Biogeosciences Discuss.,
https://doi.org/10.5194/bg-2020-384-AC1, 2021

Biogeosciences
Discussions
Open Access

Interactive comment on “The role of termite CH_4 emissions on ecosystem scale: a case study in the Amazon rain forest” *by* Hella van Asperen et al.

Hella van Asperen et al.

v_asperen@iup.physik.uni-bremen.de

Received and published: 3 February 2021

Response to Referee 1

Interactive comment on “The role of termite CH_4 emissions on ecosystem scale: a case study in the Amazon rain forest” by Hella van Asperen et al, Received and published: 5 December 2020

Van Asperen and co-authors studied methane and CO_2 emissions by a termite species at an upland site in the amazon basin. They report individual and mound-based emission factors comparable to previous studies, and suggest that methane emissions can

be employed as as rapid and non-invasive method to estimate mount populations.

Strength: The manuscript addresses a timely and important research question (methane emissions by termites) and provides a much needed data point in a previously understudied areas (termites in the neotropics). The authors followed state of the art measurements at a surely logistically challenging field location. As a bonus, the authors present both a comprehensive literature review and some very rare data on emissions of other trace gases (N_2O, CO) in the appendix. The manuscript is generally well written and surely of great interest for the Biogeosciences readership.

Limitations: Some of the measurements were poorly replicated: Only one control collar was placed at distance from termite mounts, and for termite weight estimates, only one measurement is presented.

Dear Lukas Kohl,

Thank you for your kind words and the time you spent on reviewing our manuscript. We are grateful for your suggestions, which we have used to improve the manuscript. Below you will find a point to point response to each of your raised concerns and, if applicable, the corrected and improved manuscript text.

In addition, we would like to point out that:

- we have uploaded a revised text of §4.1 (First paragraph of discussion), which is shown at the end of this review;

- we have uploaded a revised Figure 2, which is shown at the end of this review (Previous Figure 4 is Figure 2 in revised manusript);
- we have uploaded the revised Table 2, which is shown at the end of this review (Previous Table 2 and 3 are now merged into Table 2);
- we have uploaded one additional figure, belonging to a discussion point in this review ('Review-Figure 1'), which ìs shown at the end of this review;
- the given values in the text might have changed due to an improved termite weight determination.

The choice for only one blank measurement was due to practical limitations, often a leading factor in these logistically challenging field conditions. To improve this part of the manuscript, we will substitute our blank measurement by additionally measured valley soil fluxes, performed as part of sub study.

Below we will:

- **report the values of the additionally measured soil valley fluxes;**
- **argue why these values are more suitable then the original blank control value;**
- **provide the revised manuscript text and the new Figure 4 wherein the soil valley measurements are shown.**

Additional measurements: Additional flux measurements were done in the same week (March 2020) and performed in the same valley at approx. 500 m distance from the termite mounds. The chamber set up was as described in §2.5, with 10 soil collars

and 3 repetitions. We observed soil CH_4 fluxes ranging between -0.12 to 2.89 nmol m^{-2} s^{-1}, (median= -0.02, average=0.15, sd=0.55).

Fluxes from the *original* blank collar ranged between 3.9-5.4 nmol m^{-2} s^{-1} and were thereby higher than the additionally measured soil valley fluxes (-0.12 to 2.89 nmol m^{-2} s^{-1}). The original blank collar fluxes were however quite similar to the mound adjacent fluxes (0.3-8.9 nmol m^{-2} s^{-1}, 16 locations). While the blank collar was not closely located to a mound (~5 m of mound nr. 15), comparison to these 2 sets of measurements points at the presence of a local CH_4 hotspot (Subke et al. 2018), thereby not being representative as a control collar. For the revised manuscript we will use the additional soil valley flux measurements as our 'blank collar'.

The aim of the blank 'control' measurement was to show the large difference between a 'normal' valley CH_4 emission (per area), and an emission (per area) when a termite mound is present. Considering the average mound emission of 25.2 nmol $mound^{-1}$ s^{-1}, and the average valley soil emission of 0.03 nmol $collar^{-1}$ s^{-1} (0.15 nmol m^{-2} s^{-1}), an average collar area emits a factor 630 more CH_4 when a termite mound is present. Including these complementary measurements will strengthen our message that termite mounds are hotspots in comparison to their surroundings.

We have included these additional measurements for comparison, by adapting Figure 4, and by adapting the manuscript text. Manuscript parts with major changes have been copied here below. In the revised manuscript, the original Figure 4 is now Figure 2.

In Methods, §2.5: Valley and mound adjacent soil fluxes

Every mound adjacent soil flux measurement was 4 minutes, and the set of 4 collar measurements was performed once per mound, with exception of mound nr. 19. For mound nr. 13 and nr. 14, the measurements were performed on the 2^{nd} measurement day, for mound nr. 15 and nr. 16, the measurements were done on the 3^{rd} measurement day. Mound adjacent soil fluxes will be expressed per collar area (0.25 m^2), to be better comparable to mound emissions. The same chamber set up was used in a sub study at a close by transect ($\sim$ 500 m from termite mounds) where, among others, valley soil fluxes were measured (10 collars, 3 repetitions). Measured soil fluxes from the valley will be shown for comparison.

In Results, §3.1: Mound CH_4 and CO_2 emissions
Headspace concentrations increased strongly during chamber closure, and chamber concentrations reached up to 5750 nmol CH_4 mol^{-1} and 1950 μmol CO_2 mol^{-1}. Mound CH_4 emissions ranged between 17.0 and 34.8 nmol $mound^{-1}$ s^{-1} (Fig. 1), with an average emission of 25.2 nmol $mound^{-1}$ s^{-1}. Additional valley measurements showed heterogeneous soil CH_4 fluxes with small uptake and emission taking place alongside, ranging between -0.1 and 2.9 nmol m^{-2} s^{-1} (med=-0.02, avg=0.15, sd=0.54). Mound adjacent CH_4 soil fluxes, measured at 20 and 45 cm from the mound, ranged between 0.4 and 8.9 nmol CH_4 m^{-2} s^{-1} (avg=2.14, sd=2.00), and were on average enhanced in comparison to valley soils (Fig. 2). Soil valley CO_2 fluxes were found to range between 0.9 and 3.7 μmol m^{-2} s^{-1} (avg=2.14, sd=0.74) (Fig. 2). Mound adjacent soil CO_2 fluxes showed an average emission of 4.84 μmol CO_2 m^{-2} s^{-1} (range=2.0-10.1, sd=2.01), thereby being enhanced with respect to the surrounding soils (Fig. 2). Mound CO_2 emissions, corrected for the average valley soil respiration, were ranging between 1.1 and 13.0 μmol $mound^{-1}$ s^{-1}, with an average emission of 8.14 μmol $mound^{-1}$ s^{-1} (Fig 1).

In Discussion, §4.3:
Valley soil CH_4 and CO_2 fluxes were similar to what was found by earlier studies (Souza (2005), Moura (2012), Chambers et al. (2004), Zanchi et al. (2012). On average, mound adjacent soil CH_4 and CO_2 fluxes were enhanced with respect to valley soils, although differences were small, and no clear emission pattern with 'distance to mound' was observed. While mound adjacent soil fluxes are possibly enhanced, we preferred to avoid overestimation, and decided to treat termite mounds as very local hot spots, with measured fluxes only representative for the collar area of 0.25 m^2. On average, CH_4 and CO_2 fluxes per collar area were found to be a factor $\sim$630 and $\sim$16 higher when an active termite mound was present.

References:
- Chambers, Jeffrey Q., et al. "Respiration from a tropical forest ecosystem: partitioning of sources and low carbon use efficiency." Ecological Applications 14.sp4 (2004): 72-88.
- Moura, V. S. d.: Investigação da variação espacial dos fluxos de metano no solo em floresta de terra firme na Amazônia Central, MSc thesis INPA/UEA, 2012.
- Souza, Juliana Silva de. "Dinâmica espacial e temporal do fluxo de CO_2 do solo em floresta de terra firme na Amazônia Central." (2005).
- Subke, Jens-Arne, et al. "Rhizosphere activity and atmospheric methane concentrations drive variations of methane fluxes in a temperate forest soil." Soil Biology and Biochemistry 116 (2018): 323-332.

Termite weight estimates

Following the suggestion of the reviewer we repeated the measurement and use an improved weight estimate in the revised manuscript.

We repeated the measurement as described in §2.7, with a larger sample size: we measured the weight of 4 samples of each 100 termites, which resulted in an average calculated weight of 2.832 mg, 2.986 mg, 3.085 mg and 3.141 mg. The former measurement (as given in previous manuscript) with 80 termites, gave an average weight of 3.330 mg. Averaging these 5 values results in a termite weight of 3.0748 mg (sd=0.1847).

Such variation in average termite weight can be expected, due to genetics and environmental differences during development. In addition, our values are close to the values as measured by Pequeno et al (2013), who reported a termite weight of 3.0 mg (sd=0.4) for the species *N. Brasiliensis*.

In the manuscript, we will use a termite weight of 3.07 mg (sd=0.18) for the species *N. Brasiliensis*, and we will indicate the propagated uncertainty range in the relevant calculations. The new termite weights lead to the following revised manuscript text:

Previous text §2.7: Termite mass was measured in the *Laboratory of Systematics and Ecology of Soil Invertebrates* at INPA. 80 living workers of the species *N. Brasiliensis* were weighted by use of a precision scale (FA2104N). Reported individual termite mass is fresh weight per termite (mg termite^{-1}).

Revised text §2.7: Termite mass was measured in the *Laboratory of Systematics and Ecology of Soil Invertebrates* at INPA. 480 living workers of the species *N. Brasiliensis* were weighted in 5 subgroups (4x n=100, 1x n=80) by use of a precision scale (FA2104N). Reported individual termite mass is fresh weight per termite (mg termite^{-1}).

Previous text §3.2: The living weight of 80 workers was measured to be 0.264 g, which is 3.3 mg per worker. This value is similar to what was found by Pequeno et al. (2017), who measured 3.0 ($\pm$ 0.4) mg for workers and 6.6 ($\pm$ 0.3) mg for soldiers. The species *N. Brasiliensis* has a relatively low soldiers:workers ratio of 1:100 (Krishna and Araujo, 1968). For our calculations we will use an average fresh weight of 3.33 mg termite^{-1} for the species *N. Brasiliensis*.

Revised text §3.2: The average weight of 5 subsets of living workers of the species *N. Brasiliensis* was determined, and found to range between 2.83 and 3.33 mg, with an average weight of 3.07 mg (sd=0.18), which is similar as what was found by Pequeno et al. (2013), who reported 3.0 mg (sd=0.4). Since the species *N. Brasiliensis* has a relatively low soldiers:workers ratio of 1:100 (Krishna and Araujo, 1968), we will use the worker weight 3.07 (sd= 0.18) mg termite^{-1} as an average termite weight for the species *N. Brasiliensis*.

Possible improvement:

- **While the manuscript is generally very well written, I would encourage the authors to focus on editing the discussion section, which reads less easily than the rest of the manuscript. Some of this could be done by shortening and streamlining this section, which is rather long and at times meandering.**

Thank you for the suggestion. We have shortened the discussion by following the different suggestions (see revised §4.1, as shown at the end of this review). In addition, we have taken out one figure (original Figure 3: mound volume and height vs emissions), since the content of the figure did not add much to the text.

- **The authors could also improve the quality figures and tables (see below), most importantly remove the grid lines from the figures for easier readability.**

We have re-plotted all figures following your suggestions. Figure 2 (original Figure 4) is shown at the end of this review.

- **Overall, this is a very nice contribution and it was a pleasure to review it!**

Thank you once more for your review and your comments!

L48: 'which is around' - approximately instead of around, also better state the range in % as well given that 2-15 Tg is quite a wide range.
We have replaced 'which is around' for 'approximately', and will express the range in %:

Revised text: More recent literature uses estimates in the range of 2-15 Tg CH_4 per year (Ciais et al., 2014; Kirschke et al., 2013; Sanderson, 1996; Saunois et al., 2020), which is approximately 0.5-4% of the total estimated natural source CH_4 emission (Saunois et al., 2020).

L64: ‘termite CO_2 measurements’ - measurements of termite CO_2 emissions
We have corrected this.

L64: to avoid mixing weight units (gramm and tons), Pg instead of Gt
We will use Pg instead of Gt.

L119: what material was your chamber built out of?
The large flux chamber (220L) was created from a bucket from polythene, and purchased at a common household store. The collars were made from stainless steel. The small flux chamber (4.7L) and the collars were created from a common PVC sewage pipe, purchased at a construction store.

The following text has been added to §2.3 and §2.5:

Revised text in §2.3: A flux chamber was created by use of a 220 L slightly cone-shaped polythene bucket.
Revised text in §2.5: The chamber and collars were created from a common PVC sewage pipe.

L130: when were your measurements conducted (date, in what season?)
Measurements were performed in March 2020, in the wet season (stated in §2.1).

L134: ‘molar density’: concentration
We have corrected this.

L142: ‘increase’: concentration change, as you could see uptake
We have corrected this.

L176-181: The section could be improved.
We have corrected this. See below for the improved text.

Revised text §3.1: During chamber closure, the concentration changes in CH_4 and CO_2 were strongly correlated ($R^2 > 0.95$ for each chamber closure). The ratio between the mound CH_4 and CO_2 emission (CH_4/CO_2) ranged between 2.1 and 17.1 $*10^{-3}$, and showed a constant ratio when data from mound 19 (furthest away from other mounds), and mound 6 (different species) were excluded (average ratio: $2.8*10^{-3}$). The smallest mound (nr. 19) clearly showed smaller-than-average emissions, but in general no strong correlation was found between mound CH_4 emissions and mound height (R^2=0.07) or volume (R^2=0.08), and a small correlation was found between mound CO_2 emissions and mound height (R^2=0.43) and mound volume (R^2=0.44).

L195: can you state an uncertainty of this weight per individual?
Please see the beginning of this review for an elaborate answer.

L217: no need to state the original unit here, just state the values converted to the unit used in your study.
We have corrected this.

L223-235: I recommend streamlining/shortening this segment. Acknowledging mount uptake is important, but it’s not the focus of your study and comes out of left field here. Focus on why this is important to understanding your results.
We have shortened this part. The improved section §4.1 can be found at the end of this review.

L237-241: I would move this comparison with literature data up to L215-219.
We have moved this part.

L243: To be honest, these variations among individual measurements look pretty trivial to me and may not need such extensive discussion (which ends up questioning your measurements).
We have reduced this part, but have kept one sentence (see revised §4.1). In case someone else would like to do similar measurements, it is good to be aware of this possible minimal transport below the collar.

L249-254: This can be tested by looking at the concentration curves within individual closures. If a relevant air exchange between chamber and ambient air occurred, concentrations should be non-linear (dCH_4/dt decreasing over time, following a $y=a + b*e^{-c*t}$ function). If this is the case, fluxes should be calculated by fitting such an exponential function and calculating the slope as $d[CH_4/dt]$ at t=0.
We observed little variations in the linear increase, and variations were at the same moment and with the same magnitude for CO_2 and CH_4. We expect that this is a result from minor air transport below the collar, possibly as a result of little disturbances (bag filling, a forest breeze, our presence close to the flux chamber). These fluctuations are not continuous, and the gradient recovers itself after a fluctuation. As can be seen in added figure (Review-Figure 1), the concentration increase still can be represented well by a linear increase with a strong R^2 ($R^2 > 0.95$).

L280: it would be good to add an uncertainty range to your population estimates
Thank you for this suggestion.

We have propagated the uncertainty of our emission factor 0.0002985 (se=$1.77*10^{-5}$), to define an uncertainty range in our population estimate. For example, for mound nr.

13, a range of 89.5-100.9 thousand termites will be given.

L288: ‘contemplated’: considered?
We have corrected this.

L291-292: ‘hypothesize’: don’t use hypothesize that for claims you do not test. ‘It is therefore likely that.‘
We have corrected this.

L303: ‘drawback’: disadvantage
We have corrected this.

L304-305: ‘is proposed’: by whom? The authors? If that’s that’s the case, say so (ok, sorry for the snarky tone. Use active voice here - ‘We propose a follow-up study to directly compare’)
Thank you for the suggestion, this is indeed unclear. We have corrected this.

L311: ‘it was decided’: same here, use active voice: ‘we decided .. to avoid overestimating ..’
We have corrected this.

L418-419: ‘indicating no or very low N_2O emissions’: Can you provide an uncertaintyrange for that estimate (e.g., limit of detection for fluxes?)
We have calculated a detection limit of 0.027 nmol N_2O m^{-2} s^{-1}. Here below we will:

- elaborate on how this detection limit is determined (specifications FTIR-instrument and assumptions);

- support our statement (very low N_2O emissions) with additional data;
- give the revised manuscript text.

Detection limit of measurements: Reviewer 2 posed a similar question, and also asked about the precision and calibration of the FTIR-instrument. For completeness, we give the information here as well.

The FTIR-instrument has the following precision (σ) for 10 minute-averaged spectral analyses: 0.02 μmol mol^{-1}, 0.2 nmol mol^{-1}, 0.2 nmol mol^{-1}, 0.06 nmol mol^{-1}, and 0.04 permil, for respectively CO_2, CH_4, N_2O, CO, and δ^{13}C of CO_2. Measurements performed during the campaign week were set to 5 minutes, so that a precision of 1/sqrt(N) is achieved, which is 0.09 nmol mol^{-1} for N_2O. The FTIR instrument has been shown to be linear for all gases in the ambient concentration range, and linearity was tested for N_2O in the range 300-350 ppb. For the detection limit, we state the following:

- Assuming bag samples taken at 2, 5 and 8 minutes during chamber closure.
- Given: collar area 0.25 m^2, chamber volume 220 L, mound volume 50 L, headspace volume 220-50 = 170 L.
- Assuming: Molar volume of 24.5 L mol^{-1} (1 atm, 25 °C).
- Minimum detectable concentration difference is (2σ) 0.18 nmol mol^{-1}.
- A concentration difference between t=2 min and t=5 min of 0.18 nmol mol^{-1}, is caused by a flux of 0.027 nmol collar/mound^{-1} s^{-1}.

The FTIR-instrument has a cross sensitivity with CO_2, which is well determined for CO_2 <800 μmol mol^{-1}, but is less certain for high CO_2 concentrations. For this reason, we prefer to only use the N_2O headspace concentration measurements with CO_2 <800 μmol mol^{-1}. Only 5 mound chamber closures had two consecutive N_2O concentration points (t=2 min and t=5 min) with CO_2 <800 μmol mol^{-1}, and only 3 sets of two-consecutive concentration points passed the minimum concentration difference of 0.18 nmol mol^{-1}. These differences were ~0.2, ~0.3 and ~0.7 nmol mol^{-1}, leading to calculated N_2O fluxes ranging between ~0.03 - ~0.11 nmol mound^{-1} s^{-1}.

Additional measurements to support statement ‘very low N_2O emissions’: In October 2020, additional valley soil N_2O flux measurement were performed with the same chamber system and collars (5 collars, 3 repetitions), but with a longer closing time (35 min), without termite mounds (so lower CO_2), and with 4 measurements per chamber closure. Also during these measurements, concentration increases were very low. Out of 15 measurements, 8 measurements had an $R^2 > 0.90$, and calculated fluxes ranged between 0.008-0.106 nmol m^{-2} s^{-1} (average=0.032 nmol m^{-2} s^{-1}, sd=0.33). Since the valleys are known to be low on nitrogen (Quesada et al., 2010), such low fluxes are expected, and similar N_2O valley soil fluxes were found by Matson et al., (1987) in a fieldsite closeby.

For the revised manuscript: since the 3 calculated mound N_2O flux measurements are based on only 2 consecutive headspace concentration points, no uncertainty can be given, wherefore we preferred not to state the fluxes in the previous manuscript. For the revised manuscript, we state the detection limit, explain why not all mound fluxes could be calculated, and support our observation of low N_2O mound fluxes by the additional soil N_2O flux measurements:

Appendix A2: Gas samples (3 samples per chamber closure) revealed stable N_2O concentrations, and headspace concentrations ranged between 333.7 and 342.4 nmol mol^{-1} over the different chamber closures. Since headspace CO_2 concentrations sometimes exceeded 800 μmol mol^{-1}, and N_2O-CO_2

cross-sensitivity becomes uncertain at higher CO_2 concentrations, not all 3 headspace samples per chamber closure could be used, wherefore qualitative N_2O flux estimates cannot be reported. As a back-of-the-envelope calculation, N_2O fluxes were calculated if 2 consecutive headspace samples were with CO_2 <800 μmol mol^{-1}, and if a minimum N_2O concentration difference of 0.18 nmol mol^{-1} was found (FTIR precision (σ) for 5 min spectra is 0.09 nmol mol^{-1}), which gave us 3 mound flux estimates ranging between ~0.03 and ~0.11 nmol N_2O mound^{-1} s^{-1}. Similarly low fluxes were found during additionally performed flux measurements, performed as part of a substudy, which showed valley soil fluxes ranging between 0.008-0.106 nmol N_2O m^{-2} s^{-1}. The low mound fluxes would be in agreement with a previous study which suggested that termite mound N_2O emissions are dependent on the N-content of the termites diet (Brauman et al., 2015), which is expected to be low in the valleys of this ecosystem (Quesada et al., 2010).

References:

-Matson, Pamela A., and Peter M. Vitousek. "CrossâĂŘsystem comparisons of soil nitrogen transformations and nitrous oxide flux in tropical forest ecosystems." Global Biogeochemical Cycles 1.2 (1987): 163-170.

Figures

- **Remove grid lines (counter-intuitively, this makes figures easier to read), place ticks inwards.**
- **Fig 1: remove ‘per mount’ on the y axis, it’s redundant with the unit on that axis.**
- **Fig 4: A broken axis might work better than the inserts here (if you keep the inserts, state the y axis scale). The figure could also be simplified by showing the means + SD of the four mounts instead of values for individual mounts. Also, I think the direction in which you placed the soil collars from the mount wasn’t chosen deliberately, so your x axis could be just ‘distance from the center of the mount’, combining your flux measurements at the same distance at either side of the mount.**
- **Fig 5: number instead of amount**

Thank you for these suggestions.

- Figure 1: we have removed ‘per mound’, and have removed the gridlines.
- Figure 4 (now Fig 2): we have implement a ‘broken y-axes’, and have added additional measurements. We have chosen to keep the mound in the middle, to better visual the actual mound, and to visually separate the emissions measured on each side of the mound.
- Figure 5 (now Fig 4): we have corrected this.

Tables

I recommend combining Table 2 and 3 after removing reported value and reported unit (these can be placed in a supplement) to keep the table easier to read. State the unit of the converted values in the table header. This leaves the following columns: [Study] [Study area] [CH_4 emission (state units)] [CO_2 emission (state units)] [CH_4:CO_2 ratio (state units)] [Species]. Such a table would give a much better overview.

Thank you for this suggestion. We have merged the two tables, and have taken some columns out. Since it might not always be clear to which value we are referring, especially when data is taken from a graph, we prefer to also state the original value and unit. Nevertheless, we have tried to improve the readability by giving this part a smaller fontsize. The new table can be found at the end of this review.

Revised Discussion part §4.1

CH_4 and CO_2 emissions

Measured mound CH_4 emissions were of similar magnitude to emissions found by previous studies (Table 2). The termite emission factor, determined for the soil-feeding species *N. brasiliensis*, was found to be 0.35 (sd= 0.02) μmol $g^{-1}_{termite}$ h^{-1}, which is similar to values found for other species in literature (Table 2, upper part), but almost two times higher than the average value reported by Martius et al (1993) for a wood-feeding species in the Amazon (0.19 μmol CH_4 $g^{-1}_{termite}$ h^{-1}). Our emission rate is within the reported range of 0.1-0.4 μmol $g^{-1}_{termite}$ h^{-1} for soil feeders (Sugimoto et al. 2000). Mound CO_2 emissions and the termite CO_2 emission factor were similar to a little higher in comparison to the few values found in literature. Nevertheless, since mound material and termites were measured together, the contribution of *indirect* termite emissions, i.e. mound respiration, cannot be quantified, so that the direct termite-produced CO_2 emission is presumably lower.

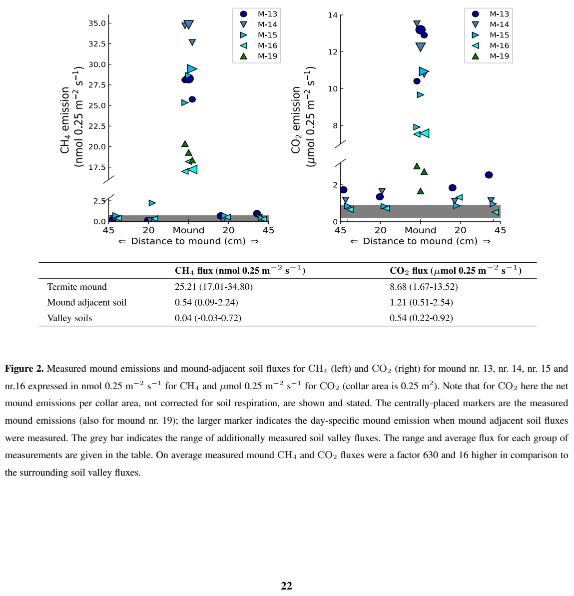
There is a large variety in type of termite mounds (shape and size are dependent on, among others, species, ecosystem, climate (Noirot and Darlington, 2000)), explaining the wide range of reported termite mound CH_4 emissions (Table 2, middle and lower part). In-situ measurement of termite mounds gives information about the *net* CH_4 emission under natural conditions, but is unable to distinguish sources and sinks inside the mound. One known CH_4 sink in termite mounds is the uptake by methanotrophic bacteria, which are also responsible for the CH_4 uptake in aerobic soils. The presence and magnitude of this process have been discussed and reviewed by different studies (Khalil et al., 1990; Macdonald et al., 1998; Nauer et al., 2018; Seiler et al., 1984; Sugimoto et al., 1998a; Ho et al., 2013; Pester et al., 2007; Reuß et al., 2015). The role of possible mound CH_4 uptake should also be acknowledged for the measurement of individual termite emissions (Table 2, upper part): most literature values, including values from this study, are based on termite incubation in presence of mound material, with ongoing CH_4 uptake, wherefore actual termite CH_4 emission values might be higher.

Small variation in emission magnitudes was observed between measurement days. This can be caused by a variation in colony size (due to foraging activities) or termite activity, driven by fluctuations in temperature or radiation (Jamali et al., 2011a; Ohiagu and Wood, 1976; Sands, 1965; Seiler et al., 1984).. However, as our termite mounds are in a tropical forest with relatively constant temperatures and only indirect daylight, strong diurnal temperature and radiation patterns are not expected. Small variation can also be caused by minimal air transport below the soil collar, through the porous upper soil layer; during preliminary tests *without* a collar, we observed that even a light forest breeze can cause chamber

headspace variations. In case our set up was subject to minor air transport below the collar, the given mound estimates will be slightly underestimated with respect to the actual mound fluxes. Another possible underestimation is caused by the estimated corrected chamber volume, as used in Eq. (2). In this study, we considered the mound volume as a solid body. A previous study considered the solid nest volume as 10% of the actual mound volume (Martius et al. 1993), leading to a larger corrected chamber volume, and therefore to larger calculated mound emissions. By use of this approach, average calculated emissions would increase by almost 30$\%$ to be 32.7 nmol CH_4 mound^{-1} s^{-1} instead of 25.2 nmol CH_4 mound^{-1} s^{-1}.

The mound emission CH_4/CO_2 ratio was found to be relatively constant over 4 of the 5 mounds, with an average ratio of 2.8*10^{-3}. While values in literature indicate a wide range of reported CH_4/CO_2 ratios (Table 2), both Seiler et al. (1984) as Jamali et al. (2013) found little variation between mounds of the same species, and concluded that the CH_4/CO_2 emission ratio is species-specific. Our overall variation of a factor of $\sim$4 for the CH_4/CO_2 ratio of mound emissions of the same species is of the same magnitude as what was observed in earlier studies (Seiler et al., 1984; Jamali et al., 2013).

Interactive comment on Biogeosciences Discuss., https://doi.org/10.5194/bg-2020-384, 2020.



	CH_4 flux (nmol 0.25 m^{-2} s^{-1})	CO_2 flux (μmol 0.25 m^{-2} s^{-1})
Termite mound	25.21 (17.01-34.80)	8.68 (1.67-13.52)
Mound adjacent soil	0.54 (0.09-2.24)	1.21 (0.51-2.54)
Valley soils	0.04 (-0.03-0.72)	0.54 (0.22-0.92)

Figure 2. Measured mound emissions and mound-adjacent soil fluxes for CH_4 (left) and CO_2 (right) for mound nr. 13, nr. 14, nr. 15 and nr.16 expressed in nmol 0.25 m^{-2} s^{-1} for CH_4 and μmol 0.25 m^{-2} s^{-1} for CO_2 (collar area is 0.25 m^2). Note that for CO_2 here the net mound emissions per collar area, not corrected for soil respiration, are shown and stated. The centrally-placed markers are the measured mound emissions (also for mound nr. 19); the larger marker indicates the day-specific mound emission when mound adjacent soil fluxes were measured. The grey bar indicates the range of additionally measured soil valley fluxes. The range and average flux for each group of measurements are given in the table. On average measured mound CH_4 and CO_2 fluxes were a factor 630 and 16 higher in comparison to the surrounding soil valley fluxes.

22

Fig. 1. Revised Figure 2 (previously Figure 4)

Table 2. Overview of literature values for CH_4 and CO_2 emission of termites per weight (upper part), emission per termite mound (middle part), and emission per area (lower part). Values from this study are indicated in bold. If reported, the average and sd are given, otherwise a range is indicated. If multiple values were reported, measurements from higher soil-feeding termite species were selected. For each study, the graph or table where the data was found, is indicated. The CH_4/CO_2 is given in molar ratio (10^{-3}). a) Sawadogo et al. (2011) reported emissions per dry weight mass. To convert to fresh weight, a formula as reported by Pequeno et al. (2017) was used. With an assumed dry weight of 0.5 mg, a conversion factor of 3.14 was deducted. b) Mound emissions are divided by collar area of 0.25 m^2; c) Calculated based on average values in this table; d) *Neocapritermes brasiliensis*; e) *Crenetermes albotarsalis*, *Cubitermes fungifaber*, *Cubitermes speciosus*, *Noditermes* sp., *Procubitermes* sp., *Thoracotermes macrothorax*; f) *Dicuspiditermes santschii*, *Dicuspiditermes nemorosus*, *Pericapritermes semarangi*, *Procapritermes* nr. *Sandakanensis*, *Homallotermes eleanorae*, *Proaciculitermes* sp. A, *Pericapritermes nitobei*; g) *Coptotermes lacteus*; h) *Ancistrotermes cavithorax*, *Odontotermes n. pauperans*; i) *Nasutitermes macrocephalus*, *Nasutitermes corniger*, *Nasutitermes surinamensis*, *Nasutitermes* sp., *Nasutitermes ephratae*, *Nasutitermes araujoi*; j) *Noditermes* sp., *Crenetermes albotarsalis*, *Cubitermes speciosus*, *Thoracotermes macrothorax*, *Astratotermes* sp.; k) *Macrotermes bellicosus*; l) *Microcerotermes* sp., *Globitermes suplhureus*, *Termes* sp., *Dicuspiditermes* sp.; m) *Drepanotermes perniger*, *Nasutitermes magnus*, *Nasutitermes triodiae*, *Tumulitermes pastinator*, *Amitermes laurensis*, *Coptotermes lacteus*; n) *Bulbitermes* sp. C, *Dicuspiditermes nemorosus*, *Dicuspiditermes santschii*; o) *Macrotermes* and *Odontotermes* (Macrotermitinae), *Trinervitermes* (Nasutitermitinae), *Amitermes* and *Cubitermes* (Termitinae), *Hodotermes* (lower termite); p) *Cubitermes fungifaber*; q) *Microcerotermes nervosus*, *Turnulitermes pastinator*, *Turnulitermes hastilis*, *Amitermes meridionalis*.

28

		Studies reporting emission per gram termite					
Study	**Study area**	**CH_4 emission** (μmol g_{tm}^{-1} h^{-1})		**CO_2 emission** (μmol g_{tm}^{-1} h^{-1})		**CH_4/CO_2**	**Species**
This study, Fig. 4	**Amazon**	**0.35 (0.2)**	(0.0002985 nmol tm^{-1} s^{-1})	**86.8 (10.0)**	(0.074 nmol tm^{-1} s^{-1})	~4^c	**Soil feeders** $^{(d)}$
Brauman et al. (1992), Tab. 1	Congo	0.39-1.09	(0.39-1.09 μmol g_{tm}^{-1} h^{-1})				Soil feeders $^{(e)}$
Eggleton et al. (1999), Tab. 4	Australia	0.17-0.27	(0.17-0.27 μmol g_{tm}^{-1} h^{-1})	1.4-9.0	(1.4-36.4μmol g_{tm}^{-1} h^{-1})	10-154	Soil feeders $^{(f)}$
Fraser et al. (1986), Fig. 2	Australia	0.04 (0.01)	(0.67 (0.2) mg kg_{tm}^{-1} h^{-1})	107 (4.5)	(4.7 (0.2) g kg_{tm}^{-1} h^{-1})	~0.38^c	Wood feeders $^{(g)}$
Konaté et al. (2003), Tab. 1	Ivory Coast			31.4-133.5	(31.4-133.5 nmol mg_{tm}^{-1} h^{-1})		Fungi feeders $^{(h)}$
Martius et al. (1993), Tab. 1	Amazon	0.19 (0.08)	(3.0 (1.3) μg g_{tm}^{-1} h^{-1})				Wood feeders $^{(i)}$
Rouland et al. (1993), Tab. 1	Congo	0.53-1.09	(0.53-1.09 μmol g_{tm}^{-1} h^{-1})				Wood feeders $^{(j)}$
Sawadogo et al. (2011), Tab. 1	Burkino Faso	0.10-0.12	(0.30-0.39 μmol g_{tm}^{-1} h^{-1})^a	19-25	(59.4-78.4 μmol g_{tm}^{-1} h^{-1})^a	~5^c	Wood feeders$^{(k)}$
Sugimoto et al. (1998a), Tab. 3	Thailand	0.03-0.20	(3.4-20.3*10^{-8} mol g_{tm}^{-1} h^{-1})				Soil feeders $^{(l)}$
		Studies reporting emission per nest or mound					
Study	**Study area**	**CH_4 emission** (μmol $mound^{-1}$ h^{-1})		**CO_2 emission** (mmol $mound^{-1}$ h^{-1})		**CH_4/CO_2**	**Species**
This study, Fig. 1	**Amazon**	**61-125**	(17.0-34.8 nmol $mound^{-1}$ s^{-1})	**4-47**	(1.1-13.0 μmol $mound^{-1}$ s^{-1})	2.8 (0.4)	**Soil feeders** $^{(d)}$
Khalil et al. (1990), Fig. 4 & Tab. 3	Australia	9-135	(0.04-0.6 μg $mound^{-1}$ s^{-1})	4-92	(0.05-1 μg $mound^{-1}$ s^{-1})	0.12-11	Wood feeders$^{(m)}$
MacDonald et al. (1999), Tab. 4	Cameroon	1-11	(4.5-49 ng $mound^{-1}$ s^{-1})				Soil & wood feeders $^{(n)}$
Martius et al. (1993), Tab. 1	Amazon	125 (150)	(2.0 (2.4) mg $nest^{-1}$ h^{-1})				Wood feeders $^{(i)}$
Seiler et al. (1984), Tab. 1	South Africa	1-644	(0.02-10.3 mg $nest^{-1}$ h^{-1})	0.7-241	(0.03-10.6 g $nest^{-1}$ h^{-1})	0.07-8.7	Soil & wood feeders $^{(o)}$
Sugimoto et al. (1998a), Tab. 3	Thailand	0.4-1.9	(4.2-18.7*10^{-7} mol $nest^{-1}$ h^{-1})				Soil feeders $^{(l)}$
		Studies reporting emission per area					
Study	**Study area**	**CH_4 emission** (μmol m^{-2} h^{-1})		**CO_2 emission** (mmol m^{-2} h^{-1})		**CH_4/CO_2**	**Species**
This study, Fig. 1	**Amazon**	**245-501**^{b}	(17.0-34.8 nmol $mound^{-1}$ s^{-1})	**16-187**^{b}	(1.1-13.0 μmol $mound^{-1}$ s^{-1})	2.8 (0.4)	**Soil feeders**$^{(e)}$
Brümmer et al. (2009a), Fig. 5	Burkino Faso	315.7	(3788.9 μg CH_4-C m^{-2} h^{-1})	37.3	(447.0 mg CO_2-C m^{-2} h^{-1})	~8.5^c	Soil feeders $^{(p)}$
Jamali et al. (2013), Fig. 1	Australia	32-500	(379-6000 μg CH_4-C m^{-2} h^{-1})	0-129	(0-1550 mg CO_2-C m^{-2} h^{-1})	2.7-11.0	Wood feeders $^{(q)}$
Queiroz (2004), Tab. 4	Amazon	10-24	(0.16-0.38 mg m^{-2} h^{-1})				unknown

Fig. 2. Revised Table 2 (merge of Table 2 and 3)

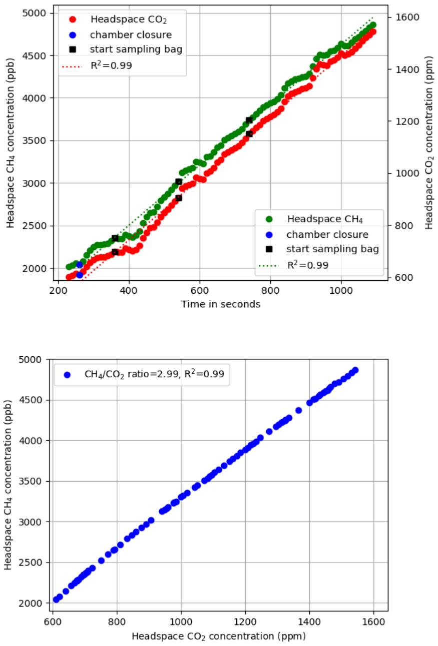


Fig. 3. Review Figure ’Review-Figure 1’