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 CO₂ 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 CO₂ emissions) to show that observed annual soil CO₂ 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 CO2 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 CO2 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 CO2 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 CO2 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 (N2O) emissions observed in Africa (Figure 3.). Second, we found relationship between nitrogen (N) input and yield scaled nitrous oxide (N2O) 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$_2$O 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$_2$O emissions in vegetable gardens due to excessive N input to get high yields, increased CO$_2$ and N$_2$O emission in incorporation of crop residues to the soil and agroforestry practices, and exponential increased of N$_2$O emission and yield-scaled N$_2$O 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 exceeding 100 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. CO₂, CH₄ and N₂O) 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 CO₂ 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 CO₂ emissions and annual mean air temperature in this study since positive relation between soil CO₂ 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 CO₂ flux. This would account for the negative relationship we observed between annual mean air temperature and annual soil CO₂ 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 CO₂ flux with soil and environmental factors. We found an unexpected result showing negative relation between annual soil CO₂ 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. CO₂ emissions). However, due to the dearth of data for above- and belowground C inputs, it was not feasible to test the relationship between soil CO₂ 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 N₂O 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, CH₄ 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 N₂O 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 CO₂ (e.g., autotrophic and heterotrophic sources), CH₄ (e.g., methanogenesis and methanotrophy) and N₂O (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 CO₂ 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 CO₂ emissions) to show that observed annual soil CO₂ 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$_2$O 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 CH₄ and N₂O emissions in CO₂ eq may have advantage and disadvantage at the same time so it can be applied depending on context. Providing CO₂ eq for CH₄ and N₂O gases would be convenient to compare them with CO₂ gas. However, it may cause unavoidable confusion to someone who wants to know the range of CH₄ and N₂O emissions. Considering the context in the referred line, we thought providing the values in both original units and CO₂ 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 CO₂ 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 CO₂ and N₂O- showing increase or decrease in CO₂ and N₂O 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 CO₂ and N₂O 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 CO₂ and N₂O emissions compared to conventional croplands. Type and quality of plant residue in the improving fallow is likely to be an important control factor affecting CO₂ and N₂O 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 CO₂ eq emissions from African natural ecosystems and agricultural lands were 56.9 ± 12.7 x 10⁹ Mg CO₂ 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), CO2 eq emission was calculated by adopting 100-year global warming potentials (GWPs) of 28 and 265 for CH4 and N2O, respectively and then summing CO2 emissions and GWPs of CH4 and N2O emissions. The method has been used in many other studies including a recent study (Tian et al., 2016, Nature).

We provided a modified unit (CO2 eq per year) by multiplying 44/12 as below:

0.9 Pg C per year x (44/12) = 3.3 Pg CO2 eq per year

Reference

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 CO2 emissions. All CO2 emissions were expressed as unit of Mg CO2 throughout the text. In case of N2O and CH4 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$_2$O 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$_2$O source in agricultural lands was vegetable gardens followed by agroforestry, cropland and rice fields (Table 1). The N$_2$O 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$_2$O EF of cropland is lower and the N$_2$O EF of vegetable gardens is higher than IPCC default N$_2$O 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$_2$O and CH$_4$ gases, some values were not large enough to apply 'Mg' unit so they were expressed as 'kg'.

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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 biogeochemistry (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**


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

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Abstract

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Acknowledgements

Reference
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 (-0.016 to 0.12 Mg CO$_2$ equivalent (eq) ha$^{-1}$ yr$^{-1}$) and nitrous oxide (N$_2$O) 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$_2$O 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$_2$O ha$^{-1}$ yr$^{-1}$ and the (0.015 to 33.4 Mg CO$_2$ eq ha$^{-1}$ yr$^{-1}$). N$_2$O emission 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 the magnitude and direction of changes were different for CO$_2$ and N$_2$O, as well as location. Soil GHG emissions from vegetable gardens ranged from 73.3 to 132.0 Mg CO$_2$ ha$^{-1}$ yr$^{-1}$ and 53.4 to 177.6 kg N$_2$O ha$^{-1}$ yr$^{-1}$ (15.9 to 52.9 Mg CO$_2$ eq ha$^{-1}$ yr$^{-1}$).
and N₂O EFs ranged from 3 to 4%. Soil CO₂ and N₂O emissions from agroforestry were 38.6 Mg CO₂ ha⁻¹ yr⁻¹ and 0.2 to 26.7 kg N₂O ha⁻¹ yr⁻¹ (0.06 to 8.0 Mg CO₂ eq ha⁻¹ yr⁻¹), respectively.

Improving fallow with nitrogen (N)-fixing trees led to increased CO₂ and N₂O emissions compared to conventional croplands. The type and quality of plant residue in the fallow is likely to be an important control factor affecting how CO₂ and N₂O emissions are affected. Throughout agricultural lands, N₂O 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 N₂O emissions were reported with N application rates ranging between 100 and 150 kg N ha⁻¹.

Overall, total CO₂ equivalent (eq) emissions from African natural ecosystems and agricultural lands were 56.9 ± 12.7 Gt CO₂ eq yr⁻¹ and natural ecosystems and agricultural lands contributed 76.3% and 23.7%, respectively. Additional GHG emission measurements throughout 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. There is also a need to develop a common strategy for addressing this data gap that may involve identifying priorities for data acquisition, utilizing appropriate technologies, and establishing 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 CO₂ eq in 2010 (IPCC, 2014), with approximately 21.2 – 24% (10.3 – 12 Gt CO₂ eq) of emissions originating from soils in agricultural, forestry and other land use (AFOLU) (Tubiello et al., 2015; IPCC, 2014). Annual non-CO₂ GHG emissions (primarily CH₄ and N₂O) from agriculture were estimated to be 5.2 – 5.8 Gt CO₂ eq yr⁻¹ in 2010 (FAOSTAT, 2014; Tubiello et al., 2013).
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 $10^9$ Mg CO$_2$ yr$^{-1}$ (Valentini et al., 2014) or 157.9 ± 23.9 Gt $10^9$ 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$3.3 \times 10^9$ Mg CO$_2$ eq per year, equivalent to about 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$_2$O fluxes in Africa drive large inter-annual variations in tropical and subtropical N$_2$O 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$_2$O 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 exceeding 100 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). 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. Only Mauritius, Botswana and South Africa had average N application rates exceeding 100 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\(_2\)O 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 savannas 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
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. CO₂, CH₄ and N₂O) 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 2376 studies, conducted in 22 countries (n=244) in SSA were used and were further categorized as GHG emission in natural land ecosystems [n=117; Supplementary Information (SI) Table 1] and agricultural lands (n=127; SI Table 2) (Fig. 42). The category of GHG emissions in natural land 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 paddies (n=1), vegetable garden (n=5), and agroforestry (n=16) (Table 1). Across all categories there were 174 CO₂, 201 CH₄ and 184 N₂O emissions measurements. To allow comparison between different GHG emissions CH₄ and N₂O emissions were converted to CO₂ eq assuming a 100 year global warming potential and values of 34 and 298 kg CO₂ eq for CH₄ and N₂O, respectively (IPCC, 2013). Where N₂O emission studies included experimental data from control plots with no N fertilizer additions (i.e. for background N₂O emissions) and from plots with different levels of applied N, a N₂O emission factor (EF) was calculated following the IPCC (2006) Tier I methodology as follows:

\[
N₂O \text{ EF}(\%) = \frac{N₂O \text{ emission}_{\text{treatment}} - N₂O \text{ emission}_{\text{control}}}{N_{\text{iput}}} \times 100
\]  [1]
where, $N_2O\ EF\ (%)$ is $N_2O$ emission factor, $N_2O\ emission_{\text{treatment}}$ is $N_2O$ emission in N input, $N_2O\ emission_{\text{control}}$ is control treatments with no N fertilizer additions, and $N_{\text{input}}$ 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
variability in 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 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 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

3.1. 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$^{-1}$ yr$^{-1}$ in natural terrestrial systems and from 11.9 to 3.5 Mg CH$_4$ ha$^{-1}$ yr$^{-1}$ to 13.7 kg N$_2$O in aquatic systems. The area weighted average was 27.6 ± 17.2 Mg CO$_2$ ha$^{-1}$ 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$^{-1}$ yr$^{-1}$. 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 Table 1).
Table 2). Vegetable gardens were the largest sources of CO$_2$ emissions, likely related to differences 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 ($r=0.849$, $P<0.001$) (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$_2$O emissions and emission factor (EF)
Nitrous oxide emissions in natural ecosystems ranged from 0.1 to 13.7 kg N$_2$O ha$^{-1}$ yr$^{-1}$ and the area weighted average was 2.5 ± 0.8 kg N$_2$O ha$^{-1}$ yr$^{-1}$ (Table 1 and SI Table 1). Our study reveals that forest, plantation and woodland were the largest source of N$_2$O followed by rivers and wetlands, savannah and termite mounds in natural ecosystems (Table 1). Soil N$_2$O emissions in agricultural lands ranged from 0.051 to 177.6 kg N$_2$O ha$^{-1}$ yr$^{-1}$ and the area weighted average was 4.5 ± 2.2 kg N$_2$O ha$^{-1}$ yr$^{-1}$ (Table 1 and SI Table 2). The largest N$_2$O source in agricultural lands was vegetable gardens followed by agroforestry, cropland and rice fields (Table 1). The N$_2$O 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$_2$O EF of cropland is lower and the N$_2$O EF of vegetable gardens is higher than IPCC default N$_2$O EF (1%, IPCC, 2006). The number of studies on N$_2$O 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$_2$O emissions were significantly affected by N input levels (Fig. 3). N$_2$O 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$_2$O emissions shows a sigmoidal pattern (Fig. 3 (C)). The observed relationship is consistent with the proposed hypothetical conceptualization of N$_2$O emission by Kim et al. (2013) showing a sigmoidal response of N$_2$O 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$_2$O emissions in Africa. The relationship between N input and N$_2$O emissions show that the lowest yield-scaled N$_2$O 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$_2$O emissions is not linear but exponential.
3.1.4 CO₂ eq emission

Carbon dioxide eq emission (including CO₂, CH₄ and N₂O) in natural lands ranged from 11.7 to 121.3 Mg CO₂ eq ha⁻¹ yr⁻¹ and the area weighted average of CO₂ eq emissions (excluding salt pans) was 29.9 ± 22.5 Mg CO₂ eq ha⁻¹ yr⁻¹ (Table 1). Water bodies or water submerged lands such as rivers and wetlands were the largest source of CO₂ 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 CO₂ eq ha⁻¹ yr⁻¹ and had an area weighted average of CO₂ eq emissions (excluding vegetable gardens and agroforestry due to lack of data) of 25.6 ± 12.4 Mg CO₂ eq ha⁻¹ yr⁻¹ (Table 1).

Total CO₂ eq emissions in natural lands (excluding salt pans) were 43.4 ± 9.3 x 10⁹ Mg CO₂ 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 CO₂ eq emissions in agricultural lands (excluding vegetable gardens and agroforestry) were 13.5 ± 3.4 x 10⁹ Mg CO₂ eq yr⁻¹ with crop land the largest source followed by rice fields (Table 1). Overall, total CO₂ eq emissions in natural ecosystems and agricultural lands were 56.9 ± 12.7 x 10⁹ Mg CO₂ 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
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 macrostachyus*, *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°C 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...
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$_2$O, 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$_2$O 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$_2$O 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$_2$O 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$_2$O 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
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). 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).

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, 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), while large pulses of CO$_2$ and N$_2$O, 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$_2$O 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$_2$O 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). 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$_2$O 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.,
Kulmala et al., 2014; Kim et al., 2011) and post-fire weather conditions. Thinning forest cover can also increase soil CO\textsubscript{2} efflux. Yohannes et al. (2013) reported 24% and 14% increases in soil CO\textsubscript{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\textsubscript{4} in African natural terrestrial systems. In Cameroon, the largest CH\textsubscript{4} oxidation rates were observed from relatively undisturbed near-primary forest sites (−14.7 to −15.2 ng m\textsuperscript{−2} s\textsuperscript{−1}) compared to disturbed forests (−10.5 to 0.6 ng m\textsuperscript{−2} s\textsuperscript{−1}) (Macdonald et al., 1998). Savannah and grassland were found to be both a sink and source of CH\textsubscript{4}. Termite mounds are known sources of CH\textsubscript{4} and CO\textsubscript{2}, and a study in a Burkina Faso savannah found that CH\textsubscript{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\textsubscript{4} sink and source during the rainy season, although overall it was a net CH\textsubscript{4} source (Brümmer et al., 2009). Termite mounds are known sources of CH\textsubscript{4} and CO\textsubscript{2}. (References). A study in a Burkina Faso savannah found that CH\textsubscript{4} and CO\textsubscript{2} released by termites (Cubitermes fungifaber) contributed 8.8% and 0.4% of total soil CH\textsubscript{4} and CO\textsubscript{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\textsubscript{4} ranging 53.4 to 636 ng s\textsuperscript{−1} mound\textsuperscript{−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\textsubscript{2} and CH\textsubscript{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\textsubscript{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\textsubscript{2} emissions in salt pan were estimated as 0.7 Mg CO\textsubscript{2} ha\textsuperscript{−1} yr\textsuperscript{−1} (Thomas et al., 2014).

3.1.2. Aquatic systems

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Greenhouse gas emissions from African aquatic systems such as streams, rivers, wetlands, floodplains, reservoirs, and lagoons range from 5.7 to 2320 Mg CO$_2$ ha$^{-1}$ yr$^{-1}$, 26.3 to 2741.9 kg CH$_4$ ha$^{-1}$ yr$^{-1}$, and 0.2 to 4.5 kg N$_2$O ha$^{-1}$ yr$^{-1}$, and lakes can be significant sources of GHG emissions (Table 1 and SI Table 1). 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$^{-2}$ yr$^{-1}$) 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 (31.6 - 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 $\times$10$^{10}$ - 6.35 $\times$10$^{12}$ 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$_2$O 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$_2$O, 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$^{-1}$) 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., 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 (0.11 - 0.19 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 were lowest downstream of the floodplains, N$_2$O concentrations were highest 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 al., 2014).
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$_2$O 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$_2$O 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 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 those 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$_2$O concentrations were lowest downstream of the floodplains in the Zambezí 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$_2$O 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$_2$O; 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 CO$_2$ flux was positively correlated with discharge in the Congo.
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$_2$ ($p$CO$_2$) 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$_2$O 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$_2$O 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 yet been identified. In the Okavango Delta (Botswana), CH$_4$ emissions were highest during the warmer, 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 $p$CO$_2$ and dissolved CH$_4$ and N$_2$O in 11 SSA river systems, although there was a positive relationship between $p$CO$_2$ and dissolved organic C in six of the rivers. They also found the lowest N$_2$O values were observed at the highest $p$CO$_2$ and lowest % O$_2$ levels, suggesting the removal of N$_2$O 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

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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$_2$O ha$^{-1}$ y$^{-1}$ (Table 1 and SI Table 1). The N$_2$O 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$_2$O emissions in croplands have been studied in several locations (Table 2). In western Kenya, the rate of N fertilizer application (0 to 200 kg N ha$^{-1}$) had no significant effect on N$_2$O emissions (620 to 710 g N$_2$O–N ha$^{-1}$ for 99 days) (Hickman et al., 2014). However, another study from western Kenya, found a relationship between N input and N$_2$O emissions that was best described by an exponential model with the largest impact on N$_2$O emissions occurring when N inputs increased from 100 to 150 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$_2$O emissions (28 vs. 55 ng N$_2$O–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$_2$O emissions (Table 2). 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$^{-1}$ 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$_2$O emissions due to N immobilization (Rabenarivo et al., 2014). In contrast, application of *Tithonia diversifolia* (tithonia) leaves led to greater N$_2$O emissions compared to urea application in maize fields in Kenya (Sommer...
et al., 2015; Kimetu et al., 2007). The higher N₂O 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, N₂O 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 N₂O 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 N₂O 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 N₂O 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 23). It was found that application of mixed crop residue or manure and inorganic fertilizers resulted in different response of CO₂ and N₂O emissions. In maize (*Zea mays* L.) and winter wheat (*Triticum aestivum* L.) fields in Zimbabwe, application of inorganic fertilizer (ammonium nitrate, NH₄NO₃-N) with manure increased CO₂ emissions (26 to 73%), compared to sole application of manure (Nyamadzawo et al., 2014a).

However, the mixed application resulted in lower N₂O emissions per yield (1.6–4.6 g N₂O kg⁻¹...
yield), compared to sole application of inorganic fertilizer (6–14 g N$_2$O kg$^{-1}$ yield) (Nyamadzawo et al., 2014a). Similarly, in a maize field in Zimbabwe, N$_2$O emissions were lower after the application of composted manure and inorganic fertilizer (NH$_4$NO$_3$-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$_2$O than plots receiving only urea fertilizer (Dick et al., 2008). The lower N$_2$O 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$_2$O (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$_2$O emissions in coarse-textured soils but it increased N$_2$O 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 23). 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$_2$O emissions (0.64 – 0.93% of applied N was lost as N$_2$O) than tomatoes (0.40 – 0.51% of applied N was lost as N$_2$O) (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$_2$O emissions (Dick et al., 2008). In Madagascar, N$_2$O 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
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 CO₂ eq Mg grain⁻¹) was lower from fields with reduced tillage plus mulch and leguminous trees (2.1–3.1 Mg CO₂ eq Mg grain⁻¹) and from fields with reduced tillage plus mulch and nitrogen fertilizer (1.9–2.3 Mg CO₂ eq Mg grain⁻¹) compared to fields under conventional agriculture (1.9–8.3 Mg CO₂ 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 CH₄. In Burkina Faso, CH₄ flux rates from croplands ranged from –0.67 to 0.70 kg CH₄-C ha⁻¹ yr⁻¹ (Brümmer et al., 2009), while in Republic of Congo, CH₄ uptake was observed in cassava and peanut fields and a recently ploughed field (Delmas et al., 1991). However, cropped and fertilized dambos in Zimbabwe were consistently sources of CH₄ (13.4 to 66.7 kg CH₄ ha⁻¹ 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 CO₂ 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
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 $^{13}$C in CH$_4$ for rice paddies was from $-57$ to $-63\%$, and $^{13}$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 $2680 \pm 27 \text{ kg CH}_4 \text{ ha}^{-1}$. Mg CO$_2$ ha$^{-1}$ yr$^{-1}$, 12.5 kg CH$_4$ ha$^{-1}$, and 0.12 kg N$_2$O 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$_2$O EF is 0.3% for rice cultivation and thus the N$_2$O emissions in the dambo rice paddies are also much lower than the IPCC estimate (0.40 kg N$_2$O N ha$^{-1}$ = 126 kg N ha$^{-1}$ × 0.003; 0.63 kg N$_2$O ha$^{-1}$).

### 3.2.4. Vegetable gardens

Greenhouse gas emissions from soils in vegetable gardens in peri-urban areas of Burkina Faso (Lombo et al., 2012) and Niger (Predotova et al., 2010) were much higher than all other land uses, ranging from 73.3 to 132.0 Mg CO$_2$ ha$^{-1}$ yr$^{-1}$ and 53.4 to 177.6 kg N$_2$O ha$^{-1}$ yr$^{-1}$ (Table 1 and SI Table 1).

In Burkina Faso, annual CO$_2$ and N$_2$O emissions from the garden soils were 68 to 85% and 3 to 4% of total C and N input, respectively (Lombo et al., 2012). The N$_2$O EFs (3 to 4%) were higher than the IPCC default value of 1.0% for all cropping systems (IPCC, 2006) and the global N$_2$O EF of vegetable fields (0.94%) (Rezaei Rashti et al., 2015). The high N$_2$O EFs may be attributed to the large amount of applied N in vegetable gardens (2700 – 2800 kg N ha$^{-1}$ yr$^{-1}$) since surplus N will stimulate N$_2$O production and also indirectly promote N$_2$O production by inhibiting biochemical N$_2$O reduction (e.g., Scherbak et al., 2014; Kim et al., 2013). In vegetable gardens of
Niger, a simple plastic sheet roofing and addition of ground rock phosphate to stored ruminant manure decreased N\textsubscript{2}O 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\textsubscript{2} and N\textsubscript{2}O emissions from African agroforestry were 38.6 Mg CO\textsubscript{2} ha\textsuperscript{-1} y\textsuperscript{-1} and 0.2 to 26.7 kg N\textsubscript{2}O ha\textsuperscript{-1} y\textsuperscript{-1}, respectively (Table 1 and SI Table 1). In agroforestry homegardens in Sudan, CO\textsubscript{2} (16.6 Mg CO\textsubscript{2} ha\textsuperscript{-1} from June to December) and N\textsubscript{2}O emissions (17.3 kg N\textsubscript{2}O ha\textsuperscript{-1} from June to December) accounted for two-thirds of total C output and one-third of total N output, respectively and the CO\textsubscript{2} and N\textsubscript{2}O 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\textsubscript{2} and N\textsubscript{2}O 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\textsubscript{2} emissions, with over 67\% of soil C lost over the first 7 years of intercropping (Kim, 2012a). In Zimbabwe, N\textsubscript{2}O 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\textsubscript{2}O than soil collected under the N-fixing crop (Arachis hypogaea) and non-N-fixing tree (Eucalyptus camaldulensis) (Dick et al., 2006). Nitrous oxide 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\textsubscript{2}O emissions were positively correlated with residue N
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$_2$O 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$_2$O 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$_2$O emissions. Therefore, there may be potential to reduce N$_2$O 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 treesagroforestry also results in
increased N$_2$O emissions following rainfall events. In an incubation experiment in Uganda, N$_2$O
emissions following simulated rainfall were 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$_2$O 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$_2$O emissions by up to 3.9 kg N$_2$O-N ha$^{-1}$ over a 122-day maize cropping
season (Millar et al., 2004). In agroforestry homegardens in Sudan, CO$_2$ and N$_2$O 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
soil GHG emissions have been observed in African woodlands and savannah. In Zimbabwe, clearing and converting woodlands to croplands increased soil emissions of CO$_2$, CH$_4$ and N$_2$O (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 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$_4$ emissions were...
emissions from natural and agricultural lands were 43.0 ± 5.8 and 19.5 ± 5.6 kg CH\textsubscript{4}\text{ha}^{-1}\text{y}^{-1}, respectively.

3.4.3. N\textsubscript{2}O emissions and emission factor (EF)

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

The relationship between N input and N\textsubscript{2}O emissions varied depending on N input level (Fig. 4). N\textsubscript{2}O emissions increase slowly up to 150 kg N ha\textsuperscript{-1}\text{y}^{-1}, after which emissions increase exponentially up to 300 kg N ha\textsuperscript{-1}\text{y}^{-1} (Fig. 5 (A)). Consistent with van Groenigen (2010) N inputs of over 300 kg N ha\textsuperscript{-1}\text{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\textsuperscript{-1}\text{y}^{-1}. Overall, the relationship between N input and N\textsubscript{2}O emissions shows a sigmoidal pattern (Fig. 5 (C)). The observed relationship is consistent with the proposed hypothetical conceptualization of N\textsubscript{2}O emission by Kim et al. (2013) showing a sigmoidal response of N\textsubscript{2}O emissions to N input increases. The results suggest that N inputs over 150 kg N ha\textsuperscript{-1}\text{y}^{-1} may cause an abnormal increase of N\textsubscript{2}O emissions in Africa. The relationship between N input and N\textsubscript{2}O emissions show that the lowest yield-scaled N\textsubscript{2}O emissions were reported for N application rates ranging from 100 to 150 kg N ha\textsuperscript{-1} (Fig. 6). The results are in line with the global..
The meta-analysis of Philiber et al. (2012) who showed that from an N application rate ~150 kg N ha$^{-1}$ the increase in N$_2$O emissions is not linear but exponential.

3.1.4. CO$_2$eq emission

- Carbon dioxide eq emission (including CO$_2$, CH$_4$, and N$_2$O) 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

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
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 CO₂ 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 CO₂ (e.g., autotrophic and heterotrophic sources), CH₄ (e.g., methanogenesis and methanotrophy) and N₂O (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 CO₂ efflux is primarily due to autotrophic
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$_2$O emissions in vegetable gardens due to excessive N input to get high yields, increased CO$_2$ and
N$_2$O emission in incorporation of crop residues to the soil and agroforestry practices, and
exponential increased of N$_2$O emission and yield-scaled N$_2$O 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;
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 GHGs such as N₂O and CH₄ fluxes in addition to CO₂ 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 advanced technology and utilisation of automatic chamber systems measurements can be conducted at a much 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.
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.

### 4. Conclusions

This paper synthesizes the available data on GHG emissions from African agricultural and
natural lands. Emissions of CO₂, CH₄ and N₂O 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.

### 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/](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
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, N₂O 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).

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


Table 1 Summary of greenhouse gas carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) emissions and CO₂ equivalents (CO₂ eq) in natural ecosystems and agricultural lands in sub-Saharan African countries. Mean ± standard error (number of data) are shown.

<table>
<thead>
<tr>
<th>Type</th>
<th>Area (Mha)</th>
<th>CO₂ emission</th>
<th>CH₄ emission</th>
<th>N₂O emission</th>
<th>N₂O emission factor</th>
<th>CO₂ eq emission</th>
<th>Total CO₂ eq emission</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mg CO₂ ha⁻¹ yr⁻¹</td>
<td>kg CH₄ ha⁻¹ yr⁻¹</td>
<td>kg N₂O ha⁻¹ yr⁻¹</td>
<td>%</td>
<td>Mg CO₂ eq ha⁻¹ yr⁻¹</td>
<td>Pg x 10⁻¹ Mg CO₂ eq yr⁻¹</td>
</tr>
<tr>
<td>Forest/ plantation/ woodland</td>
<td>740.6</td>
<td>32.0 ± 5.0 (34)</td>
<td>-1.5 ± 0.6 (15)</td>
<td>4.2 ± 1.5 (10)</td>
<td>*</td>
<td>34.0 ± 5.7</td>
<td>25.2 ± 4.2</td>
</tr>
<tr>
<td>Savannah/grassland</td>
<td>638.9</td>
<td>15.5 ± 3.8 (11)</td>
<td>0.5 ± 0.4 (18)</td>
<td>0.6 ± 0.1 (6)</td>
<td>*</td>
<td>15.8 ± 3.8</td>
<td>10.1 ± 2.4</td>
</tr>
<tr>
<td>Stream/river</td>
<td>28.2</td>
<td>78.1 ± 13.2 (27)</td>
<td>436.3± 133.8 (24)</td>
<td>1.6 ± 0.3 (17)</td>
<td>*</td>
<td>93.4 ± 17.9</td>
<td>2.8 ± 1.0</td>
</tr>
<tr>
<td>Wetlands/floodplains/lagoons/reservoir</td>
<td>43.8</td>
<td>96.6 ± 31.0 (7)</td>
<td>950.4 ± 350.4 (5)</td>
<td>2.0 ± 1.5 (2)</td>
<td>*</td>
<td>121.3 ± 39.7</td>
<td>5.3 ± 1.7</td>
</tr>
<tr>
<td>Termite mounds</td>
<td>0.97</td>
<td>11.6 ± 6.2 (3)</td>
<td>2.3 ± 1.1 (3)</td>
<td>0.01 (1)</td>
<td>*</td>
<td>11.7 ± 6.3</td>
<td>0.01 ± 0.01</td>
</tr>
<tr>
<td>Salt pan</td>
<td>*</td>
<td>0.7 (1)</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Total natural ecosystems¹</td>
<td>1452.5</td>
<td>27.6 ± 2.9⁵</td>
<td>43.0 ± 5.8⁵</td>
<td>2.5 ± 0.4⁵</td>
<td>*</td>
<td>29.9 ± 22.5⁵</td>
<td>43.4 ± 9.3 (76.3%)³⁶⁷</td>
</tr>
<tr>
<td>Cropland</td>
<td>468.7</td>
<td>23.4 ± 5.1 (45)</td>
<td>19.3 ± 4.2 (26)</td>
<td>4.0 ± 1.5 (83)</td>
<td>0.5 ± 0.2 (24)</td>
<td>26.1 ± 6.0</td>
<td>12.2 ± 2.8</td>
</tr>
<tr>
<td>Rice field</td>
<td>10.5²</td>
<td>6.5 (1)</td>
<td>30.5 (1)</td>
<td>0.19 (1)</td>
<td>*</td>
<td>7.3</td>
<td>1.3 ± 0.6</td>
</tr>
<tr>
<td>Vegetable gardens</td>
<td>*</td>
<td>96.4±10.2 (5)</td>
<td>*</td>
<td>120.1 ± 26.1 (5)</td>
<td>3.5 ± 0.5 (2)</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Agroforestry</td>
<td>190¹</td>
<td>38.6 (1)</td>
<td>*</td>
<td>4.7 ± 2.2 (15)</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Total agricultural lands²</td>
<td>479.2</td>
<td>23.0 ± 8.5⁴</td>
<td>19.5 ± 5.6⁴</td>
<td>4.5 ± 2.2⁴</td>
<td>*</td>
<td>25.6 ±12.4³</td>
<td>13.4 ± 3.4 (22.7%)³⁶⁷</td>
</tr>
<tr>
<td>Total natural ecosystems and agricultural lands³</td>
<td>1931.7</td>
<td>*</td>
<td>*</td>
<td>56.0 ± 12.7</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
</tbody>
</table>

*GloCOver 2009
0.07% of savanna and rainforest (Brümmer et al., 2009)
FAO STAT (http://faostat3.fao.org/home/E), year 2012
No data available
²Area weighted average
²°Zomer et al., 2009
²Zomer et al., 2009
¹Contributions to CO₂ eq. emission in total natural and agricultural lands
except salt pan
except vegetable gardens and agroforestry
except salt pan, vegetable gardens and agroforestry
Table 2: Correlation between annual soil CO\textsubscript{2} emissions (Mg CO\textsubscript{2} ha\textsuperscript{-1} yr\textsuperscript{-1}) and environmental factors in African natural terrestrial systems

<table>
<thead>
<tr>
<th></th>
<th>Annual mean Air temperature (°C)</th>
<th>Annual rainfall (mm)</th>
<th>Soil organic carbon (%)</th>
<th>Soil total nitrogen (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation coefficient</td>
<td>-0.322</td>
<td>0.518</td>
<td>0.626</td>
<td>0.849</td>
</tr>
<tr>
<td>P- value</td>
<td>0.01</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Number of samples</td>
<td>60</td>
<td>61</td>
<td>31</td>
<td>26</td>
</tr>
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- U+DAP instead U+NPK;  
- N$_2$O study;  
- Low C:N ratio clover residues compared to high C:N ratio barley residues;  
- Application of ammonium nitrate with manure to maize (*Zea mays* L.) and winter wheat (*Triticum aestivum* L.) plant residues;  
- Plant residues of maize, calliandra, and tithonia + urea;  
- Mixed application of composted manure and inorganic fertilizer (AN);  
- Manure and urea;  
- Lettuces vs cabbages vs beans;  
- Tomatoes vs rape
Figure captions


Figure 3. Maps showing study sites of CO₂, CH₄ and N₂O fluxes.


Figure 5. Maps showing study sites of CO₂, CH₄ and N₂O fluxes.

Figure 6. Relationship between nitrogen (N) input and nitrous oxide (N₂O) 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 6A. Relationship between nitrogen (N) input and yield scaled nitrous oxide (N₂O) 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.
Figure 1

Year

Agricultural area
Forest area

Agricultural area (ha, x 10^7)

Forest area (ha, x 10^7)
Urea fertilizer (ton N yr\(^{-1}\) \(\times 10^4\))

Year


0 5 10 15 20 25
Figure 2
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<td>2020</td>
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- **Cattle and Buffaloes**
- **Sheep and Goats**
- **Poultry Birds**

![Graph showing the trend of Head (Cattle and Buffaloes, Sheep and Goats, x 10^8) and Head (Poultry Birds, x 10^8) from 1960 to 2020.](image-url)
Figure 3
Figure 4
Figure 5
Figure 6

**A**

Yield scaled N\(_2\)O emissions (g N\(_2\)O-N kg\(^{-1}\) N yield)

**B**

Yield scaled N\(_2\)O emissions (g N\(_2\)O-N kg\(^{-1}\) N yield)

**C**

Yield scaled N\(_2\)O emissions (g N\(_2\)O-N kg\(^{-1}\) N yield)

N input (kg N ha\(^{-1}\))
## Supplementary Information (SI)

Table S1 Summary of greenhouse gas carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) emissions and N₂O emission factor (%) in natural ecosystems. More detail information is available in 'Soil greenhouse gas emissions in Africa database' (http://ghginafrica.blogspot.com/).

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<th>CH₄/CO₂ (Mg CO₂ ha⁻¹ yr⁻¹)</th>
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*Values in italics are estimates or approximations.*

Mapa et al., 2010; Thomas et al., 2012; Thomas, 2012; Brimmer et al., 2009; Prieme and Christensen, 1999; Delmas et al., 1991; Caquet et al., 2012; Delmas et al., 1991; Zepp et al., 1996; Fan et al., 2015; Reese et al., 2006; Gondwe and Masamba, 2014; Brunet et al., 2009; Bouillon et al., 2012; Kone et al., 2009; Borges et al., 2015; Kone et al., 2010; Borges et al., 2015; Borges et al., 2015; Wang et al., 2013; Mann et al., 2014; Borges et al., 2015; Wen et al., 2014; Fan et al., 2015; Debroque et al., 2015; Teodoru et al., 2015; Teodoru et al., 2015.
Table S2 Summary of *in situ* carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) fluxes and N₂O emission factor (%) in agricultural ecosystems. More detail information is available in 'Soil greenhouse gas emissions in Africa database' (http://ghginafrica.blogspot.com/).

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