 1.7
Termite mounds	0.97[†]	11.6 ± 6.2 (3)	2.3 ± 1.1 (3)	0.01 (1)	*	11.7 ± 6.3	0.01 ± 0.01
Salt pan	*	0.7 (1)	*	*	*	*	*
Total natural ~~lands[1]~~ecosystems[1]	1452.5	27.6 ± 2.9[$]	43.0 ± 5.8[$]	2.5 ± 0.4[$]	*	29.9 ± 22.5[$]	43.4 ± 9.3 (76.3%)[††]
Cropland	468.7[#]	23.4 ± 5.1 (45)	19.3 ± 4.2 (26)	4.0 ± 1.5 (83)	0.5 ± 0.2 (24)	26.1 ± 6.0	12.2 ± 2.8
Rice field	10.5[##]	6.5 (1)	30.5 (1)	0.19 (1)	*	7.3	1.3 ± 0.6
Vegetable gardens	*	96.4±10.2 (5)	*	120.1 ± 26.1 (5)	3.5 ± 0.5 (2)	*	*
Agroforestry	190[‡]	38.6 (1)	*	4.7 ± 2.2 (15)	*	*	*
Total agricultural lands[2]	479.2	23.0 ± 8.5[$]	19.5 ± 5.6[$]	4.5 ± 2.2[$]	*	25.6 ±12.4[$]	13.5 ± 3.4 (23.7%)[††]
Total natural ecosystems and agricultural lands[3]	1931.7						56.9 ± 12.7

[#] GlobCover 2009

[†] 0.07% of savanna and rainforest (Brümmer et al., 2009)

[##] FAO STAT (http://faostat3.fao.org/home/E), year 2012

[*] No data available

[$] Area weighted average

[‡] Zomer et al., 2009

[††] Contribution to CO_2 eq. emission in total natural and agricultural lands

[1] except salt pan

[2] except vegetable gardens and agroforestry

[3] except salt pan, vegetable gardens and agroforestry

~~Table 2~~Table 2 Correlation between annual soil CO_2 emissions (Mg CO_2 ha^{-1} yr^{-1}) and environmental factors in African natural terrestrial systems

	Annual mean Air temperature (^{o}C)	Annual rainfall (mm)	Soil organic carbon (%)	Soil total nitrogen (%)
Correlation coefficient	-0.322	0.518	0.626	0.849
P- value	0.01	< 0.001	< 0.001	< 0.001
Number of samples	60	61	31	26

Table 3 Summary of the effect of management practices on greenhouse gas (GHG) emissions. + indicates increasing, · indicates no change, and – indicates decreasing.

Land use/ecosystem type	Management practices	Impact on GHG			Country (data source)
		CO_2	N_2O	CH_4	
Forest/ plantation/ Woodland	Burning	+			Ethiopia (Andersson et al., 2004)
	Thinning	+			Ethiopia (Yohannes et al., 2013)
	Land use change (cleaning and conversion to croplands)	+	+	+	Zimbabwe (Mapanda et al., 2012; Mapanda et al., 2010)
	Flooding			+	Cameroon (Macdonald et al., 1998); Republic of Congo (Tathy et al., 1992); Mali (Delmas et al., 1991)
Savannah/grassland	Burning	·	·	·	Republic of Congo (Castaldi et al., 2010; Delmas et al., 1991); South Africa (Zepp et al., 1996)
	Land use change (cleaning and conversion to croplands)	+			^{1}Republic of Congo (Nouvellon et al., 2012)
Croplands	Increase in N fertilization rate		+		Kenya (Hickman et al., 2015)
	Type of synthetic fertilizer		·		Madagascar (Rabenarivo et al., 2014)
	Application of plant residues		–		Tanzania (Sugihara et al., 2012); ^{2}Madagascar (Rabenarivo et al., 2014)
		+	+		Kenya (Kimetu et al., 2006); ^{3}Ghana (Frimpong et al. 2012)
	Crop residues + N fertilizer		+		^{4}Zimbabwe (Nyamadzawo et al., 2014a,b)
			–		^{5}Zimbabwe, Ghana and Kenya (Gentile et al., 2008)
	Combination of synthetic and organic fertilizers	+	–		^{6}Zimbabwe (Mapanda et al., 2011)
			–		^{7}Mali (Dick et al., 2008)
	Crop type	·			^{8}Uganda (Koerber et al., 2009)
			–		^{9}Zimbabwe (Masaka et al., 2014)
	Introducing N fixing crops in rotations		–		Mali (Dick et al., 2008)
	Direct seeding mulch-based		·		Madagascar (Chapuis-Lardy et al., 2009)
	Hand-ploughing after harvesting		·		Madagascar (Chapuis-Lardy et al., 2009)
	Intensive grazing	+			Botswana (Thomas, 2012)
	Reduced tillage + mulch, leguminous crop/tree, or N fertilizer	+	+	+; –	Tanzania (Kimaro et al., 2015)
Vegetable gardens	Plastic cover for ruminant manure		–		Niger (Predotova et al. 2010)

Formatted: Font color: Auto

Formatted: Font color: Auto

Formatted: Font color: Auto

Formatted: Font color: Auto

Formatted: Font color: Auto

Formatted Table

Formatted: Font color: Auto

	Incorporation of fallow residues		+		Kenya (Baggs et al., 2006; Millar and Baggs, 2004; Millar et al., 2004)
Agroforestry	Improving fallow with N-fixing crops		+		Zimbabwe (Chikowo et al., 2004)
	Cover crops		+		Kenya (Millar et al., 2004)
	N-fixing tree species	+	+		Malawi (Kim, 2012; Makumba et al., 2007); Senegal (Dick et al., 2006)

[1] U+DAP instead U+NPK; [2] N_2O study; [3] Low C:N ratio clover residues compared to high C:N ratio barley residues; [4] Application of ammonium nitrate with manure to maize (*Zea mays* L.) and winter wheat (*Triticumaestivum* L.) plant residues; [5] Plant residues of maize, calliandra, and tithonia + urea; [6] Mixed application of composted manure and inorganic fertilizer (AN); [7] Manure and urea; [8] Lettuces vs cabbages vs beans; [9] Tomatoes vs rape

Formatted: Font color: Auto

Formatted: Font color: Auto

Formatted: Font color: Auto

Formatted: Font color: Auto

Formatted: Font color: Auto

Formatted: Font color: Auto

Formatted: Font color: Auto

Formatted: Font color: Auto

Figure captions

Figure 1. Change of areas of agricultural land and forest in Africa. Data source: FAOSTAT, http://faostat.fao.org/site/377/default.aspx#ancor, Access 23 April 2015.

Figure 2. ~~Change of use of urea fertiliser in Africa. Data source: FAOSTAT, http://faostat.fao.org/site/422/default.aspx#ancor, Access 23 April 2015.~~Maps showing study sites of CO_2, CH_4 and N_2O fluxes

~~Figure 3. Trends of African livestock population. Data source: FAOSTAT, http://faostat3.fao.org/faostat-gateway/go/to/download/Q/QA/E, Access 23 April 2015.~~

~~Figure 4. Maps showing study sites of CO_2, CH_4 and N_2O fluxes~~

~~Figure 5.~~

Figure 3. Relationship between nitrogen (N) input and nitrous oxide (N_2O) emissions observed in Africa. N input ranged from 0 to 300 (A), 300 to 4000 (B) and 0 to 4000 kg N ha^{-1} yr^{-1} (C). The dashed lines indicate 95% confidence intervals. *Control* indicates no fertilizer application, *Organic fertilizer* is manure, *Inorganic fertilizer* includes NPK, ammonium nitrate and urea fertilizers, and *Mixture* indicated mixed application of organic and inorganic fertilizers.

Figure ~~6~~4. Relationship between nitrogen (N) input and yield scaled nitrous oxide (N_2O) emissions. Grain type: (A) rape (*Brassica napus*) and (B) and (C) maize (*Zea mays* L.). Data sources: (A) from Nyamadzawo et al. (2014), (B) from Hickman et al. (2014) and (C) from Hickman et al. (2015). The dashed lines indicate 95% confidence intervals. Note the different scales across panels.

Formatted: Font color: Auto

Formatted: Font color: Auto

Formatted: No underline, Font color: Auto, English (U.S.)

Formatted: Default Paragraph Font, English (U.S.)

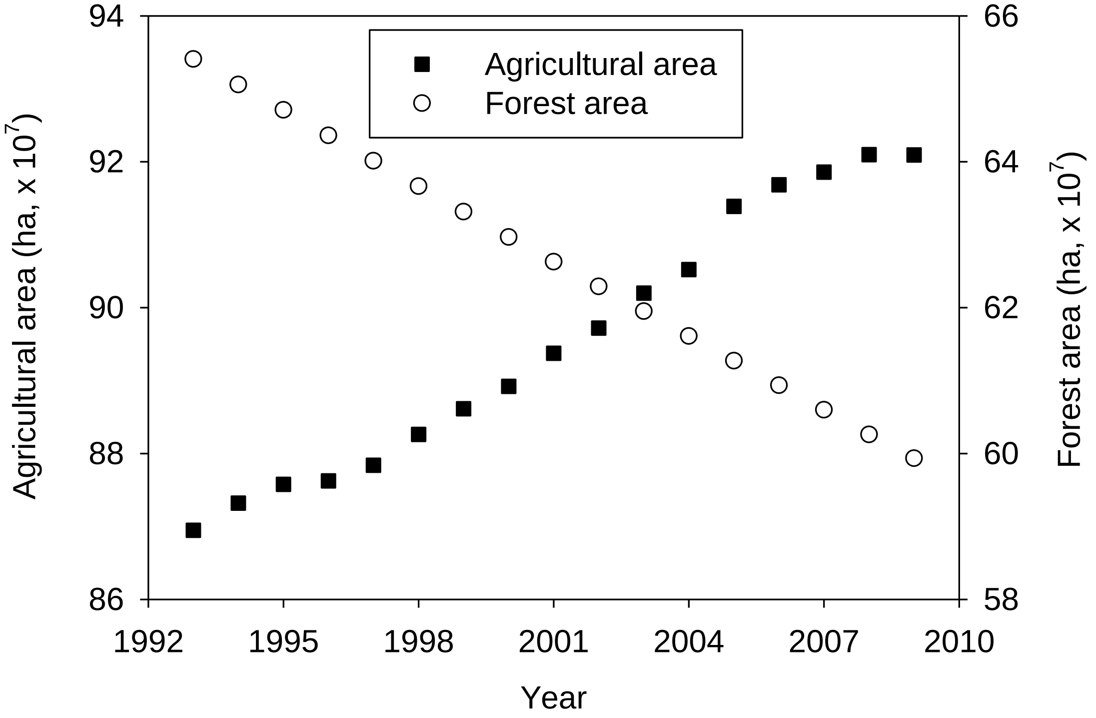
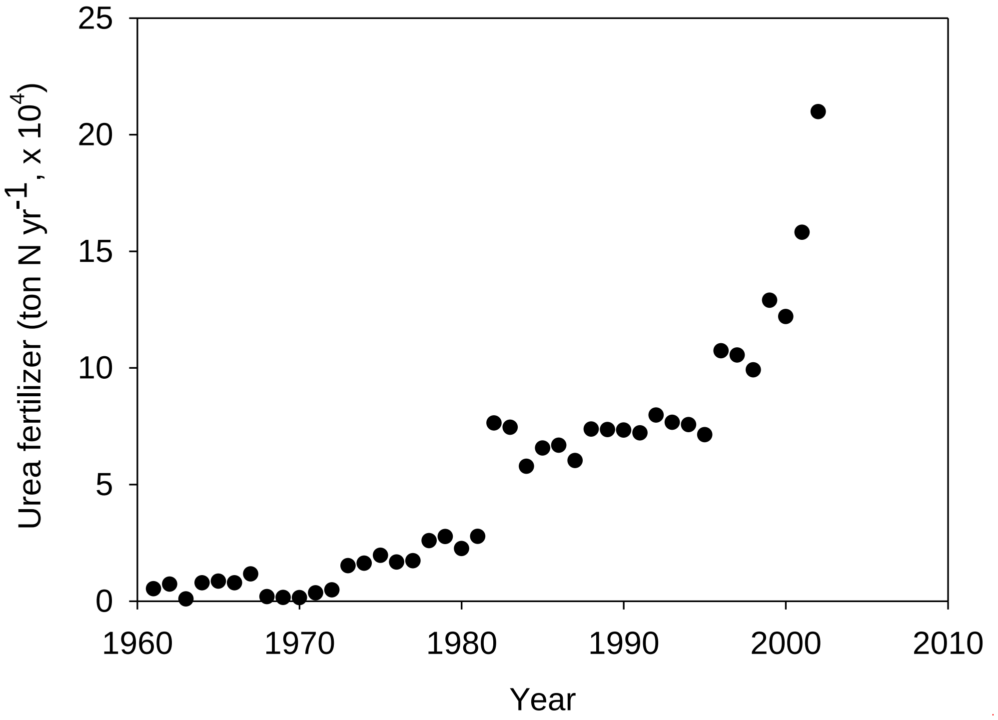

Agricultural area
Forest area
Agricultural area (ha, x 10^7)
Forest area (ha, x 10^7)
94
92
90
88
86
66
64
62
60
58
1992
1995
1998
2001
2004
2007
2010
Year

Figure 1



Formatted: English (U.K.)

Formatted: No underline, Font color: Auto

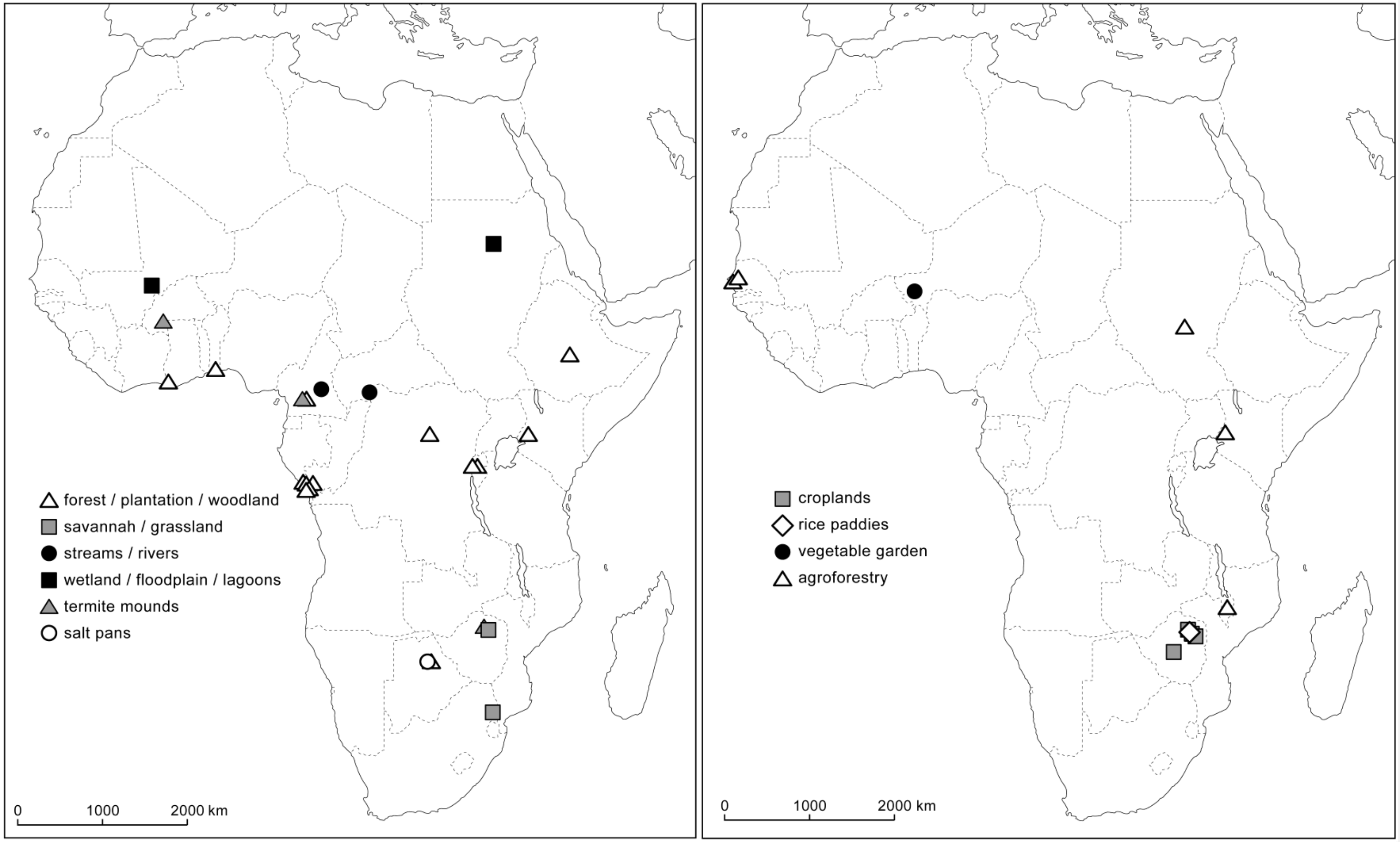
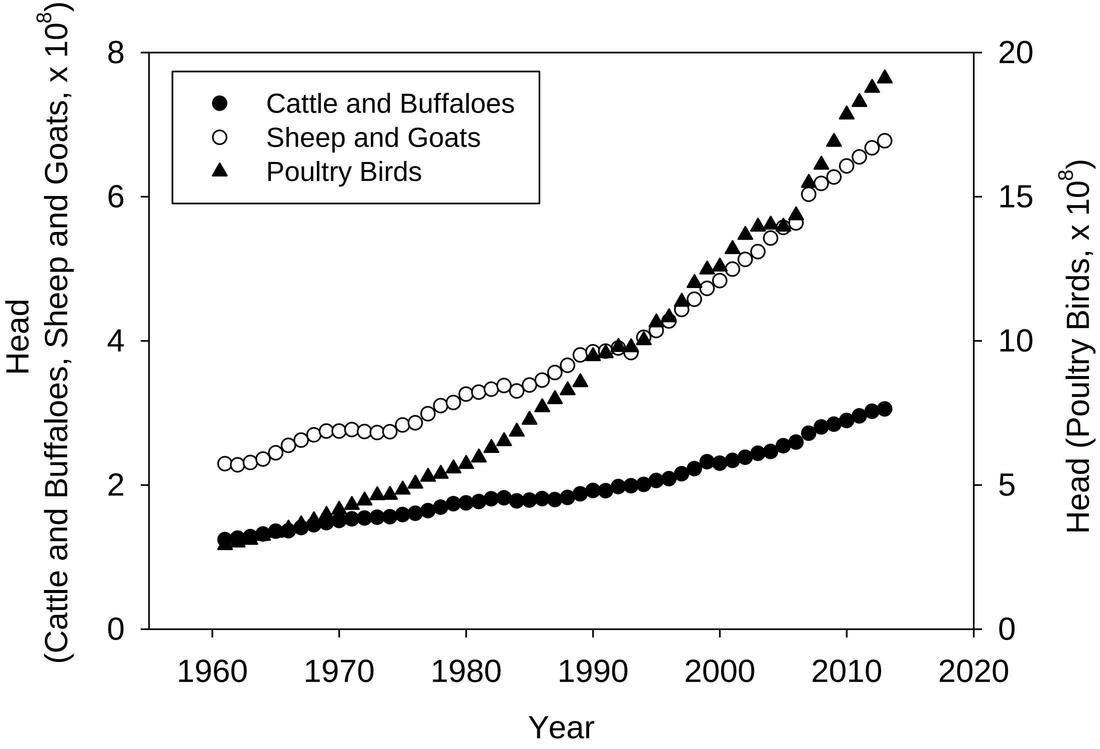


Figure 2

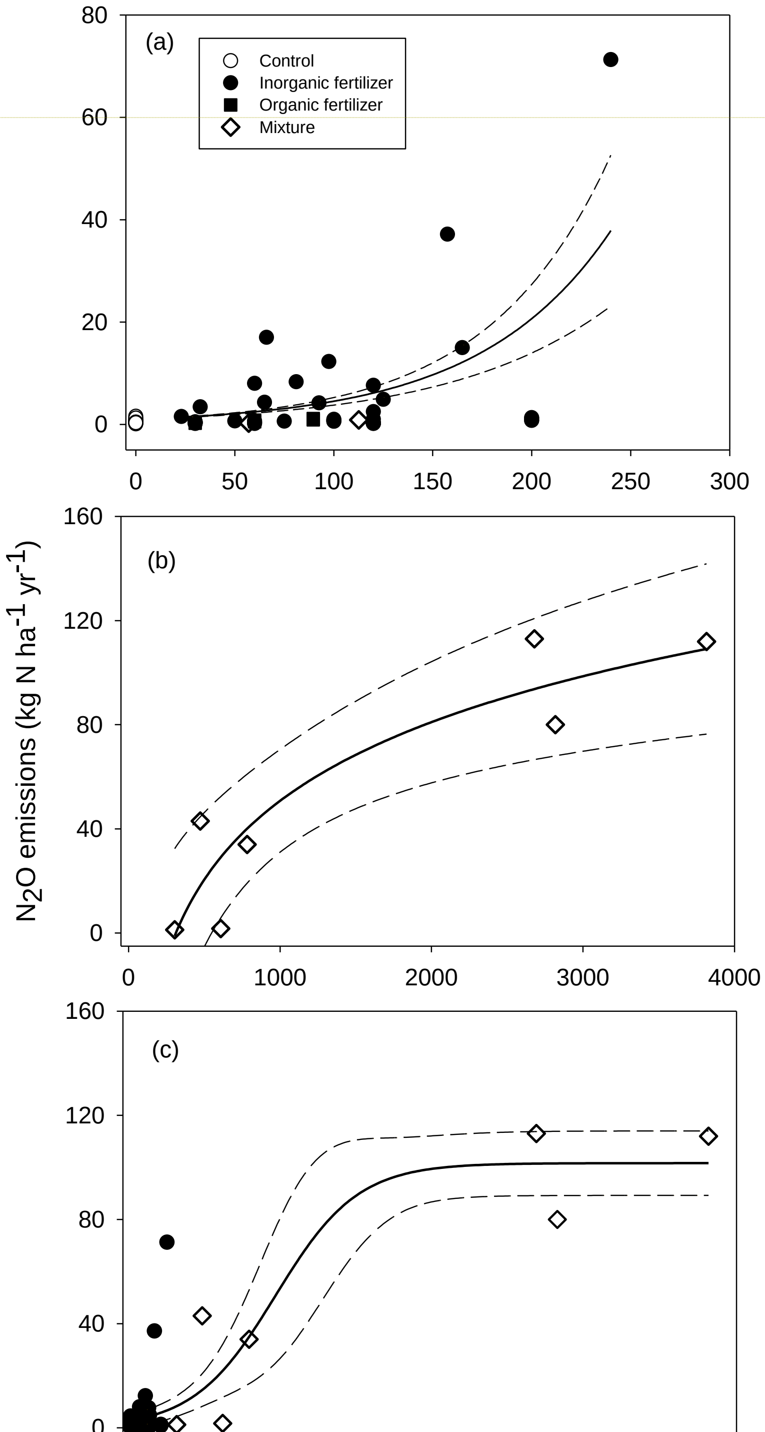
Formatted: Font: (Asian) Times New Roman, No underline, Font color: Auto

Formatted: No underline, Font color: Auto, English (U.S.)

Formatted: English (U.S.)

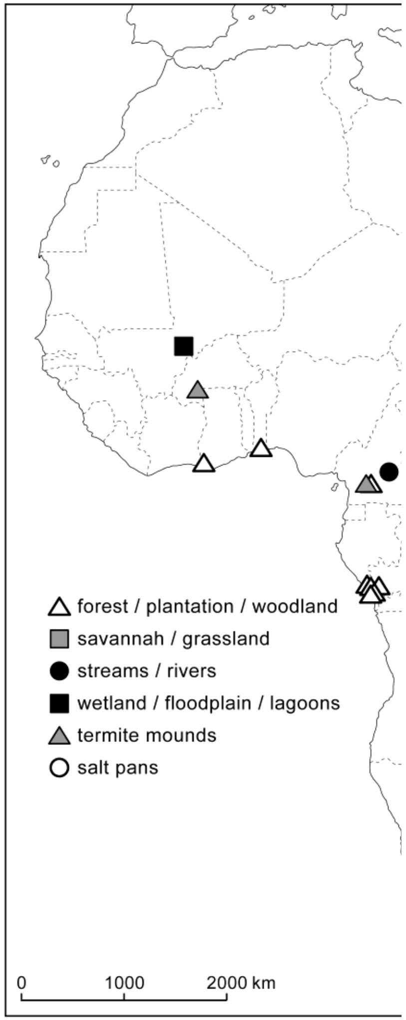


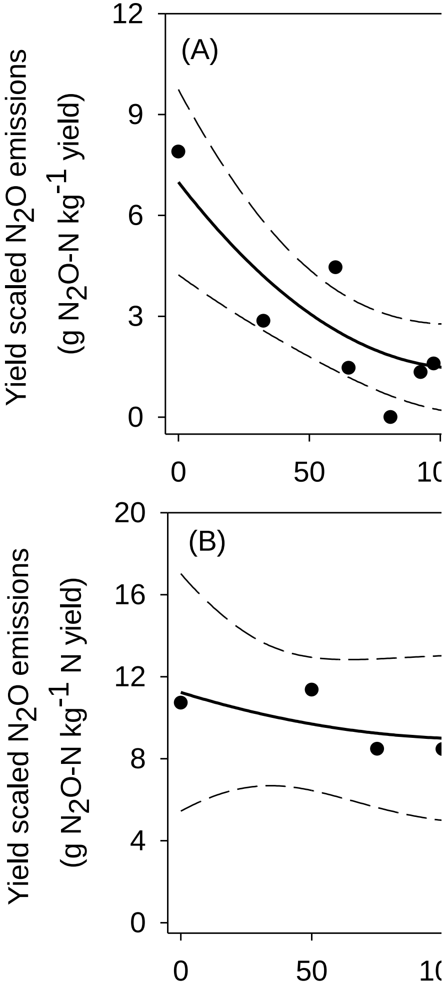
Formatted: No underline, Font color: Auto

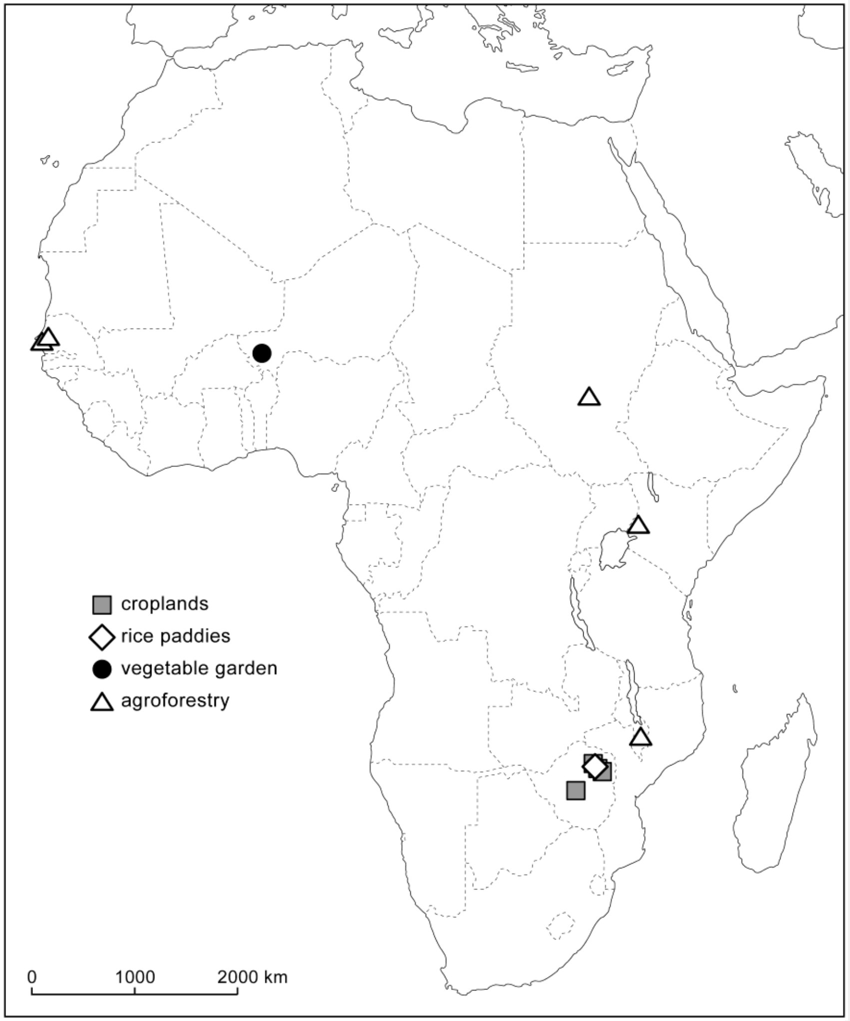


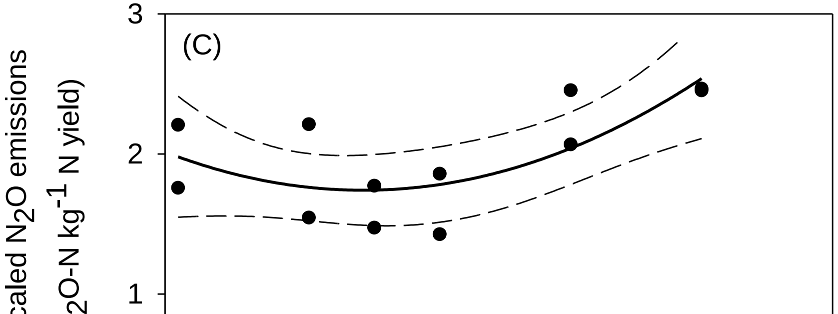
Formatted: No underline, Font color: Auto

Figure 3





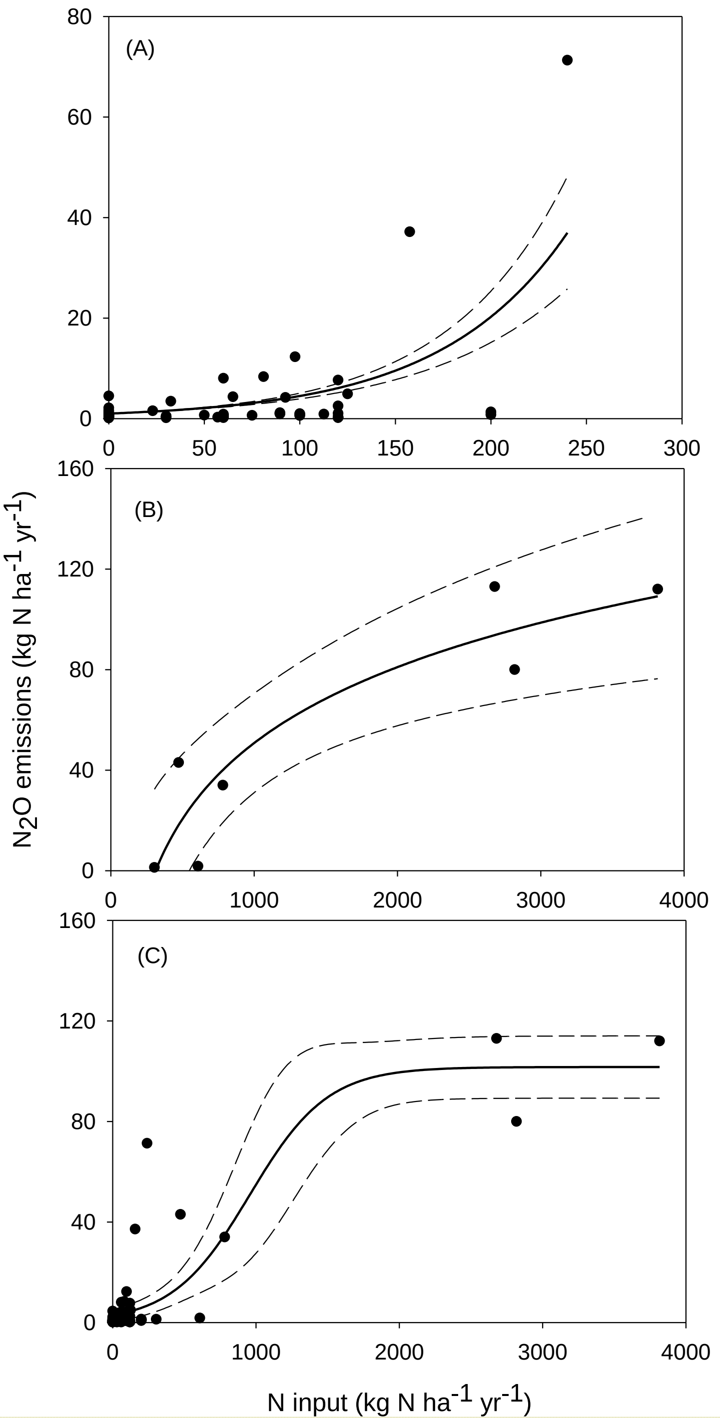




Formatted: Font: (Asian) Times New Roman, No underline, Font color: Auto

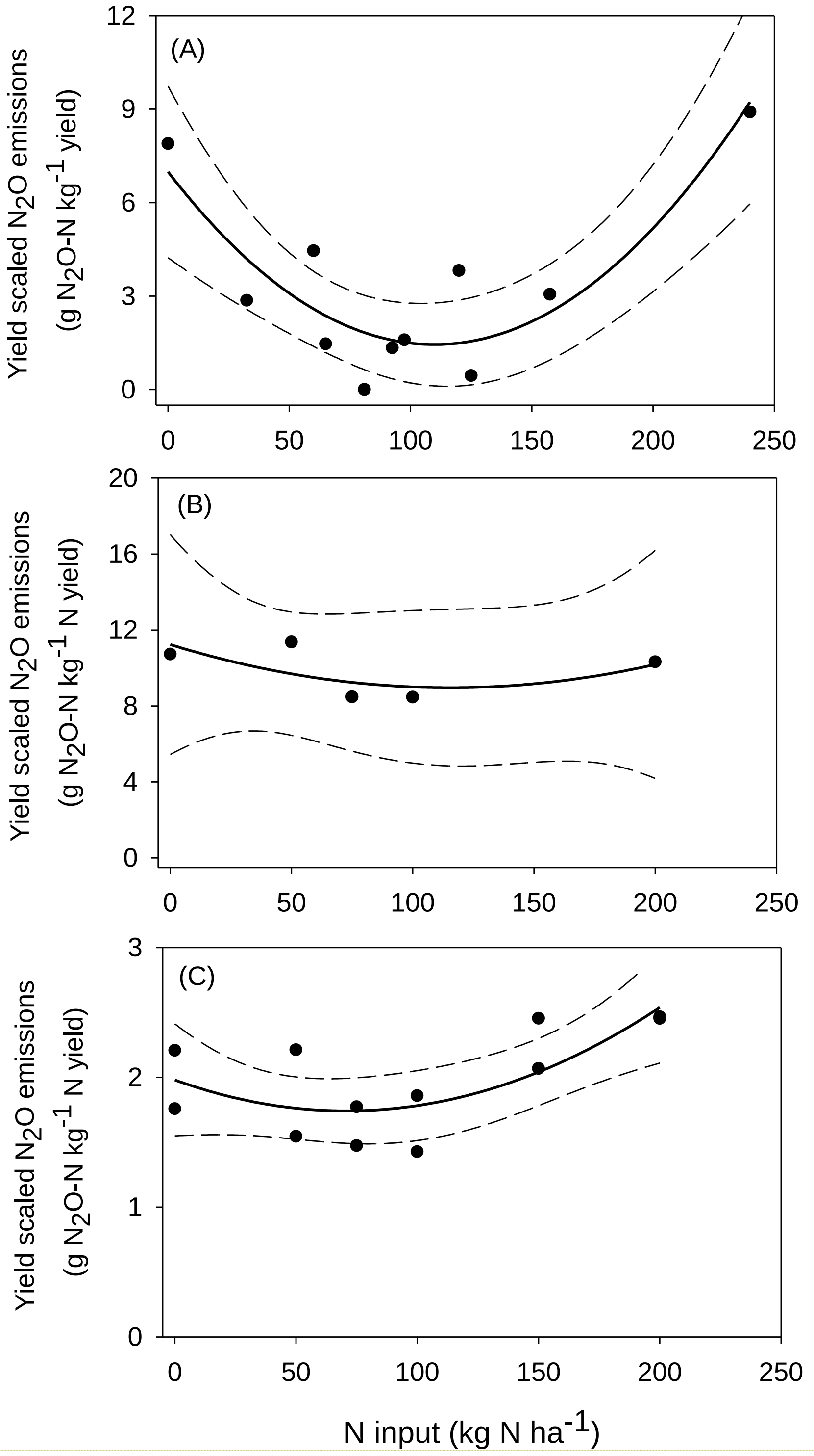
Figure 4

Formatted: No underline, Font color: Auto, English (U.K.)



~~Figure 5~~

Formatted: No underline, Font color: Auto



~~Figure 6~~

Formatted: No underline, Font color: Auto

Supplementary Information (SI)

Table S1 Summary of greenhouse gas carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions and N_2O emission factor (%) in natural ecosystems. More detail information is available in 'Soil greenhouse gas emissions in Africa database' (http://ghginafrica.blogspot.com/).

Ecosystem type	~~Country~~Quality check†	~~Temp~~Location	~~Rainfall~~Temp	~~CO_2 (Mg CO_2 ha^{-1} y^{-1})~~Rainfall	~~CH_4 (kg CH_4~~CO_2 (Mg CO_2 ha^{-1} y^{-1})	~~N_2O~~ CH_4 (kg ~~N_2O~~CH_4 ha^{-1} y^{-1})	N_2O ~~emission factor (%)~~ (kg N_2O ha^{-1} y^{-1})	Reference
Forest/ plantation/ woodland	~~Benin~~-	~~27~~Benin	~~1200~~27	~~57~~1200	~~*~~57	~~*~~ *	*	Lamade et al., 1996
Forest/ plantation/ woodland	~~Botswana~~-	~~*~~Botswana	~~*~~ *	~~13.8~~*	~~*~~13.8	~~*~~ *	*	Thomas et al., 2014
Forest/ plantation/ woodland	~~Cameroon~~-	~~23.8~~Cameroon	~~1513~~ 23.8	~~*~~1513	~~-4.8 to 0.2~~*	~~*~~ -4.8 to 0.2	*	Macdonald et al., 1998
Forest/ plantation/ woodland	~~Ethiopia~~+	~~15~~Ethiopia	~~1200~~ 15	~~15.7 to 19.4~~1200	~~*~~ 15.7 to 19.4	*	*	Yohannes et al., 2011
Forest/ plantation/ woodland	~~Ghana~~*	~~25~~Ghana	~~1750~~25	~~*~~ 1750	*	~~3.6~~*	~~*~~3.6	Castaldi et al., 2013
Forest/ plantation/ woodland	~~Kenya~~+	~~23.3~~Kenya	~~1662~~ 23.3	~~20.2~~1662	~~–~~20.2~~.9~~	~~4.1~~ -2.9	~~*~~4.1	Werner et al., 2007
Forest/ plantation/ woodland	~~Republic of Congo~~?	~~24.4~~Republic of Congo	~~1875~~ 24.4	~~11.4 to 15.2~~1875	~~*~~11.4 to 15.2	~~*~~ *	*	Maldague and Hilger, 1963
Forest/ plantation/ woodland	~~Republic of Congo~~-	~~25~~Republic of Congo	~~1200~~ 25	~~*~~1200	~~-3.7 to 3.4~~*	~~-0.1~~-3.7 to ~~0.1~~3.4	~~*~~ -0.1 to 0.1	Castaldi et al., 2010
Forest/ plantation/ woodland	~~Republic of Congo~~-	~~25.3~~Republic of Congo	~~1400~~ 25.3	~~*~~1400	*	~~4.6~~*	~~*~~ 4.6	Serca et al., 1994
Forest/ plantation/ woodland	~~Republic of Congo~~*	~~25~~Republic of Congo	~~1200~~ 25	~~13.3~~1200	~~*~~13.3	*	*	Epron et al., 2004
Forest/ plantation/ woodland	~~Republic of Congo~~*	~~25~~Republic of Congo	~~1400~~ 25	~~9.1 to 15.7~~1400	~~*~~9.1 to 15.7	*	*	Epron et al., 2006
Forest/ plantation/ woodland	~~Republic of Congo~~*	~~25~~Republic of Congo	~~1274~~ 25	~~23.9 to 24.3~~1274	~~*~~23.9 to 24.3	*	*	Nouvellon et al., 2008
Forest/ plantation/ woodland	~~Republic of Congo~~*	~~25~~Republic of Congo	~~1266~~ 25	~~17.2 to 27.1~~1266	~~*~~17.2 to 27.1	*	*	Nouvellon et al., 2012
Forest/ plantation/ woodland	~~Republic of Congo~~ *	~~25.7~~Republic of Congo	~~1430~~ 25.7	~~50.6 to 74.1~~1430	~~*~~50.6 to 74.1	*	*	Epron et al., 2013
Forest/ plantation/ woodland	~~Republic of Congo~~ *	~~25~~ Republic of Congo	~~1350~~25	~~29.3 to 130.9~~1350	~~*~~ 29.3 to 130.9	*	*	Versini et al., 2013
Forest/ plantation/ woodland	~~Rwanda~~ *	~~21~~Rwanda	~~1246~~ 21	~~11.8 to 14.8~~1246	~~*~~11.8 to 14.8	*	*	Nsabimana et al., 2009
Forest/ plantation/ woodland	~~Rwanda~~ -	~~17~~Rwanda	~~1660~~17	~~*~~1660	*	~~6.4 to 13.7~~*	~~*~~ 6.4 to 13.7	Gharahi Ghehi et al., 2012

Formatted ...
Formatted ...
Formatted ...
Formatted Table ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted

Forest/ plantation/ woodland	~~Zimbabwe~~ -	~~*~~ Zimbabwe	*	*	~~-1.2 to 2.0~~*	~~*~~-1.2 to 2.0	*	Mapanda et al., 2010
Savannah/grassland	~~Botswana~~-	~~*~~Botswana	*	~~8.0~~*	~~*~~8.0	*	*	Thomas et al., 2014
Savannah/grassland	~~Botswana~~ +	~~21.0 to 23.5~~Botswana	~~331~~21.0 to 23.5	~~3.3 to 6.4~~331	~~*~~3.3 to 6.4	*	*	Thomas, 2012
Savannah/grassland	~~Burkina Faso~~+	~~29.5~~Burkina Faso	~~926~~29.5	~~14.1 to 21.3~~926	~~2.8~~14.1 to 21.3~~.5~~	~~*~~2.8 to 3.5	*	Brümmer et al., 2009
Savannah/grassland	~~Ghana~~-	~~26.5~~Ghana	~~787~~26.5	~~*~~787	~~-1.1 to 0.3~~*	~~*~~-1.1 to 0.3	*	Prieme and Christensen, 1999
Savannah/grassland	~~Mali~~-	~~27.6~~Mali	~~1100~~27.6	~~*~~1100	~~-0.2~~*	~~*~~-0.2	*	Delmas et al., 1991
Savannah/grassland	~~Republic of Congo~~*	~~25~~Republic of Congo	~~1200~~25	~~32.5 to 39.7~~1200	~~*~~32.5 to 39.7	*	*	Caquet et al., 2012
Savannah/grassland	~~Republic of Congo~~-	~~23.6~~Republic of Congo	~~1600~~23.6	~~3.7 to 4.3~~1600	~~-2.2~~3.7 to ~~-2~~4.3	~~*~~-2.2 to -2.3	*	Delmas et al., 1991
Savannah/grassland	~~South Africa~~*	~~17.9~~South Africa	~~740~~17.9	~~*~~740	~~0.3 to 2.5~~*	~~*~~0.3 to 2.5	*	Zepp et al., 1996
Savannah/grassland	~~South Africa~~*	~~*~~South Africa	~~550~~*	~~12.9 to 24.2~~550	~~*~~12.9 to 24.2	*	*	Fan et al., 2015
Savannah/grassland	~~Zimbabwe~~ -	~~17.5 to 18.5~~Zimbabwe	~~760~~17.5 to ~~840~~18.5	~~*~~760 to 840	*	~~0.3 to 0.8~~*	~~*~~0.3 to 0.8	Reese et al., 2006
Streams/rivers	~~Botswana~~nd	~~*~~Okavango Delta, Botswana	*	*	~~2741.9~~*	~~*~~2741.9	*	Gondwe and Masamba, 2014
Streams/rivers	~~Cameroon~~nd	~~*~~Nyong basin, Cameroun	*	~~54.5 to 66.0~~*	~~*~~54.5 to 66.0	*	*	Brunet et al., 2009
Streams/rivers	~~Central African Republic~~nd	~~*~~Oubangui River (Congo River basin)	~~1500~~*	~~5.7~~1500	5.7	~~0.2~~5.7	~~*~~0.2	Bouillon et al., 2012
Streams/rivers	~~Ivory Coast~~nd	~~*~~Ivory Coast	*	~~7.9 to 27.3~~*	~~58.6~~7.9 to ~~97.4~~27.3	~~*~~58.6 to 97.4	*	Kone et al., 2009; Borges et al., 2015
Streams/rivers	nd	Ivory Coast	1500 to 1800	*	*	8.8 to 16.4	*	Koné et al., 2010
Streams/rivers	~~Gabon~~nd	~~*~~Gabon	*	*	~~123.5 to 272.6~~*	~~2.1~~123.5 to ~~4.5~~272.6	~~*~~2.1 to 4.5	Borges et al., 2015
Streams/rivers	~~Kenya~~nd	~~*~~Kenya	*	~~29.9 to 49.1~~*	~~33.2~~29.9 to ~~80.2~~49.1	~~1.0~~33.2 to ~~4.5~~80.2	1.0 to 4.5	Borges et al., 2015
Streams/rivers	~~Madagascar~~nd	~~*~~Madagascar	*	~~31.2 to 84.0~~*	~~76~~31.2 to ~~265~~84.0	~~0.6~~76.2 to ~~1.9~~265.0	0.6 to 1.9	Borges et al., 2015
Streams/rivers	~~Republic of Congo~~nd	~~*~~Congo River	*	~~49.5 to 228.9~~*	~~29.3~~49.5 to ~~1082.4~~228.9	~~0.6~~29.3 to ~~3.1~~1082.4	~~*~~0.6 to 3.1	Wang et al., 2013; Mann et al., 2014; Borges et al., 2015
Streams/rivers	~~Zambia~~nd	~~*~~Zambezi River	~~1450~~*	~~39.6 to 67.6~~1450	~~97.3~~39.6 to ~~793.0~~67.6	~~0~~97.3 to 793.0	~~*~~0.3	Teodoru et al., 2015; Borges et al., 2015
Wetlands/floodplains/lagoons /reservoir/lake	~~Zambia~~nd	~~*~~Zambezi River	~~1450~~*	~~-4.8 to 9.9~~1450	~~6-~~4.8 to ~~125.6~~9.9	6.8 to 125.6	*	Teodoru et al., 2015

Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted Table ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...
Formatted ...

Wetlands/floodplains/lagoons /reservoir/lake	~~Botswana~~nd	~~*~~Okavango Delta, Botswana	*	*	~~1480.4 to 1787.0~~*	~~*~~1480.4 to 1787.0	*	Gondwe and Masamba, 2014
Wetlands/floodplains/lagoons /reservoir/lake	~~Ivory Coast~~nd	~~*~~Ivory Coast	*	~~-11.9 to 161.7~~*	~~*~~-11.9 to 161.7	*	*	~~Kone~~Koné et al., 2009
Wetlands/floodplains/lagoons /reservoir/lake	~~Republic of Congo~~nd	~~*~~Congo River	*	*	~~246.4~~*	~~*~~246.4	*	Tathy et al., 1992
Wetlands/floodplains/lagoons /reservoir/lake	~~Mali~~nd	~~*~~Mali	*	*	~~3.1~~*	~~*~~3.1	*	Delmas et al., 1991
Wetlands/floodplains/lagoons /reservoir/lake	~~Zimbabwe~~nd	~~*~~Zimbabwe	*	~~65.0 to 232.0~~*	~~-26.3~~65.0 to ~~1235.2~~232.0	~~0.5~~-26.3 to ~~3.5~~1235.2	~~*~~0.5 to 3.5	Nyamadzawo et al., 2014
Wetlands/floodplains/lagoons /reservoir/lake	nd	Lake Kivu	*	*	1.7 to 85.8	2.1 to 6.0	*	Borget et al., 2011 and 2014
Wetlands/floodplains/lagoons /reservoir/lake	nd	Lake Kariba	*	*	*	11 to 7665	*	Delsontro T et al., 2011
Wetlands/floodplains/lagoons /reservoir/lake	nd	Ivory Coast	*	1500 to 1800	*	4.4 to 19.3	*	Koné et al., 2010
Termite mound	~~Burkina Faso~~+	~~29.5~~Burkina Faso	~~926~~29.5	~~13.5 to 21.3~~926	~~3.0~~13.5 to 21.3~~.7~~	~~*~~3.0 to 3.7	*	Brümmer et al., 2009
Termite mound	~~Zimbabwe~~-	~~18~~Zimbabwe	~~850~~18	~~0.002~~850	0.~~1~~002	0.~~01~~1	~~*~~0.01	Nyamadzawo et al., 2012
Salt pan	~~Botswana~~-	~~*~~Botswana	*	~~0.7~~*	~~*~~0.7	*	*	Thomas et al., 2014

Symbols: +: methods are *good*; *: methods are *marginal*; -: methods are *poor to very poor*; ?: methods are unclear; nd: cannot comment due to no available criteria

Table S2 Summary of *in situ* carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) fluxes and N_2O emission factor (%) in agricultural ecosystems. More detail information is available in 'Soil greenhouse gas emissions in Africa database' (http://ghginafrica.blogspot.com/).

Ecosystem type	Quality check†	~~Country~~Location	Temperature (°C)	Rainfall (mm)	CO_2 (Mg CO_2 ha^{-1} y^{-1})	CH_4 (kg CH_4 ha^{-1} y^{-1})	N_2O (kg N_2O ha^{-1} y^{-1})	N_2O emission factor (%)	Reference
Croplands	+	Burkina Faso	29.5	926	9.2 to 16.5	-0.9	*	*	Brümmer et al., 2009

Formatted: Centered
Formatted: Font: 10 pt
Formatted: Centered
Formatted: Font: 10 pt
Formatted: Centered
Formatted: Font: 10 pt
Formatted: Font: 10 pt
Formatted: Centered
Formatted: Centered
Formatted: Font: 10 pt
Formatted: Centered
Formatted Table
Formatted: Font: 10 pt
Formatted: Centered
Formatted: Font: 10 pt
Formatted: Centered
Formatted: Font: 10 pt
Formatted Table
Inserted Cells

Croplands	+	Kenya	*	1750	*	*	1.0 to 1.3	*	Hickman et al., 2014
Croplands	+	Kenya	*	1750	*	*	0.2 to 0.5	0.01 to 0.1	Hickman et al., 2015
Croplands	+	Madagascar	16	1300	*	*	0.4	0.47	Chapuis-Lardy et al., 2009
Croplands	+	Malawi	24	930	15.0	*	*	*	Kim, 2012
Croplands	-	Mali	27.6	1100	*	*	0.9 to 2.4	0.3 to 4.1	Dick et al., 2008
Croplands	-	Republic of Congo	23.6	1600	1.7 to 3.7	-1.3 to -1.8	*	*	Delmas et al., 1991
Croplands	-	Senegal	29.7	670	*	*	0.05 to 0.1	*	Dick et al., 2006
Croplands	+	Tanzania	24.5	626 to 905	3.4 to 14.8	*	*	*	Sugihara et al., 2012
Croplands	+	Tanzania	*	*	17.6 to 20.2	-1.7 to 5.6	0.6 to 1.1		Kimaro et al., 2015
Croplands	*	Uganda	21.9	1224	111.1 to 141.2	*	*	*	Koerber et al., 2009
Croplands	*	Zimbabwe	19.1	940	*	*	0.5 to 1.4	*	Rees et al., 2012
Croplands	*	Zimbabwe	*	*	*	*	0.9 to 7.1	*	Chikowo et al., 2004
Croplands	*	Zimbabwe	19.1	940	*	*	0.3 to 0.8	*	Rees et al. 2013
Croplands	-	Zimbabwe	*	*	*	*	0.5	*	Mapanda et al., 2010
Croplands	-	Zimbabwe	18.6	750	19.0 to 44.9	13.4 to 66.7	0.3 to 112.0	*	Nyamadzawo et al., 2014b
Croplands	-	Zimbabwe	18.9	748	1.9 to 10.4	-0.04 to 49.1	0.2 to 3.9	*	Mapanda et al., 2012
Croplands	*	Zimbabwe	21	725	*	*	0.5 to 2.7	0.3 to 1.0	Masaka et al., 2014
Croplands	-	Zimbabwe	*	*	*	3.2 to 11.9	0.8 to 3.5	*	Mapanda et al., 2010
Rice paddy	-	Zimbabwe	18.6	750	6.5	12.5	0.2	*	Nyamadzawo et al., 2013
Vegetable gardens	*	Burkina Faso	27	900	80.7 to 132.0	*	125.7 to 177.6	*	Lompo et al., 2012
Vegetable gardens	*	Niger	30.3	542	73.3 to 100.8	*	53.4 to 176.0	*	Predotova et al., 2010
Agroforestry	-	Senegal	25.8	370	*	*	0.2 to 2.7	*	Dick et al., 2006
Agroforestry	*	Sudan	28.2	698	*	*	23.6 to 26.7	*	Goenster et al., 2014
Agroforestry	+	Kenya	24	1880	*	*	0.3 to 6.4	*	Millar et al., 2004
Agroforestry	+	Malawi	24	930	38.6	*	*	*	Kim, 2012

†Symbols: +: methods are *good*; *: methods are *marginal*; -: methods are *poor to very poor*.

Formatted: Space After: 0 pt, Line spacing: single

Formatted: Font: Not Bold, Font color: Auto