Dear editor,

Please find attached a new version of our manuscript entitled "Automatic high-frequency measurements of full soil greenhouse gas fluxes in a tropical forest" for consideration as publication in Biogeosciences,

We have revised the manuscript based on the feedback of the five reviewers and you can find below a rebuttal letters where we give our detailed responses to each point raised by the reviewers.

You can also find below the a marked-up manuscript version.

On behalf of the authors,

Elodie Courtois & Clement Sthal

Referees' comments:

RC1, Referee #1 (Remarks to the Author):

This manuscript presents a protocol for measuring three greenhouse gases (CO_2,CH_4 and N_2O) at high temporal frequency in a tropical forest soil using a combination of commercially available systems. This is a very timely and relevant manuscript, particularly for measurements of CH_4 and N_2O. Continuous high frequency measurements with clear sampling protocols will help researchers capture and model, transient changes in CH_4 and N_2O fluxes often missed by more infrequent sampling strategies. This looks like a nice, efficient system for measuring these important greenhouse gases.

Response: *We thank the reviewer for the positive comments and constructive inputs.*

The technical write-up is comprehensive and easy to follow however I do have technical questions regarding their methodology that should be addressed.

1. How did the authors keep moisture from affecting sampling, either within the tubing lines or when moving from IRGA to Picarro? Was there any moisture buildup in the tubing lines?

Response: *We also worried about moisture problems prior to our experiment, but such problems never occurred. No significant condensation occurred in our system, we assume because temperature variations were typically small below the canopy, varying from 22°C in the night to 28°C during the day (see Figure attached). We regularly checked that no liquid water accumulation occurred in the sampling tubes. Moreover, both analysers measure water vapor and account for its effect on concentration of CO_2, CH_4 and N_2O .*

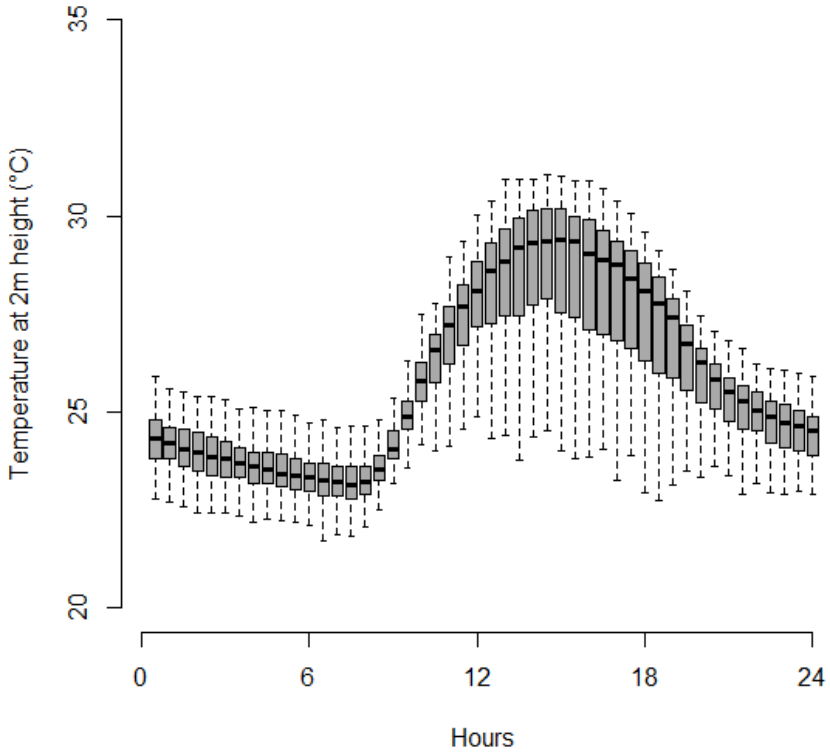

Figure 1: Daily temperature variation at 2m height under the canopy cover during the study period (June-September 2016).

***Changes in the manuscript**: Temperature variations are typically small below the canopy due to the shadowing by dense canopy crown and microclimatic conditions. During the study period, temperature at 2m height varies during the day from 22 °C in the night to 28 °C during the day. The presence of water condensation inside the tubing lines was carefully checked every week and never occurred during the study period.*

2. Were the instruments kept within operating temperature ranges: specifically the upper end of operating ranges? Where there diel changes in Licor and Picarro instrument temperatures?

***Response:** In our study site, all the systems were operating below dense understory vegetation and canopy cover, which naturally create a buffer maintaining air temperature relatively constant over the year (i.e. at daily and seasonally time scale). There were no diel changes in Licor and Picarro inside operating temperature: Picarro temperature was monitored and remained between 44.99 °C and 45.01 °C and Licor temperature at 51.7 °C.*

3. How often were the instruments calibrated?

***Response:** All the systems used at this time, i.e. from June to September 2016, were new and received from the manufacturers. We therefore did not re-calibrate them during the study period. We are confident that the data of the gas concentrations recorded by our analysers were robust.*

4. The authors subsampled from the flow downstream of the Li-8100A-IRGA into the Picarro G2308.What was the flow rate through the Picarro analyzer- was it 2.8L/min or some lowerrate? I don't see the flow controller in Figure 1a diagram- is it built into the external pump?

Response: *The flow rate of 2.8L/min corresponds to the flow between the chambers and the multiplexer which cannot be adjusted. This high rate inside the chamber allows to achieve a sufficient air mixing in the chamber headspace during the measurements. Flow rates in the subsampling lines (Li8100 and Picarro) were lower and set between 1.5 and 1.7L/min as recommended by the manufacturers.*

Changes in the manuscript*: Flow rates in the subsampling lines (Li8100 and Picarro) were lower and set between 1.5 and 1.7 L min-1 as recommended by the companies.*

5. What is the sampling volume inside the Picarro G2308? My concern is that if there is subsampling from a high flow rate at the T piece subsampling loop (Figure1 a) through a secondary instrument, and then flow is re-merged downstream of the external pump and returned to the closed chamber there may be a dilution effect. This might not impact a 2 minute sampling time period but may have a greater impact on a 25 minute time period.

Response: *The volume of the PICARRO analyser together with tubing from the subsampling loop represents 130 cm^3. It represents only 2% of the total volume (6088 cm^3) and the dilution effect was therefore limited.*

6. Did the authors also use their Picarro G2308 to measure CO_2 as well and if so how does that compare to the LI-8150 analyzer? This would provide confidence in running the two systems inline.

Response: *One step of our data quality check / quality control consisted in comparing the soil CO_2 effluxes measured by the PICARRO with the soil CO_2 effluxes measured by the Li-8100A. This method was also used to control that there were no leaks. Overall, both systems agreed very well. However, while the PICARRO G2308 analyser automatically reports dry mol fraction of CH_4 and N_2O, it only reports CO_2 uncorrected by H_2O concentration. As the precision of measurement was better for CO_2 using the Li8100 and as it also automatically reports dry mol fraction for this gas, we decided to use Picarro estimation for CH_4 and N_2O and Li8100 estimation for CO_2.*

<u>Specific questions:</u>

Pg 2 line 26: are the reference [17,18] in the correct format? This is the only location that lists reference numbers as opposed to first author.

Response: *This has been corrected*

Pg 3 line 23: the authors used an external pump, however the LI-8150 has an internal diaphragm pump- was this turned off or was it used in line with the external pump?

Response: *The system was always operating with the two pumps, the internal diaphragm pump of the Li-8150 and the external pump of the PICARRO, turned on, which limited the risk of water condensation inside the tubing line.*

Pg 3 line 28: the CRDS is not the "only" method that can detect low concentrations of N_2O. Can you change to "one of the only" as opposed to "only".

Response: *This has been corrected.*

Pg 4 line 14: the flow rate of 2.8L/min is very high. Was this flow rate tested to determine if pressure within the closed chambers was altered? I assume that the Licor 8100 chamber tops had their patented pressure relief value installed?

Response: *The flow rate of 2.8L/min corresponds to the flow between the chambers and the multiplexer which cannot be adjusted. This high rate inside the chamber allows to achieve a sufficient air mixing in the chamber headspace during the measurements. Flow rates in the subsampling lines (Li8100 and Picarro) were lower and set between 1.5 and 1.7L/min as recommended by the manufacturers.*

Figure1b) are all the tubing lines from the 16 chambers to the multiplexer 15m (as in the text)in length? A small point but they look like different lengths in the diagram.

Response: *Yes the length of tubing was 15 m for all chambers but as chambers are installed in a grid around the instruments, they are not all 15m away from the instruments. The length of the tubing lines (15 m) is cited in the caption.*

RC2, Referee #2 (Remarks to the Author):

The authors measured in situ soil fluxes of CO2, CH4 and N2O continuously with a commercially available automated chamber system coupled with a CRDS analyser in a tropical forest for four months. The manuscript is focused entirely on the methodological aspect of these measurements, stressing the importance of adjusting chamber closure times for the different gases for reliable flux calculations. The effect of closure times on flux calculation results were studied by trying different chamber closure times in the field and by adjusting the number of data points used for the actual flux calculation. This is a well-designed study, and overall, the manuscript is well written and structured. Also choosing appropriate chamber closure times and the operation of automated chamber systems are important topics for the soil flux community. However, I recommend publication of this manuscript after major revision because I have some general concerns with this manuscript.

Response: *We express our deep thanks to reviewer for his positive comments about our manuscript and constructive remarks. We have addressed, see below, our answers to each comment / remark.*

1. Soil Flux Pro provides for each chamber measurement linear and non-linear flux calculations. Why did you choose to use only the linear flux calculation results?

Response: *We firstly decided to use linear flux calculations only because we thought that the saturation effects characterised by a plateau after a certain time would be low. However, following your comment and comment from other reviewers, we changed flux calculations in the new version of the manuscript to use exponential estimations.*

The underestimation of fluxes with linear regression due to saturation effects is well-known. That's why numerous non-linear calculation schemes have been developed. Could you have significantly reduced the chamber closure time for the N_2O flux calculation if you had used non-linear flux calculation?

Response: *See previous comment.*

The selection of the flux calculation scheme can change the MDF at least for chamber measurements with only few gas samples over time. Does this effect disappear with high-frequency analysers, i.e. selection of the flux calculation scheme becomes less crucial in that regard? Would there still be a significant difference between the SHORT and LONG flux calculation for the different gases when using non-linear flux estimates?

Response: *The standard error approach that we used (Nickerson, 2016) is a first order approximation for the MDF from high-frequency measurements and the "true" MDF is a function of the chamber time-series fit type as well (i.e. Linear, exponential, quadratic). Nonetheless, while the use of linear regression resulted in systematically smaller fluxes as compared to exponential regression. It is therefore recommended to initially calculate fluxes with linear regression to determine the threshold for "low" fluxes and to recalculate them using exponential regression (Korkiakoski et al., 2017).*

Korkiakoski, M., Tuovinen, J.-P., Aurela, M., Koskinen, M., Minkkinen, K., Ojanen, P., Penttilä, T., Rainne, J., Laurila, T. and Lohila, A.: Methane exchange at the peatland forest floor–automatic chamber system exposes the dynamics of small fluxes, 2017.

Nickerson, N.: Evaluating gas emission measurements using Minimum Detectable Flux (MDF), Eosense Inc Dartm. N. S. Can., 2016.

2. You write about high-frequency measurements only as sampling measurement plots more frequently over time. However, you could also address the high-frequency sampling during a chamber closure since you use high-frequency gas analysers and work with MDF in your data analysis. There are several automated chamber systems which do not employ high frequency analysers, but still collect discrete gas samples which have to be analysed with a GC. Especially for N_2O it is very interesting to see what fluxes we can capture with CRDS in comparison to GC analysis.

Response: *In a previous study in the same environment (Courtois et al., 2018), we estimated that the minimum detectable fluxes using Gas Chromatography analysis of four discrete gas samples over 30 minutes for N2O was ± 8.3 μg N m−2 h−1. MDF estimated in the present study using high frequency measurement was 0.002 nmol m-2 s-1 or 0.2 μg N m-2 h-1 for N_2O which is therefore ~ 40 times lower. We added a sentence in the manuscript to highlight this interesting fact.*

Courtois, E. A., Stahl, C., Van den Berge, J., Bréchet, L., Van Langenhove, L., Richter, A., Urbina, I., Soong, J. L., Peñuelas, J. and Janssens, I. A.: Spatial Variation of Soil CO_2, CH_4 and N_2O Fluxes Across Topographical Positions in Tropical Forests of the Guiana Shield, Ecosystems, 1–14, 2018.

3. You only write how the SHORT and LONG measurements affected the flux estimates. But how did they affect the uncertainty of the single flux estimates? How large/small were the error bars for the flux estimates?

Response: *Comparison of standard error of single flux estimates using 2 minutes or 25 minutes estimations for two weeks (from August 2nd for August 9th and from August 16th for August 25th) shows that standard errors are always higher for 2 minutes than for 25 minutes estimation for all three gases (Figure 2 below). Nonetheless, we decided not to integrate this figure in the manuscript because it does not add much to the study.*

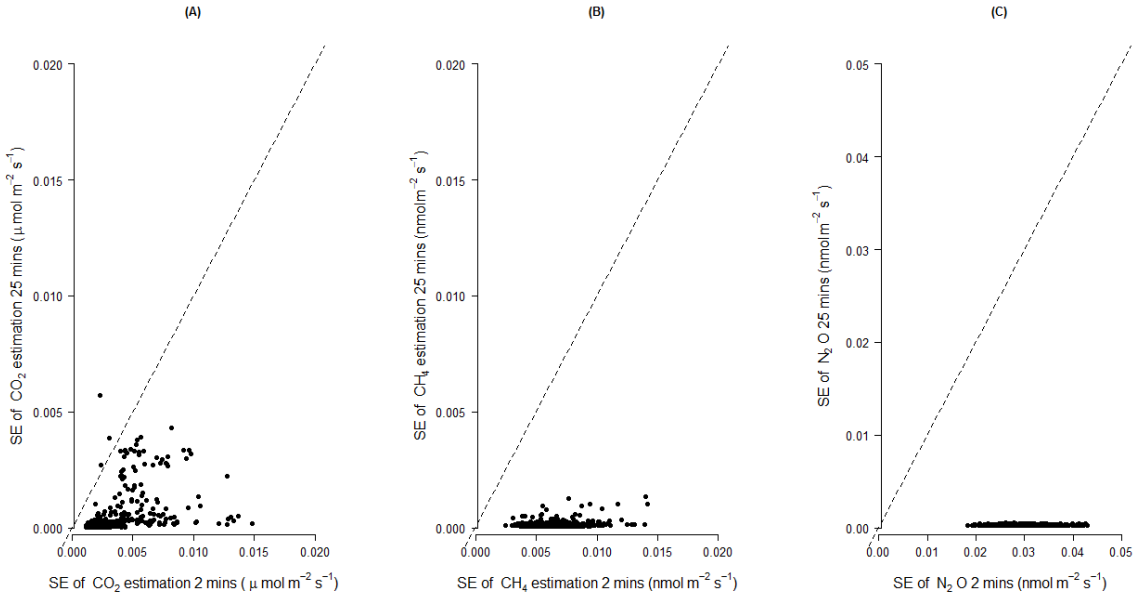

Figure 2: Comparison of standard error of single flux estimates using 2 minutes or 25 minutes estimations for two weeks (from August 2nd for August 9th and from August 16th for August 25th)

4. Could you have just used one, namely the LONG, closure time for all chambers and only choose for the flux calculation between SHORT and LONG calculation times? This would be more practical than rotating closure times between chambers.

Response: *Setting all chambers as LONG measurements would have led to a maximum of ~ 3 measurements only per chamber and per day. Mixing LONG and SHORT measurements allows to maximise the number of measurements per chamber and per days while ensuring a reliable estimation of the low N_2O fluxes and to capture transient peaks of CH_4 and N_2O.*

5. In section 3, the results are clearly presented, but the discussion part is very limited.

Response: *The main aim of our study was not to identify controls and mechanisms of the soil GHG fluxes but rather to test novel soil GHG systems for continuous high-frequency measurements. We think that this manuscript could be used as technical support to set up new soil systems and contribute to record comparable soil GHG data in other regions around the world. Nonetheless, the discussion has been revised in the new version of the manuscript to integrate discussion on spatio-temporal variability of fluxes based on our study.*

Specific comments:

Page 2, line 26: numbers instead of author names for references

Response: *This has been corrected.*

You are not always consisted in how you write company names (capital versus small letters). Also often you write 'minute' when you could just use 'min'.

Response: *We corrected this in the new version of the manuscript.*

Page 3, line 23: What are the pump specifications? Was it the pump supplied by Picarro with the instrument or did you use another pump?

Response: *We have included more information in the manuscript about the external pump provided by PICARRO: recirculation pump A0702*

Page 4, lines 9.: The soil temperature and soil moisture probes, were those the ones which can be directly attached to the chambers?

Response: *The soil temperature and soil moisture probes were those provided by Li-COR, which are directly attached to the chambers. The probes measured soil temperature and soil moisture around the PVC collars. We have added more details in the text.*

Page 5, line 5.: Did you use the analytical accuracy specified on the technical data sheets of the analysers or did you perform measurements yourself?

Response: *We used the analytical accuracy specified on the technical data sheets of the analysers. This is now specified in the new version of the manuscript.*

Where there significant air pressure and ambient temperature changes at your site over the four months? If yes, did you test how different temperature and pressure values could change the MDF estimate? Is nincl. or excl. the deadband?

Response: *Please, see our response to reviewer 1 above (2.). In our study site, because all the systems were operating under dense understory vegetation and canopy cover, air temperature*

remained relatively constant over the year (i.e. at daily and seasonally time scale) near the soil surface. This is also true for air pressure.

Page 6, line 6: What CO2 concentrations were reached during LONG closure times (and forCH4)?

Response: *CO_2 concentration can reach 2000 ppm and CH_4 concentration 4 ppm.*

Page 6, line 7: I find that confusing in comparison to section 2.5. So considering the deadband, the chambers were closed for 3 and 26 minutes, respectively?

Response: *No, the chamber stayed close for 2 minutes and 25 minutes and the first minute was not used for the flux estimation. As we have a sampling frequency of 1 second, it still represents 60 points for curve fitting. Nonetheless, we agree that this could be considered as a too short period for CH_4 and CO_2 estimation using the SHORT (2 minutes) closure time. We therefore compared the CO_2 and CH_4 estimations with a deadband of 60 seconds (fluxes estimation with 60 seconds) with a deadband of 30 seconds (fluxes estimation with 90 seconds) for the week from August 16th to August 25th. These two estimations were very well correlated (see figure 3 below) so we decided to keep our 60 s deadband results.*

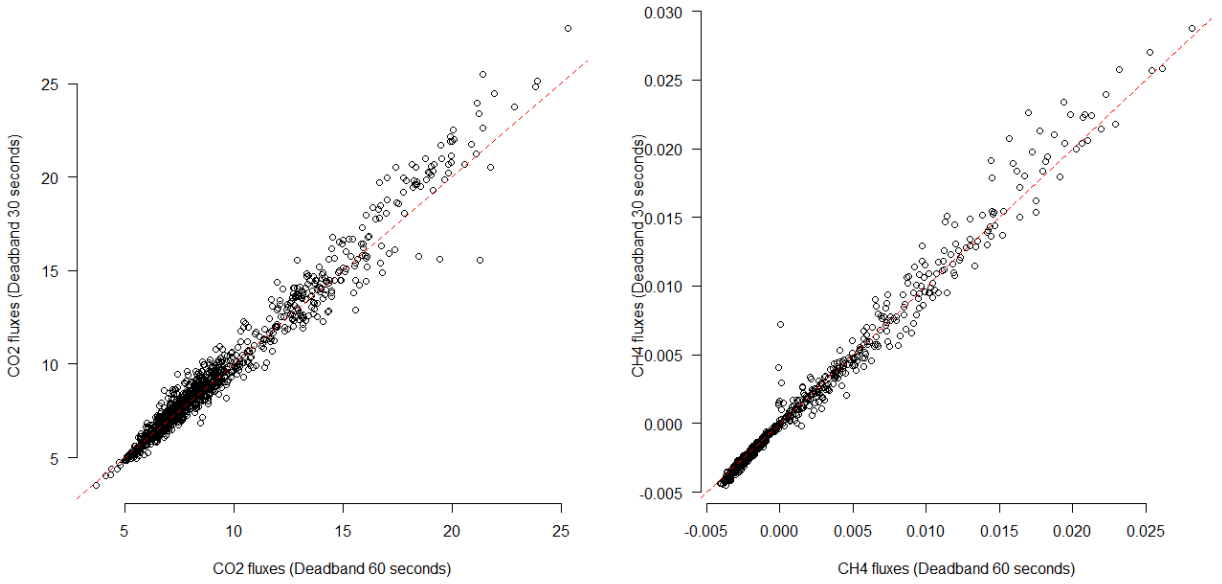

Figure 3: Comparison of CO_2 and CH_4 fluxes with a 30 seconds and a 60 seconds deadband for the week from August 16th to August 25th. The red dotted lines represents the 1:1 line.

Page 6, line 20: Why did you consider these fluxes as unreliable when the chamber quality check using the R^2 for CO_2 was passed? Are you not unnecessarily filtering out fluxes which are not significantly different from zero, and thus introducing a bias in your data? Because this often happens when using R^2 as a filter criterion for low fluxes.

Response: *Because of the high soil respiration activity, low soil CO_2 fluxes do not really occur in this tropical rainforest, not even during the dry season. When the R^2 criterion for CO_2 was not passed, it always corresponded to situations of imperfect closure of the chamber, due to leaves or small branches lying on the soil collars (381 measurements over 17796, i.e. 2.1%). In these cases, it was therefore necessary to remove flux data for the three gases.*

Page 6, first paragraph of section 3: You had no problems with humidity and the automated chamber system at your site?

Response: *Please, see our response to reviewer 1 above (1.); at the given flow rate and the small diel cooling, we had no problems with water condensation inside the tubing lines of our system.*

Page 7, line 3: The conclusion about the 2 min sampling time sounds absolute, but it is only valid for your small chambers. Except for the necessary descriptions in the method section, you completely disregard the role of chamber volume for choosing the right chamber closure time.

Response: *We added a sentence to precise that our result is valid for small chambers only.*

Page 7, lines 20/21: That sentence does not make any sense to me. 85.6 % of the fluxes were above or below?

Response: *This sentence has been considerably modified.*

Page 8, line 4: You didn't show the diurnal variation in your data. This is more a point for the discussion than a conclusion from your presented data.

Response: *We agree with the reviewer; however, ecological interpretation of our data will require more long-term data and will be published in a future paper. Here, we wanted to provide a technical report with information on how to get robust results on GHG flux estimations rather than on how these fluxes are produced and vary.*

The references are not well formatted.

Response: *References were reformatted*

Table 1: Use superscript for the units.

Response: *This has been corrected*

Table 2: Include n for each chamber.

Response: *This information has been added.*

Check how the units are written on the y-axis of the figures.

Response: *This has been checked..*

RC3, Referee #3 (Remarks to the Author):

In this manuscript, the authors detail a field-deployed and field-tested system for measuring soil greenhouse gas (GHG) emissions (CO2, CH4 and N2O) from a tropical wet forest; the system leverages a commercially-available automated flux chamber system with a commercially-available CRDS analyzer. More specifically, the authors (a) outline the technical protocol for implementing such a system, (b) report the mean fluxes and variability of CO2, CH4 and N2O observed over the four-month deployment period and (c) test two chamber closure lengths to determine the most effective experimental design for capturing fluxes above minimum detectable levels. Successfully implementing such a system in the tropics is both difficult and has only been done rarely, so a technical note detailing how to do so is absolutely a contribution to the literature. I have two general/more broad comments about the manuscript, which I detail below, and also include several more specific comments at the end of this review

Response: *We thank the reviewer for the positive comments and constructive inputs.*

1. Concerns regarding flux calculation protocols

In these automated, high-frequency GHG systems, one important set of experimental design and protocol decisions govern how to calculate flux rates and screen for acceptable data points. The authors lay out fairly transparent information about how they calculated their flux rates for each gas, but I wonder if more discussion of the implications of their calculation choices is warranted. I have a few specific questions. Am I correct in understanding that the authors only calculated flux rates for all three gases based on a linear model (Pg 4, Ln 27)? If so, I wonder why they didn't consider also fitting exponential models to the CH_4 and N_2O fluxes, if not the CO_2 fluxes.

Response: *We first decided to use linear flux calculations only because we thought that the saturation effects characterised by a plateau after a certain time would be low. However, following your comment and comment from other reviewers, we changed flux calculations in the new version of the manuscript to use exponential estimations.*

The authors themselves note on Pg 5, Ln 17 that using certain chamber closure times (which, of course, this paper is very interested in) in combination with a linear flux fit can lead to flux underestimation. Couldn't the "optimal" chamber closure time that the authors attempt to find also include some experimental designs with different closure lengths but non-linear flux fits?

Response: The standard error approach that we used (Nickerson, 2016) is a first order approximation for the MDF from high-frequency measurements and the "true" MDF is a function of the chamber timeseries fit type as well (i.e. Linear, exponential, quadratic). Nonetheless, while the use of linear regression resulted in systematically smaller fluxes as compared to exponential regression. It is therefore recommended to initially calculate fluxes with linear regression to determine the threshold for "low" fluxes and to recalculate them using exponential regression (Korkiakoski et al., 2017).

Korkiakoski, M., Tuovinen, J.-P., Aurela, M., Koskinen, M., Minkkinen, K., Ojanen, P., Penttilä, T., Rainne, J., Laurila, T. and Lohila, A.: Methane exchange at the peatland forest floor–automatic chamber system exposes the dynamics of small fluxes, 2017.

Nickerson, N.: Evaluating gas emission measurements using Minimum Detectable Flux (MDF), Eosense Inc Dartm. N. S. Can., 2016.

Additionally, the Picarro G2308 records numerous diagnostic variables alongside GHG concentrations, including measures of moisture, temperature, pressure, etc. From methods section 2.6, I am under the impression that fluxes were only struck from the dataset if they were (a) below the MDF, (b) had an R^2 for $CO_2 < 0.9$, or (c) only struck N_2O data if the SHORT $R^2 < 0.8$. First, the authors might consider including a supplemental figure that justifies their decision not to have data quality rules around CH_4, as they do for N_2O.

Response: *We decided to use the same quality check for CH_4 than for N2O and to only struck CH_4 data if the SHORT $R^2 < 0.8$. As you can see in the CH_4 figure, the main emission or consumption peak during the 2 minutes measurements are still present.*

Second, like the other reviewers, I was curious as to how humidity was dealt with, since it appears that the moisture-related diagnostics weren't used to evaluate data quality. Was there a water trap that isn't marked in the instrument set-up diagram?

Response: *We regularly checked that no liquid water accumulation occurred in the sampling tubes. Moreover, both analyzers measure also water vapor and its effect on concentration of CO_2, CH_4 and N_2O was accounted for. We also monitored Licor and Picarro inside operating temperature: Picarro temperature remained between 44.99 and 45.01 C and Licor temperature at 51.7 C.*

More broadly, as this paper aims to outline best practices for setting up this kind of experiment in the tropics, fleshing out the data management aspect of things would improve the paper, in my opinion.

Response: *We think that we already included many aspect of quality check and data management and more information can be found in the new version of the manuscript. All the subsequent figure and analysis were done using R software and we would be happy to share the codes upon request.*

2. Technical note vs. data exploration paper

The aspects of this paper that serve as a technical note are novel and helpful. That said, the results and discussion section, in which the observed GHG fluxes are analyzed, is perfunctory and is relatively focused on a methodological question: what chamber closure time should be used in this system, and how can others determine what chamber closure time to use in their analogous system? I found myself wishing that there was a more robust analysis of the GHG data itself and the ecological implications of their various findings.

See also my comment below about Table 2.

Response: *See RC2 (5)*

Specific comments:

* Pg 7, Ln 30: The authors ultimately recommend a sampling protocol that rotates between short and long closure times. What is preventing them from recommending always doing LONG chamber closures and only using the first two minutes of chamber closure time to calculate the CO_2 flux, thus decreasing the amount of human labor needed to swap out the system program once a week?

Response: *Setting all chambers as LONG measurements would have led to a maximum of ~ 3 measurements only per chamber and per day. Mixing LONG and SHORT measurements allows to maximise the number of measurements per chamber and per days while ensuring a reliable estimation of the low N_2O fluxes and to capture transient peaks of CH_4 and N_2O. Moreover, under tropical conditions, a visit once a week is absolutely necessary to ensure a proper maintenance of the setting (removing fallen leaves, branches, etc…).*

* Pg 7, Ln 23 / Figure A2: This figure is used to justify why LONG chamber readings weren't reliable for N_2O flux estimation, but these data don't indicate that the variable fluxes are unreliable, only that they are variable and considerably larger in magnitude than the SHORT N_2O flux estimates. Can an additional supplemental figure be added showing the R^2 values for the LONG vs. SHORT N_2O fluxes? Or some similar figure that shows why the LONG fluxes are considered unacceptable?

Response: *If we understood well your question, you are asking why we considered SHORT (not LONG) N_2O fluxes as unacceptable. In order to compare the fluxes from SHORT and LONG closure time, we have added a third graph to the Figure 2 (previously supplementary Figure 1). It shows that N_2O fluxes estimated using the SHORT closure time are not correlated with fluxes estimated with the LONG closure time (R^2 of 0.02) and should not be considered.*

* Pg 7, Ln 31: "Our unique system…" and Pg 8, Ln 12: "this is the first time that this experimental set up is described and tested under tropical field conditions." I believe an analogous system was described in Puerto Rico (O'Connell et al 2018, Nature Communications, https://doi.org/10.1038/s41467-018-03352-3), though not as a technical or methods paper.

Response: *We realised that, although the suggested reference was in the list of references, it was not mentioned in the text and we now cite this reference in the introduction. In this reference, the authors are measuring CO_2 and CH_4 but not N_2O fluxes. Moreover, the description of the experimental design of the automated soil fluxes measurement system in this paper is very short and does not give the specification of the multiplexer not the exact model of the CRDS Picarro analyser that they used. We therefore still believe that our study is the first one describing in detail the simultaneous measurement of the three GHGs under tropical field conditions.*

* Appendix Figure A1: Might be worth including the N_2O comparison just as the CO_2 comparison is included even though the authors discard the LONG CO_2 flux estimates

.

Response: *In the revised manuscript, this figure is now presented in the main text (Figure 2) and also includes the N_2O.*

* Table 2: A number of the authors' chambers reported mean N_2O fluxes below 0. This seems worth mentioning in the results and/or discussion.

Response: *We agree with the reviewer and, as suggested, we have added some comments about the respective parts of the N_2O and also CH_4 emissions and absorptions. We have estimated that 28% of our fluxes indicated a sink for N_2O and 72% a source for N_2O and that 59% of our fluxes indicated a sink for CH_4 and 41% a source for CH_4.*

SC1, Referee #4 (Remarks to the Author):

In the recent years, several studies highlighted the need for continuous measurements of soil GHG other than CO2, which has been technically challenging for long time. However, combination of different new instrumentation allows addressing this challenge nowadays. I think this manuscript a timely technical note addressing one of the most important issues regarding continuous measurements: which is the balance between frequency and reliability of measurements? Despite some of the points discussed in the paper are instrument specific considerations (Li8100 and G2308), I think that most of them apply for high-frequency studies using other instrumentation. In my opinion, two points could be covered more in depth in order to make the manuscript more strong and inspiring for the community:

(i) suitability of linear or exponential fits for estimating GHG fluxes, especially under high emissions and long chamber closure time

Response: *We first decided to use linear flux calculations only because we thought that the saturation effects characterised by a plateau after a certain time would be low. However, following your comment and comment from other reviewers, we changed flux calculations in the new version of the manuscript to use exponential estimations.*

(ii) which threshold criterions do we have to apply for low rate fluxes and which are the consequences of using different criterions on temporal patterns (both short and long term scales) and on accumulated emission estimates.

Response: *Some information regarding this issue were added in the new version of the manuscript.*

Finally, I want to recognize the challenge of running this complex instrument setup in a tropical forest. Dealing with high moisture when using IRGAS and CRDS is not easy, but the authors succeeded.

Response: *Thank you for this positive comment.*

I am looking forward to see the data in the full experiment context with their ecological implications. Here you could find some specific comments, suggestions and open discussion points:
Pg3 L19-28. Li-8100 can detect really small fluxes of CO_2 as well. I guess that the main reason for using both Li-8100 and Picarro G2308 is that one instrument controls the chambers and the

other measures the three gases. Additionally, measuring simultaneously CO_2 with two independent systems is a good control to validate the proper performance of the instruments. I wonder which was the agreement in CO_2 between Li8100 and G2308.

Response: *In our system, the automated chambers were controlled by the Li-8150, which was controlled by the Li-8100A. The gas analysers were Li-8100A for the CO_2 and PICARRO G2308 for the CH_4 and N_2O. We recommend using the Li-8100A to determine the soil CO_2 effluxes but recognise that CO2 information provided by the PICARRO can still be used to check for potential leaks in the analysers / tubing.*

P4 L24-28. I don't know if I understand this statement, but SoilFluxPro (Li-COR software) allows to directly upload hundreds of Picarro files simultaneously (up to 2 months). You can choose to open all the files in one single file, and directly merge it with the Li-COR data.

Response*: When we first used this import function in SoilFluxPro, we realised that there were problems when importing Picarro files (that are split in one file per hour) by suing the function IMPORT. When a measurement was overlapping two distinct hours (for example a flux estimation from 8:50 am to 9:15 am, the function RECOMPUTE in SoilFluxPro only take into account the first Picarro file. We contacted Licor for this issue and they agree that this was a weakness of the software. They are currently working on it to implement this in a new version of the software. In the meantime, the use of the R function that we developed and that can be found in the supplementary material to merge all Picarro files in one file allows to overcome this issue.*

P4 L28-30. One of the best things of using SoilFluxPro is that calculates the fluxes using both linear and exponential fits, which could result in substantial differences in fluxes (see the attached example from my own data). My experience is that exponential equations usually fits better than linear ones (in terms of R^2), especially for high flux rates under long chamber closure times.

Response: *See responses to previous comments, exponential fits were now used for all flux computations.*

P4 L29. Which was the actual length of each measurement without including the deadband?

Response: *See comment from RC2*

P5 L5. Why are you not using CO_2 measured with Picarro?

Response: *Please, see our response to reviewer 1 above (6.).*

P5 L7-8. I guess that it has to be the volume of the system (chamber, Li8100, Picarro, multiplexer and tubing). This is really important since the volume of the system is a parameter controlling the minimum detectable flux, so Table 1 might substantially change depending on this "detail".

Response: *Yes, it is the volume of the whole system.*

P5 L16-17. Again, this can be solved using exponential fits.

Response: *See responses below*

P6 L7, L13 and L17. I guess these are not the correct figures.

Response: *This has been corrected*

P6 L14-20. As far as I understood, you kept values higher than MDF (for emissions) and lower than –MDF (for sinks), but what happen with values close in between (-MDF < x < MDF)? What did you do with values close to 0 flux? And what happen if a flux was higher than MDF but had low R^2? The same applies for N_2O. Which criterion we have to use when measuring gas emissions at low rates? Is it a 0 flux, NA, should we keep the calculated flux regardless of the R^2? Choosing one or other criterion might have several implications in order to estimate cumulative or mean fluxes, especially if the data does not have normal distribution and it's not 0 centered. In L11 you describe an R^2 criterion for considering stable micrometeorological and chamber conditions based on CO_2. Then, why we should apply other criterion for the other gases if the conditions are stable? I understand that for this might not be super relevant for a technical note, but this is a key question if you want to quantify emissions in natural conditions. In my opinion, this is the core of the study, and one of the most challenging issues we need to address when measuring CH_4, N_2O and other trace gases. When we have high fluxes, everything is clear, but when we have low fluxes, it turns more complicated. We were discussing this issue in Petrakis et al. 2017, but I still don't have the answers. I guess there is not a silver bullet.

Response: *We agree with the reviewer that this is one of the main challenge of CH_4 and N_2O soil fluxes estimation. For CO_2, fluxes from tropical soils are always high so the R^2 criterion allows to easily detect measurement issues such as imperfect chamber closure. In this case, it is logical to remove fluxes estimation for the three gases. For CH_4 and N_2O, we decided (1) to consider fluxes below MDF as null fluxes (i.e. fluxes so small that they are below detection limit) (2) to consider fluxes above MDF but with a low R^2 were considered as NA (Not available, fluxes estimation impeded by unknown measurement issues).*

Figure 1A. There is something in this panel it's not completely clear. As far as I understand, the air goes from the chamber to the multiplexer, to Li8100, to G2308, to the external pump, to the multiplexer and again into the chamber. However, in the schematic view there is a black circuit (T piece sub-sampling loop) that connects the multiplexer, Li8100, G2308 and the external pump. Since the air composition does not change between these four elements, why the subsampling tub was not inserted in serial at one point of the circuit?

Response: *Inserting the subsampling loop in parallel rather in in serial was a proposition from the manufacturer that we followed here.*

Table 2. I wonder which closure time did you use in this table (2 or 25min). It would be interesting a comparison between 2 and 25 closure times. I'm not sure you will find differences in the means. This would suggest that short closure times might not affect the annual balance but deviation of the data (as we can see in Ap Figure 2).

Response: *In this table, we used all fluxes estimation available after quality checking. Your proposition is interesting but as 2 and 25 minutes estimation were not made on the same weeks, it is difficult to compare them. We therefore propose to keep this table as it is but we stated in the table caption that this estimation was made using all the data available and we also added the number of data points that were used for this estimation.*

Appendix Figure A1. In my opinion, this is one of the most interesting figures in the manuscript and I think it should be place in the main manuscript.

Response: *The figure was placed in the main text*

Some suggestions:

a) Regressions will have better fit if you use exponential equations for estimating the flux. For each flux you can choose linear or exponential depending on the R^2.

Response: *Exponential fits were now used for all fluxes estimation.*

b) Could you display R^2 and the coefficients of the regressions between 2 and 25min? Regression B shows a good fit, but it seems that 2 min fluxes tends to overestimate fluxes compared to 25min estimates. Again, this could be an artifact of using linear regressions and not exponential.

Response: *This figure has been modified by using exponential fits and the R^2 were added*

c) It would be interesting plotting the regression for N_2O including all values (without removing data using R^2 or MDF criterions)? This is related to my comment on Table 2.

Apendix Figure A2. Please, edit the figure caption. Petrakis, S., Barba, J., Bond-Lamberty, B. and Vargas, R.: Using greenhouse gas fluxes to define soil functional types, Plant Soil, 1–10, 2017.

SC2, Referee #5 (Remarks to the Author):

This manuscript focused on a very important topic about soil CO2/CH4/N2O fluxes in tropical rainforest. The experiment was well designed. Particularly, this may be the world's first report about in situ and simultaneously measurement of soil CO2/CH4/N2O fluxes at low latitude (between 10◦N and 10◦S). I would like to give the authors my comments.

Response: *Thank you for this positive comment.*

1. Important references:

To date, through the "Web of Science", I could not find any publication about continuous measurement of soil CO2 efflux (Rs) using the automated chambers in the low latitude tropical forests that between 10_ N and 10_ S. Though two campaign studies in very humid forests (ï´C ,s3500 mm of annual precipitation) using automated chambers each in northeastern Australia (17_ S) (Kiese and ButterbachBahl, 2002) and northeastern Puerto Rico (18_ N) (Wood et al., 2013) were conducted only less than 6-month period, they observed similar phenomenon with Rs was higher during the dry season but lower during the wet season. Kiese and ButterbachBahl

(2002) also measured N2O flux. Conversely, a 4-year continuous measurement of Rs in a seasonal dry (1,250 mm of annual precipitation) tropical forest in western Thailand (14_ N) showed higher Rs in wet season than that of dry season (Hanpattanakit et al., 2015).

Response: *In fact, a very recent paper reported continuous monitoring of Rs during three years in the tropical forest of Panama (Rubio and Detto, 2017). Moreover, a previous study conducted at the same site as ours (Paracou site, near the Guyaflux tower) also reported 577 days of Rs measurement (Rowland et al., 2014). Both references highlighted a significant effect of soil moisture on seasonal and diurnal cycles of Rs. Together with the two other references from tropical that you cited, there provide evidences that Rs in tropical forest soils are typically higher in the wet than in the dry season. The other study that you cited (Hanpattanakit et al., 2015) was conducted in a seasonally dry forest which are apparently reacting differently than typical tropical wet forest (precipitations > 2000m/year). Nonetheless, the results that we are presenting in our study were conducted from June to September 2016 which corresponds in our site to the end of the wet season and the onset of the dry season. With these data, we cannot discuss seasonal effects, at least one full year, or more, of measurements would be necessary for this.*

Rowland, L., Hill, T. C., Stahl, C., Siebicke, L., Burban, B., Zaragoza-Castells, J., Ponton, S., Bonal, D., Meir, P. and Williams, M.: Evidence for strong seasonality in the carbon storage and carbon use efficiency of an Amazonian forest, Glob. Change Biol., 20(3), 979–991, 2014.

Rubio, V. E. and Detto, M.: Spatiotemporal variability of soil respiration in a seasonal tropical forest, Ecol. Evol., 7(17), 7104–7116, 2017.

2. CO2 flux:

Empirically, also see the above references, CO2 flux is largely controlled by soil moisture (rain events) at tropical forests. However, based on Fig 3, during 4-month experiment (June-September 2016), most of the chambers did not show temporal variation in CO2 flux. Thus, the authors are suggested to add soil moisture (and temperature) data to Fig 3 and provide some discussion about the (lack of) relationships between Rs and soil moisture and temperature.

Response: *As discussed in above, a four months period is limited to go deep into such relationships, especially in tropical forest where temporal and spatial variability of fluxes are high. You can find below a figure that can now be found in the supplementary material of the manuscript displaying the relationship of the three gases with soil moisture. Nonetheless, going deeper in the discussion of the effect of rain event, soil moisture and the relative importance of spatial, seasonal and diurnal variability of fluxes cannot be done with these dataset that was specifically constructed to demonstrate the feasibility of running the system under tropical conditions.*

3. CH4 flux:

Generally speaking, upland forest soil is a CH4 sink, even lowland tropical forest soil. Compared to Rs, however, CH4 flux is more complex and generally has large spatial variation, because the termite activity can emit CH4 thus offset a partial of the soil CH4 sink. I am confused with Table 2, because ten of the sixteen chambers showed CH4 source. Li-Cor soil chamber (8100-104) can

be considered to block most activity of the termite, because the chamber base (collar; 7 cm in height) was inserted _7 cm into the soil and left another 4 cm above the soil; in addition, the chamber has relative additional big metal base surround the collar. On the other hand, inserted chamber base (collar) into the tropical (clay) soil can (sometimes) cause waterlogging inside the Li-Cor soil chamber (8100-104), which might convert the CH4 sink to CH4 source. Same with CO2 flux, temporal variations in CH4 fluxes also could not be detected in Fig. 4. Also, megascopically, the chambers did not show the common pattern of temporal variation in CH4 fluxes (Fig 4). Sure, this forest has plentiful precipitation (about 3000 mm) and very low elevation, both of these abiotic factors may cause the site as CH4 source. Thus, the authors are suggested to provide some more discussion about (the lack of) spatio-temporal variation in CH4 flux.

Response: *Again here, this result can be easily explained by the time frame of the study. Tropical soils are generally considered as sink at a yearly basis but much study show that there are seasonal variation in CH_4 fluxes and that tropical soils tend to shift from a sink in the dry season to a sources during the wet season. Here, a four months period is limited to go deep into such relationships, especially in tropical forest where temporal and spatial variability of fluxes are high. You can find below a figure that can now be found in the supplementary material of the manuscript displaying the relationship of the three gases with soil moisture. Nonetheless, going deeper in the discussion of the effect of rain event, soil moisture and the relative importance of spatial, seasonal and diurnal variability of fluxes cannot be done with these dataset that was specifically constructed to demonstrate the feasibility of running the system under tropical conditions.*

4. Appendix Figure A1:
This figure shows a very general (basic) chamber-problem for measurement of soil GHGs fluxes. Long closure time will cause higher GHGs concentration (if the soil is GHGs source) or lower GHGs concentration (if the soil is GHGs sink) inside the chamber, which will induce underestimation of GHGs flux (saturation effect). Saturation effect is generally positively associated with both flux rate and ratio of the effective chamber volume to the measured soil surface area. Empirically, I believe the 2-mintute
closure time is enough for measurement of both CO2 and CH4 flux in tropical forests, even for most temperate and boreal forests. For Li-Cor soil chamber (8100-104), the ratio is (0.0040761/ 0.03178=0.12826 m) = 12.3 cm. However, for many of the custommade soil chambers, the ratio is generally higher than 12.3 cm, thus this is might be the specific problem (issue) only for Li-Cor soil chamber (8100-104). I suggest the authors feedback this problem to Li-Cor and suggest Li-Cor to draw this problem to their instrument user manual.

Response: *Thank you for this feedback. Following comments from the other reviewers, we used exponential fit for estimating all fluxes which improved this saturation issue. Also, as stated in the manuscript, we always used 2 minutes estimation for CO_2 fluxes to overcome this issue.*

5. Also for Appendix Figure A1:
The authors are suggested to re-draw the Appendix Figure A1 indicating different symbols (or color) for each of the four chambers.

Response: *Following comments from the other reviewers, this figure has been moved to the main text and now also include N_2O. We decided to use different colours (black and grey) for the two distinct weeks that were used for this comparison instead that different colours for the different chambers because it allows a better view of the fact that these two weeks are covering almost the whole range of fluxes that can be encountered in the site.*

6. Closure time:
When compared Table 1 with Table 2, the closure time of 10 minutes for measurement of N2O flux was enough. Thus, the Table 1 is suggested to be deleted.

Response: *We disagree with this comment. A closure time of 10 minutes would have led to a MDF of 0.009 instead of 0.002. In this case, only 82% instead of 96% of the fluxes would have been considered of reliable. We therefore decided to maintain Table 1 in the manuscript as it allows to show that a MDF of 0.002 can only be achieved with a 25 minutes closure time.*

7. Additional suggestion 1:
To prove the data quality or measurement precision, the authors are suggested to add a plot showing changes in CO2, CH4 and N2O concentrations in the chambers. Following is a sample plot (Sample Fig).

Response: *We think that this information is not adding much to the comprehension of the study and it was not included in the new version of the manuscript.*

8. Additional suggestion 2:
As I mentioned in the above, this may be the world's first report about in situ and simultaneously measurement of soil CO2/CH4/N2O fluxes at low latitude (between 10_N and 10_ S). I believe this paper will be a potential high citation rate if the authors can give some more discussion about spatio-temporal variation in CO2/CH4/N2O fluxes and their control factors. For example, the coefficient of variation (CV) was used to represent the spatial variation. CV of Rs can be calculated by CV = (SD/(mean Rs))_100.

Response: *Mean and SD per chambers are available in Table 2 and we added a figure with mean value of each chamber per days for the three gases allowing to visualize the spatio-temporal variability of fluxes.*

Automatic high-frequency measurements of full soil greenhouse gas fluxes in a tropical forest

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Abstract. Measuring *in situ* soil fluxes of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) continuously at high frequency requires appropriate technology. We tested the combination of a commercial automated soil CO_2 flux chamber system (LI-8100A) with a CH_4 and N_2O analyzer (Picarro G2308) in a tropical rainforest for 4 months. A chamber closure time of 2 minutes was sufficient for a reliable estimation of CO_2 and CH_4 fluxes (100% and 98.5% of fluxes were above Minimum Detectable Flux – MDF, respectively). This closure time was generally not suitable for a reliable estimation of the low N_2O fluxes in this ecosystem but was sufficient for detecting rare major peak events. A closure time of 25 minutes was more appropriate for reliable estimation of most N_2O fluxes (85.6% of measured fluxes are above MDF ± 0.002 nmol m^{-2} s^{-1}). Our study highlights the importance of adjusted closure time for each gas.

Keywords: Soil fluxes, French Guiana, methods, optimizing, Minimum Detectable Fluxes

1. Introduction

Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the three main greenhouse gases (GHGs) in terms of radiative forcing. Increases in these GHG concentrations in the atmosphere is driving anthropogenic global warming. Understanding the magnitude of GHG fluxes in natural ecosystems has recently become a priority in the study of GHG balances (Merbold et al., 2015). Tropical intact forests cover 1392 Mha globally and represent about 70% of the total tropical forest area (1949 Mha), which accounts for the largest area of global forest biomes (~50%). Very few reliable long term datasets on full GHG balances are available from tropical ecosystems, despite their known importance for the global cycles of these three GHGs (Dutaur and Verchot, 2007). This is in part due to the challenges of designing and operating continuous, multi-gas flux analysis systems in tropical forests. Soil processes in particular are responsible for an important part of GHGs that are produced or consumed in tropical ecosystems (Oertel et al., 2016). Soil physical, chemical, and biological characteristics are linked to variation in GHG emissions from soils, which in turn can display very high spatial and temporal variability (Arias-Navarro et al., 2017; Silver et al., 1999).

Historically, soil GHG fluxes (emission or consumption) have been measured using the static chamber method. This involves closing chambers manually for a known period of time, usually 30-60 minutes, and repeated collection of air samples for further analysis via gas chromatography (Verchot et al., 1999, 2000). Fluxes are then computed from the increase (or decrease) in gas concentration per unit time, per surface area enclosed by the chamber, and corrected by the volume of the chamber. While these labor-intensive and time-consuming manual measurements are well adapted to capture high spatial flux variability (Arias-Navarro et al., 2017; Pumpanen et al., 2004), they do not capture high temporal variation, which is necessary for the

accurate estimation of annual GHG budgets. Moreover, short term, transient spikes in the emission or consumption of these GHGs likely remains undetected with static chamber methods, imposing a lost opportunity to fully understand the production or consumption processes of GHGs and their response to rapidly changing environmental conditions. One of the key challenges of contemporary GHG flux research is to close these knowledge gaps in order to improve the quantitative prediction of GHG fluxes (Merbold et al., 2015).

The use of automatic chambers is one approach to obtain continuous estimation of soil GHG flux data at high temporal frequency (several measurements per days) at various sampling points. Since the 1970s (Denmead, 1979), a variety of technical solutions for automated flux sampling have been developed (Ambus et al., 2010; Breuer et al., 2000; Görres et al., 2016; Kostyanovsky et al., 2018; O'Connell et al., 2018; Petrakis et al., 2017a; Savage et al., 2014)~~(Ambus et al., 2010; Breuer et al., 2000; Görres et al., 2016; Kostyanovsky et al., 2018; Petrakis et al., 2017a; Savage et al., 2014)~~, particularly for soil CO_2 fluxes. However, accurate detection of CH_4 and N_2O fluxes from soils via flow through systems is more difficult than CO_2 due to significantly lower background concentrations and lower flux rates (Kostyanovsky et al., 2018). The budgetary requirements for large infrastructure and intensive maintenance as compared to manual chamber measurements have prevented the widespread application of automated systems. The use of automated and continuous methods to estimate full GHG budgets *in situ* remains scarce, especially in complex biomes with extreme climate such as tropical forests. Therefore, only a few studies actually address the difficulties and challenges associated with operating these systems under field conditions (Görres et al., 2016; Koskinen et al., 2014).

Recent technological advances have now made more automated chamber systems commercially available, and an increasing number of custom-made systems are being designed

and deployed for soil GHG flux measurements (De Klein and Harvey, 2012) ~~[17,18]~~. Here, we present a detailed field deployment of a custom built, automated soil GHG flux system – the LI-8100A Soil CO_2 Flux System (LI-COR Biosciences Inc., Lincoln, NE, USA) running in line with a Picarro G2308 (Picarro Inc., Santa Clara, CA, USA). Using a 4 month dataset of continuous measurements of CO_2, CH_4, and N_2O fluxes simultaneously under tropical forest conditions, we present an optimized sampling protocol for the estimation of the full GHG budget in this ecosystem.

2. Methods

2.1. Measurement site

This study was conducted in the Paracou research station (5°15'N, 52°55'W), located in the coastal area of French Guiana, South America. The automated soil GHG flux system was deployed in the footprint of the Guyaflux site, which holds a 55 m-tall tower upon which canopy CO_2, H_2O and energy fluxes have been monitored since 2004 using the eddy covariance technique (Aguilos et al., 2018; Bonal et al., 2008). The site is covered with tropical pristine forest and located in the northernmost part of the Guiana shield. It is characterized by a succession of small, elliptical hills rising to 10–40 m a.s.l., sometimes associated with plateaus of similar altitude.

The soils are mostly nutrient-poor acrisols (FAO-ISRICISSS, 1998) with pockets of sandy ultisols developed over a Precambrian metamorphic formation called the 'Bonidoro series', and composed of schist and sandstone, sporadically traversed by veins of pegmatite, aplite and quartz (Bonal et al., 2008). The forest around the tower is characteristic of a tropical pristine forest with both high tree density (~ 620 trees with a dbh>10 cm ha^{-1}) and species richness (~ 140 species ha^{-1}). The climate is highly seasonal due to the north/south movement of the Inter-Tropical

Convergence Zone. The wet season, characterized by heavy rain events, lasts for 8 months (December–July) and alternates with a 4 month dry period (August–November) during which precipitation is typically lower than 100 mm per month. For the period 2004-2015, annual rainfall quantities were on average 3103 mm $year^{-1}$, relative extractable water (an index of soil water availability (Wagner et al., 2011)) varied from 0.93 in the wet season to 0.46 in the dry season and soil temperature was on average 25.1 with little seasonal nor diurnal variation (Aguilos et al., 2018).

2.2. Automated sampling system

A schematic view of the automatic sampling system is shown in Figure 1(A). The system consisted of four main components: sixteen automated long-term chambers (8100-104, LI-COR Biosciences), a multiplexer to link one chamber at a time to the gas analyzers (LI-8150, LI-COR Biosciences), an infrared gas analyzer (IRGA) to measure CO_2 concentrations (LI-8100A, LI-COR Biosciences), and a cavity ring down spectroscopy (CRDS) instrument to measure CH_4 and N_2O concentrations (G2308, Picarro) that was fitted with an external recirculation pump (A0702, Picarro). Both the IRGA and CRDS systems were necessary to measure all three GHG concentrations due to the different abundances and flux rates of CO_2, CH_4 and N_2O. The IRGA methodology is accurate and precise enough to detect small CO_2 concentration changes at high background concentrations (approximately 400 ppmv; parts per million in volume units). However, the detection of small changes in CH_4 and N_2O concentrations, even at their low background atmospheric concentrations in the order of 2000 ppbv (ppbv=parts per billion in volume units) and 300 ppbv, respectively, requires higher accuracy and precision levels that can ~~only~~ be detected with the CRDS.

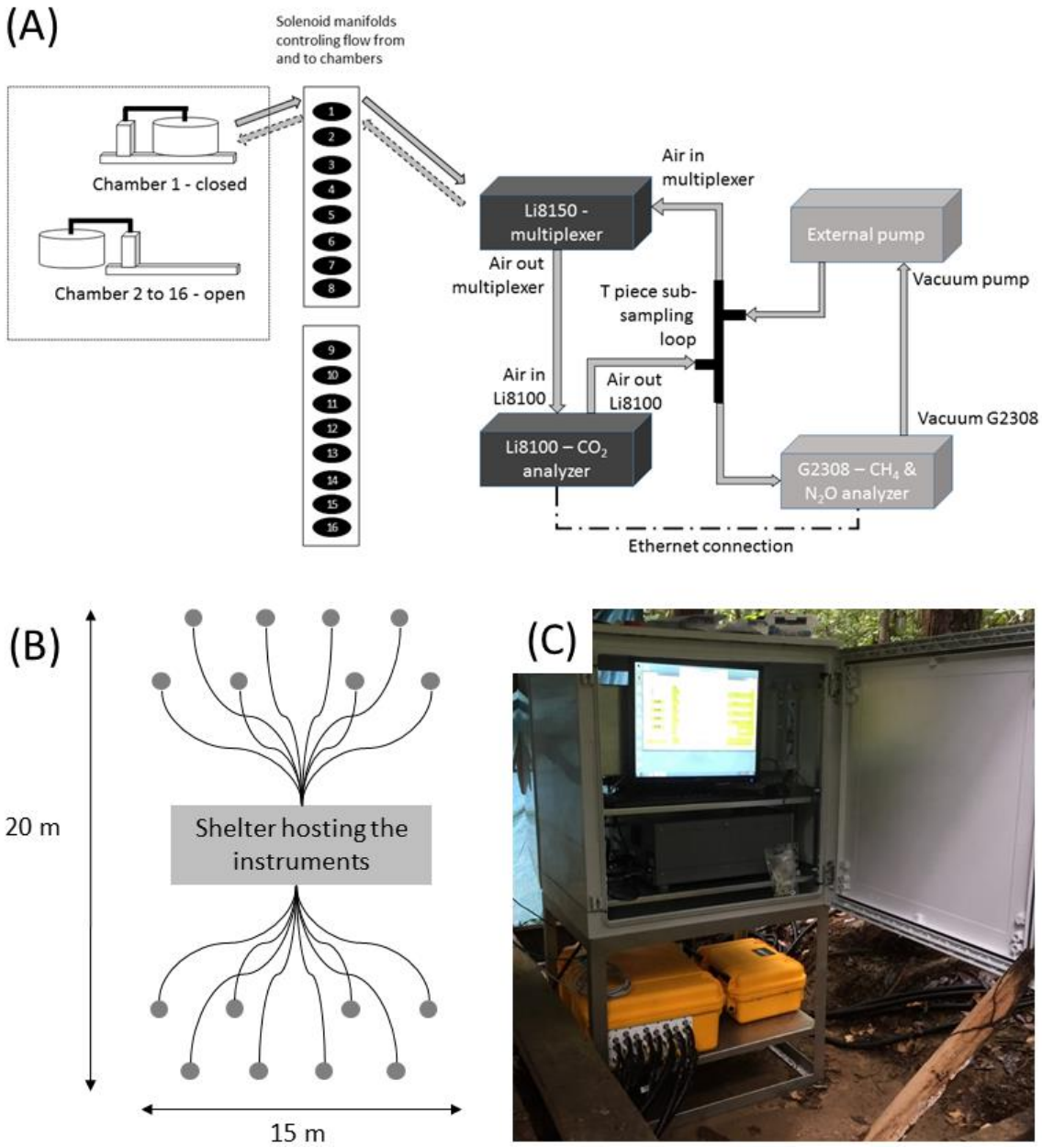

Figure 1: Experimental Design: (A) Schematic view of the installation composed of four main components: sixteen automated long-term chambers (8100-104, LI-COR Biosciences), a multiplexer to link one of these chambers to the gas analyzers (LI-8150, LI-COR Biosciences), an infrared gas analyzer (IRGA) to measure CO_2 concentrations (LI-8100A, LI-COR Biosciences), and a cavity ring down spectroscopy (CRDS) instrument to measure CH_4 and N_2O concentrations (G2308, Picarro) that was fitted with an external pump. (B) Schematic representation of the grid with the shelter housing the equipment in the middle and the 16 chambers (grey dots) linked to the Li-8150 multiplexer with 15 meters cables (black lines). (C) Picture of the instruments in the field.

941 Power supply was delivered through a 12 kVa generator (Perkins STORM15) fitted with
942 batteries located 400 m away from the instruments. Both the CO_2 analyzer control unit and the
943 multiplexer (LI-COR) had their own weather-proof casing, requiring no additional protection in
944 the field. Nonetheless, in consideration of the high precipitation at the site, these devices were
945 placed under a wooden shelter for added protection. The CH_4 and N_2O analyzer (Picarro), its
946 external pump and a computer monitor were housed in a waterproof shelter that was specifically
947 designed to host them (Figure 1(C)). The Li-8100 and the G2308 computers were connected
948 through ethernet connection to ensure time synchronization. The sixteen automated soil chambers
949 (8100-104, LI-COR Biosciences) were installed in a grid in the forest (Figure 1(B)) covering in
950 total an area of approximately 300 m^2 (15 m x 20 m). Each chamber was only closed during
951 individual chamber measurement periods, and was fully open when not sampling. The PVC collars
952 that were provided with the 8100-104 automatic chambers were inserted in the soil one month
953 prior to the first measurement (20.3 cm inner diameter/21.3 cm outer diameter; enclosed soil area
954 ~ 318 cm^2; insertion depth ~ 7cm; offset ~ 4cm; green PVC). When the chambers close, they are
955 automatically lowered so that they cover each soil collar and ensure a fully sealed chamber. The
956 chamber lid does not directly rest on the collar rim, but on a metal plate surrounding the collar,
957 leaving the collar undisturbed and minimizing lateral leaks (Hupp et al., 2009).
958 The 16 chambers were connected via 15 m Bev-a-line tubing (8 mm inner diameter) with
959 the multiplexer (LI-8150), which allows for switching between each of the 16 chambers in any
960 given sequence. Soil temperature (at a depth of 10 cm) was monitored with 8100-201 Ω thermistor
961 probes (Omega Engineering Inc., Stamford, CT, USA), and soil volumetric water content (0-10
962 cm) was monitored with 8100-202 ECH_2O Model EC-5 soil moisture sensors (Decagon Devices

Inc., Pullman, WA, USA). Soil temperature and soil volumetric water content were directly connected to the chambers and recorded by the Licor system using the same time step.

Each chamber was purged for 15 sec prior to each measurement and 45 sec after each measurement in order to flush the lines and restore background gas levels in the system. The flow rate during the purging and the measurements was ~2.8 L min^{-1} between the Li-8150 and the chambers, which ensures sufficient air mixing in the chamber headspace during the measurements (Görres et al., 2016). Flow rates in the subsampling lines (Li8100 and Picarro) were lower and set between 1.5 and 1.7 L min^{-1} as recommended by the manufacturers. The LI-8100 software provided the rate of CO_2 concentration increase in the chamber which was used to quantify the flux of CO_2 from the soil surface into the atmosphere (taking into account the enclosed soil surface area and the total system volume). A subsampling loop was inserted after the analyzer (LI-8100A) and before the multiplexer (LI-8150), to pull the air sample through the Picarro G2308 CRDS analyzer for the determination of CH_4 and N_2O concentrations and flux estimations, before going back to the chamber (Figure 1(A)). All three gas concentrations were recorded every second over the sampling periods.

2.3. Flux calculations

All fluxes estimation were done by using commercially available Soil Flux pro software (LI-COR Biosciences). An R script (Supplementary file 1) was created to merge all the Picarro files from a given week in order to import them into the Soil flux Pro software. The Picarro creates one file per hour and when Picarro files are not merged, Soil flux Pro software is not able to deal with measurements overlapping between two distinct Picarro files (e.g. when a single measurement is done from 9:50 am to 10:15 am) leading to incorrect estimation of CH_4 and N_2O fluxes. CO_2, CH_4 and N_2O fluxes were measured as ~~linear changes in~~exponential fit of gas concentration with time

using Soil flux Pro software and include a 60 sec dead band to account for soil surface pressure disturbances due to the closing of the chamber.

Table 1: Minimum Detectable Fluxes (MDF) for each gas and for closure times from 2 to 30 minutes. The two closure times that were used in this study (2 minutes and 25 minutes) are highlighted in bold.

Closure time (minutes)	N_2O (nmol m^{-2} s^{-1})	CH_4 (nmol m^{-2} s^{-1})	CO_2 (nmol m^{-2} s^{-1})
2	0.100	**0.040**	**2.393**
5	0.025	0.010	0.605
10	0.009	0.004	0.214
15	0.005	0.002	0.117
20	0.003	0.001	0.076
25	**0.002**	**0.001**	0.054
30	0.002	0.001	0.041

2.4. Minimum Detectable Fluxes

The minimum detectable flux (MDF) for each gas was estimated by using a metric originally developed by Christiansen et al. (2015), which was modified by Nickerson (2016) to make it more suitable for high-frequency measurements (Christiansen et al., 2015; Nickerson, 2016):

$$MDF = \left(\frac{A_a}{t_c\sqrt{n}}\right)\left(\frac{VP}{SRT}\right)$$

Where Aa is the analytical accuracy of the analyzer (25 ppb for N_2O and 10 ppb for CH_4 with the Picarro G2308 and 600 ppb for CO_2 with the Li8100, recorded from the technical data sheets of the analyzers), t_c is the closure time of the chamber in seconds, n is the number of points that are available to compute the flux (i.e. t_c divided by the sampling periodicity, every 1 second in this study), V is the chamber volume (0.0040761 m^3), P is the atmospheric pressure (101325 Pa), S is the chamber surface area (0.03178 m^2), R is the ideal gas constant (8.314 m^3 Pa K^{-1} mol^{-1}) and T

is the ambient temperature (298.15 K). We computed the MDF of each gas for closure times from 2 minutes to 30 minutes in order to select the optimal chamber closure time for each gas in our integrated system (Table 1).

2.5. Closure time

Selecting the best length of time for soil GHG measurements and accurate flux calculation in an integrated CO_2, CH_4 and N_2O automated measurement system requires careful consideration. At low fluxes, longer measurement periods are needed to reach reliable measurements of real concentration changes, while at high fluxes possible storage and saturation effects in the chamber headspace might result in non-linear concentration increases and thereby underestimated fluxes. In order to maximize the detectable percentage of fluxes for N_2O and CH_4 without impeding spatial coverage and temporal resolution, we built a combined program with two different closure times. Each week, four out of sixteen chambers were programmed to stay closed for a longer measurement period to ensure a reliable estimation of low fluxes while the other twelve chambers were programmed to stay closed for a shorter period to capture diel variation and detect high fluxes. For the short closure time (SHORT hereafter), we used a 2 minute measurement period because (1) this is a standard closure time for soil CO_2 flux calculations (Janssens et al., 2000), even in tropical forests (Epron et al., 2006; Sayer et al., 2007) of this region where MDF for CO_2 flux is typically low (Bonal et al., 2008; Bréchet et al., 2009; Courtois et al., 2018), (2) corresponding MDFs of CH_4 (0.04 nmol m^{-2} s^{-1} or) and N_2O (0.1 nmol m^{-2} s^{-1}) are compatible with the detection of emission or consumption peaks of these two gases in this region (Courtois et al., 2018; Petitjean et al., 2015). For the long closure time (LONG hereafter), we decided to use a 25 minute measurement period in order to optimize the trade-off between a reliable estimation of

low N_2O fluxes (Table 1) and a program length that allows for a sufficient number of flux measurements per chamber and per day.

We therefore programmed the multiplexer for 2.5-h cycles (9-10 measurements per chamber per day), which included four chambers with LONG measurements and twelve chambers with SHORT measurements. Each week, the program was modified manually so that the four LONG measurements were rotated across the chambers. Each chamber was therefore measured with the LONG closure time for one 7 consecutive day period per month (4 weeks).

2.6. System maintenance and data processing

The automated sampling system was installed on June 1st 2016 and operated until September 29th 2016 (4 months), totaling ~~17652~~ 17592 individual measurements for each gas (~~4326~~ 4098 with LONG closure time and ~~13326~~ 13494 with SHORT closure time). Coarse wood debris ~~was~~ were removed weekly but small litter, such as leaves, fruits, and twigs, was left in the collar area. Every week, living plants growing inside the collars, and the dead leaves on the chambers, were carefully removed by hand. The R^2 value of the exponential increase of CO_2 over 2 minutes was used as an indicator that the system was functioning correctly and not impeded by debris (Görres et al., 2016; Savage et al., 2014). When the R^2 of the regression between time and CO_2 concentration was lower than 0.9, we considered this as an indication that there may have been an issue with the chamber closing and sealing correctly and removed the flux measurement for all three gases from our analysis.

For CO_2, we observed a strong concentration saturation effect when using the LONG closure time (25 minutes), leading to an underestimation of fluxes (~~Supplementary Figure 1~~Figure 2). All CO_2 flux estimates were therefore based on 2 minute regressions only, using either full concentration measurements of the SHORT closure time or the 2 first minutes of the LONG

closure time. ~~The R^2 value of the linearly increasing CO_2 over 2 minutes was used as an indicator that the system was functioning correctly and not impeded by debris (Görres et al., 2016; Savage et al., 2014). When the R^2 of the regression between time and CO_2 concentration was lower than 0.9, we considered this as an indication that there may have been an issue with the chamber closing and sealing correctly and removed the flux measurement for all three gases from our analysis.~~ Following recommendations (Rubio and Detto, 2017), we removed anomalous values, i.e. CO_2 fluxes estimation with a difference greater than 5 µmol m^{-2} s^{-1} between with previous or following measurements or lower than 0 µmol m^{-2} s^{-1}. For CH_4, we observed only a slight saturation effect when using the LONG closure time (~~Supplementary~~ Figure 2~~1~~). Variation in the flux calculations did not differ between the SHORT and LONG chamber closure measurements. ~~All fluxes above or below (for negative fluxes) MDF were considered as reliable and were calculated using the full data available (2 minutes measurement for the SHORT closure time and 25 minutes for the LONG closure time).~~ N_2O flux calculations were much more variable when measuring with the SHORT closure time compared to the LONG closure time (~~Supplementary~~ Figure 2~~2~~). Even if fluxes were above the detection limit, the low fluxes estimated with the SHORT closure time were not reliable as shown by the low correlation in Figure 2. For both CH_4 and N_2O, w~~W~~e therefore decided to apply the following quality check procedure (1) ~~to keep all~~ All ~~the~~ fluxes ~~estimated with the LONG closure time~~ that were not complying with MDF criterion ~~even with low R^2 for the regression between time and N_2O concentrations and~~were discarded. (2) All ~~to consider all~~ fluxes estimated with the SHORT closure time with a R^2 lower than 0.8 ~~as unreliable~~were discarded (Savage et al., 2014). (3) We applied the same procedure than for CO_2 regarding anomalous values (difference greater than 5 nmol m^{-2} s^{-1} between consecutive measurements).

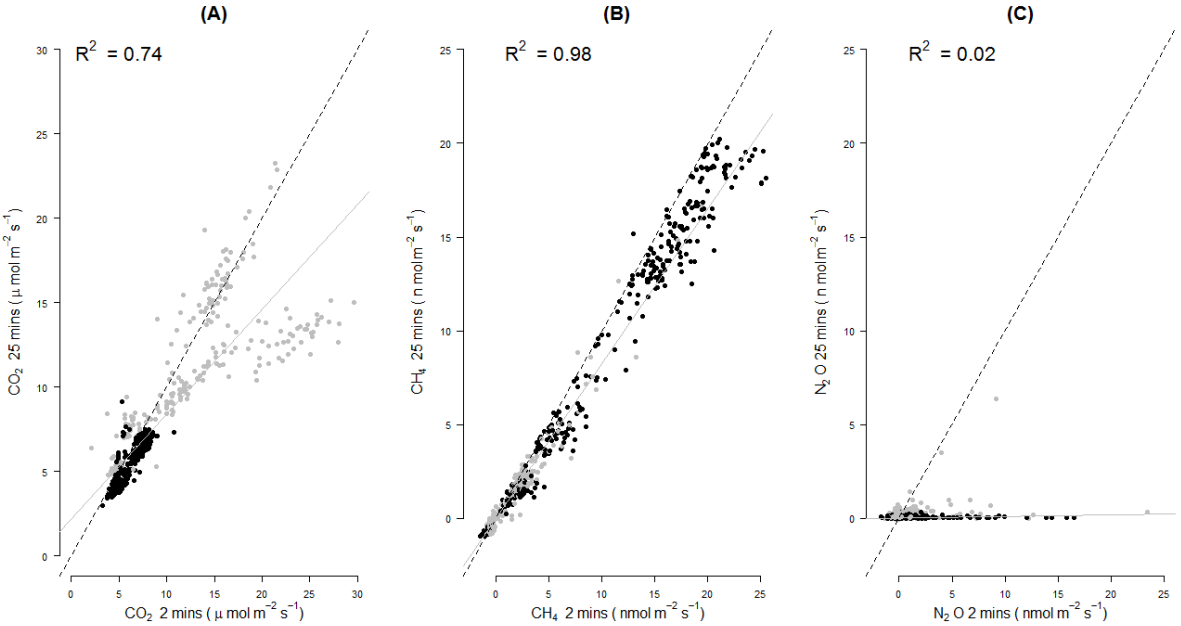

Figure 2: Comparison of 2 minutes and 25 minutes estimations for (A) CO_2 (B) CH_4 and (C) N_2O fluxes. For this, we used measurements made over 25 minutes and recomputed the flux with the two firsts minutes for two weeks (from August 2nd for August 9th in black and from August 16th for August 25th in grey) covering the whole range of fluxes during the study period. All fluxes were computed using exponential fit. The dashed line represent the 1:1 line while the solid grey line represents the linear regression between 2 minutes and 25 minutes estimations (R^2 of these regressions are indicated on each panel).

3. Results and discussions

A cleaning frequency of once a week was necessary and sufficient to remove falling leaves and branches from the automatic chamber system, prevent leaks and generate a continuous dataset of soil GHG fluxes from this tropical forest. Temperature variations are typically small below the canopy due to the shadowing by dense canopy crown and microclimatic conditions. During the study period, temperature at 2m height varies during the day from 22 °C in the night to 28 °C during the day. The presence of water condensation inside the tubing lines was carefully checked every week and never occurred during the study period. The automatic chamber system worked well most of the time, but some data gaps did exist. Over the ~~17724~~ 17592 individual flux estimations, ~~276~~ 343 (1.~~95~~ %) had to be discarded because of (1) problems in the connection

between the chamber and the multiplexer (~~196~~ 154 measurements, 0.9~~1~~% of data points); (2) imperfect chamber closing, which was detected by an insufficient increase of CO_2 (~~103~~ 189 measurements, 1~~0.6~~% of data points).

Table 2: Mean, standard deviation (SD), minimum (Min) and maximum (Max) values of each gas and each chamber over the study period. These values are computed using all fluxes estimation (either with SHORT or LONG closure time) remaining after quality check. The number (N) of fluxes that were used is also indicated for each chamber. The last line of the table is the mean of all fluxes by chambers by gas and the min and max for all chambers by gas.

	CO_2 (µmol m^{-2} s^{-1})					CH_4 (nmol m^{-2} s^{-1})					N_2O (nmol m^{-2} s^{-1})				
	Mean	**Sd**	**Min**	**Max**	**N**	**Mean**	**Sd**	**Min**	**Max**	**N**	**Mean**	**Sd**	**Min**	**Max**	**N**
Chamber 1	7.19	0.93	2.14	10.81	940	10.97	7.73	-2.08	28.79	840	0.10	0.12	-0.48	0.70	284
Chamber 2	7.60	1.11	4.00	12.21	1166	-1.62	1.75	-4.09	11.68	899	0.00	0.14	-1.03	0.75	285
Chamber 3	5.58	0.99	2.11	11.12	1135	0.35	2.95	-2.48	22.94	745	0.03	0.23	-0.61	2.85	208
Chamber 4	7.94	1.37	4.36	12.13	1154	-1.85	1.23	-3.63	6.09	1105	0.04	0.10	-0.66	0.60	224
Chamber 5	4.14	0.92	0.53	10.05	1139	1.37	3.26	-2.20	12.61	752	0.15	0.33	-1.04	3.23	382
Chamber 6	8.87	1.70	3.36	17.68	1070	-1.38	1.78	-3.20	8.04	801	-0.02	0.12	-1.04	0.63	272
Chamber 7	13.47	2.78	0.89	22.12	988	1.37	3.60	-2.63	19.56	749	0.64	1.37	-0.85	7.93	216
Chamber 8	7.44	1.19	2.03	11.02	1099	0.03	2.96	-3.37	18.47	785	0.02	0.15	-1.36	0.84	202
Chamber 9	4.25	1.20	0.44	11.37	1002	2.06	3.13	-2.14	11.53	879	0.02	0.11	-0.62	0.58	332
Chamber 10	5.60	1.30	0.69	13.13	1037	1.21	2.46	-1.91	10.34	657	0.04	0.13	-0.64	0.77	252
Chamber 11	11.97	2.19	6.84	18.78	1004	6.72	7.61	-1.06	41.49	855	0.03	0.17	-1.01	1.04	199
Chamber 12	9.42	2.70	3.45	21.54	968	1.40	6.68	-3.29	41.94	891	0.02	0.09	-0.75	0.30	204
Chamber 13	5.85	1.34	0.42	8.49	944	5.29	5.92	-4.60	26.64	654	0.10	0.19	-0.84	1.71	335
Chamber 14	5.66	1.15	0.72	10.72	987	2.78	6.22	-2.48	35.15	691	0.09	0.17	-0.63	0.93	231
Chamber 15	16.63	3.27	9.42	29.64	850	-0.46	2.05	-3.25	8.26	839	-0.02	0.16	-0.96	0.72	185
Chamber 16	7.35	1.13	3.98	11.37	994	-1.34	1.48	-3.60	6.11	843	0.00	0.11	-1.00	0.83	187
	8.06	**1.58**	**0.42**	**29.64**	**16477**	**1.68**	**3.80**	**-4.60**	**41.94**	**12985**	**0.08**	**0.23**	**-1.36**	**7.93**	**3998**

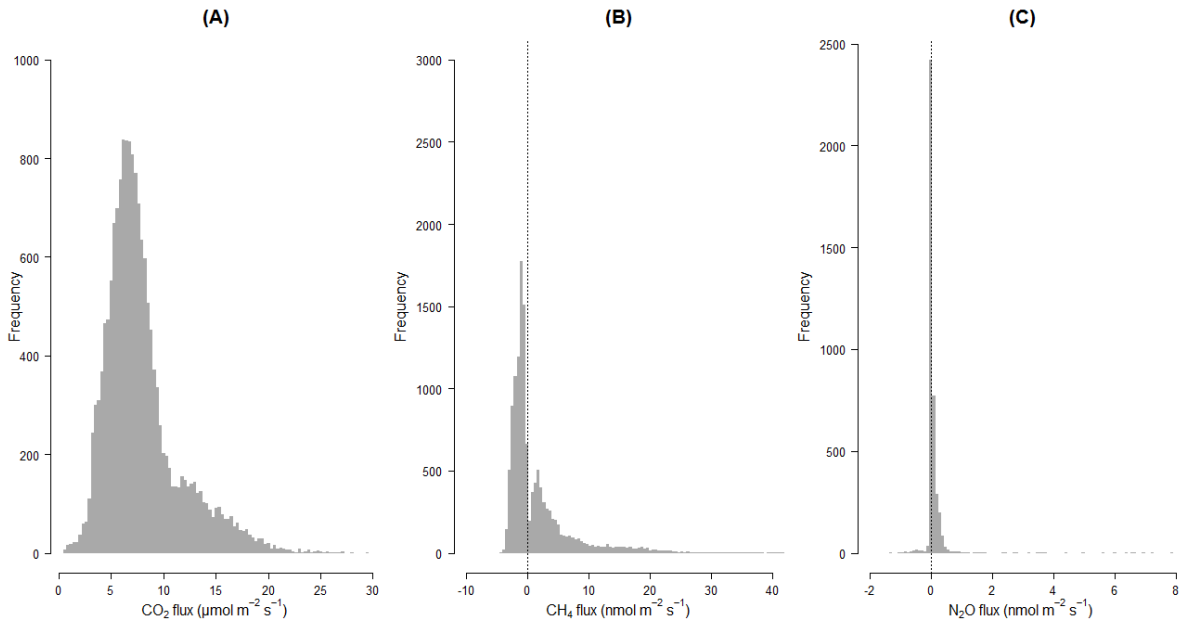

Figure 3~~2~~: Distribution of fluxes: Histogram of (A) CO_2, (B) CH_4 and (C) N_2O fluxes over the study period. For (B) and (C), the dotted line represents null fluxes.

3.1. CO_2 fluxes

Additionally to the 343 fluxes than were removed after the firsts steps of quality check procedure, 758 CO_2 fluxes estimations were also considered as anomalous, either because the difference with previous or following measurements where greater than 5 µmol m^{-2} s^{-1} (758 measurements, i.e. 4.3%) or because they were lower than 0 µmol m^{-2} s^{-1} (14 measurements). In total, 16477 CO_2 fluxes over 17592 (93.6%) can be used over the four month period. CO_2 fluxes were on average 8~~7~~.~~1~~0634~~34~~ ± 1~~3~~.6~~21~~ µmol m^{-2} s^{-1} (Table 2) which would correspond to a mean annual soil CO_2 efflux of 3050 gC m^{-2} $year^{-1}$ which falls into the upper range of the extensive review of mean annual soil CO_2 effluxes estimations in tropical forest provided recently by Rubio and Detto (2017). Nonetheless, our study period (June-September) only covered the end of the wet season and more data are needed to precise this estimation. ~~with a high variability among chambers (Table 2). The minimum flux measured during the study period was 0.19 µmol m^{-2} s^{-1} (Table 2) and the~~

~~majority of fluxes were between 3 to 10 µmol m^{-2} s^{-1} (Figure 2).~~ All two-minute measurements of CO_2 fluxes from the four-month study period were ~~therefore~~ above the MDF of 2.39 nmol m^{-2} s^{-1} for the LI8100 analyzer (Table 1). No saturation effect was detected using the SHORT closure time and estimation of CO_2 over a shorter time period is not recommended (Davidson et al., 2002). CO_2 fluxes using the LONG closure time would be underestimated due to the buildup of high CO_2 concentrations due to large fluxes over this long time period (~~Supplementary Figure 1~~Figure 2), and are not recommended. For small chambers as the one that were used in this study, w~~W~~e therefore conclude that a 2 minute sampling time should be used for CO_2 flux calculations since the MDF of this short measurement period allowed for the retention of 100% of the data. When the chambers stay closed longer for accurate detection of N_2O fluxes, only the first two minutes of data should be used for CO_2 flux calculations.

The use of 16 automated flux chambers allowed for the capture of spatial and temporal variability of soil respiration. O~~o~~ver this four month period~~.~~, corresponding to the end of the wet season in French Guiana, ~~-~~temporal variability remained low (Figure 4). This dataset is therefore not long enough to detect seasonal variation of soil respiration that were highlighted in previous study (Rowland et al., 2014; Rubio and Detto, 2017). We did found that soil respiration tended to decrease in very humid soils (Supplementary Figure 1) as highlighted previously at the same site (Rowland et al., 2014) but more data are needed to disentangle precisely the importance of seasonal and diurnal variability from the responses to environmental triggers on soil respiration. Nonetheless, even during this relatively short period, our data clearly demonstrated a strong spatial variability of soil respiration, even at a low spatial scale (Figure 5, Table 2), some local spots clearly displaying stronger values of soil respiration during the study period. ~~which is needed to constrain ecosystem carbon budgets (Figure 3).~~

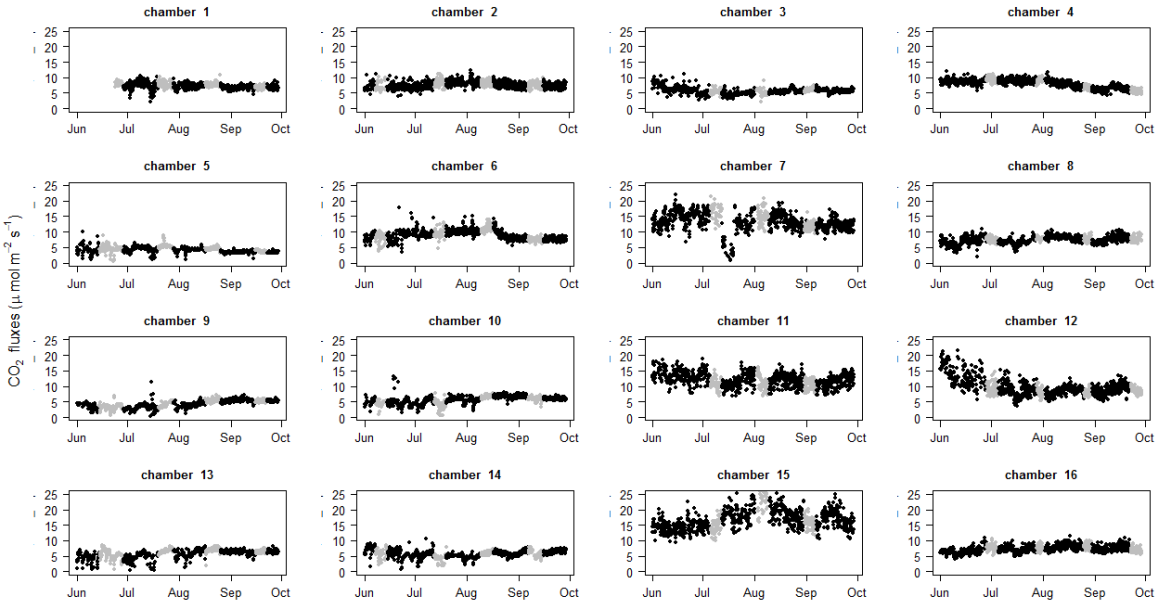

Figure 43: CO_2 fluxes through time: CO_2 fluxes for each chamber (1 to 16) over the study period with fluxes estimated with SHORT (2 minutes) closure time in black and fluxes estimated with the 2 first minutes of the LONG (25 minutes) closure time in grey. All panels have the same limits on the y axis (from 0 to 25 µmol m^{-2} s^{-1})

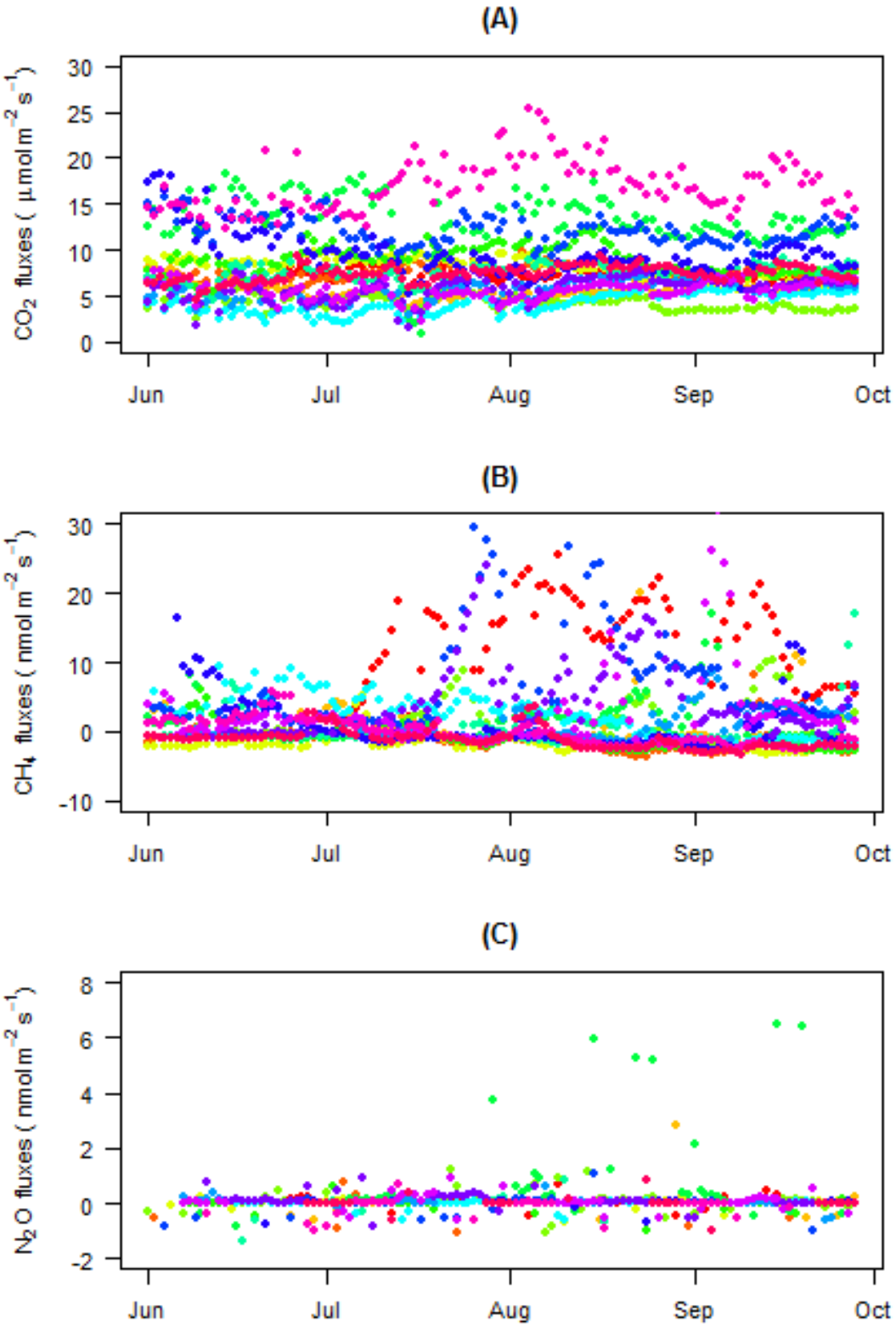

Figure 5: Mean values per days for (A) CO_2, (B) CH_4 and (C) N_2O fluxes over the study period. Each chamber is represented by a distinct color.

3.2. CH_4 fluxes

Additionally to the 343 fluxes than were removed after the firsts steps of quality check procedure, CH_4 fluxes estimations were also discarded because of (1) problems with Picarro files (12 measurements), (2) application of the MDF criterion (137 measurements), (3) application of the R^2 criterion for SHORT closure time (3751 measurements, i.e. 28% of the SHORT measurements) (4) detection of anomalous values (364 measurements). In total, 12985 CH_4 fluxes over 17592 (73.8%) can be used over the four month period. No saturation effect was detected using the LONG closure time and fluxes estimated with the SHORT closure time were very well correlated to fluxes using the LONG closure time, even for small fluxes (Figure 2). ~~CH_4 fluxes were on average 1.06 ± 4.52 nmol m^{-2} s^{-1} with a high variability among chambers (Table 2). Minimum detectable fluxes for CH_4 were ± 0.04 nmol m^{-2} s^{-1} using the SHORT closure time and ± 0.001 nmol m^{-2} s^{-1} using the LONG closure time (Table 1). 98.5~~68.4 % and ~~99~~98.2~~9~~% of fluxes measured with the SHORT and LONG closure times, respectively, were retained in our quality control data processing over the four-month study period. These measurement periods, therefore, allowed for the retention of a large majority of CH_4 emission or consumption fluxes in our data analysis. ~~.~~

CH_4 fluxes were on average 1.7~~06~~ ± 3~~4~~.8~~52~~ nmol m^{-2} s^{-1} with a high variability among chambers (Table 2) but ~~.~~ ~~T~~the frequency of negative CH_4 fluxes (consumption, 59% of fluxes) was greater than positive fluxes (emission, 41% of fluxes) during this period (Figure 3~~2~~). Most of the time, soils were either consuming or emitting small amounts of CH_4, but transient, large emission peaks were periodically detected at individual chamber locations during the study period (Figure 6~~4~~). Tropical soils are generally considered as sink at a yearly basis (Dutaur and Verchot, 2007) but it is known that these soils can shift from a source in the wet to a sink in the dry season (Courtois et

al., 2018; Davidson et al., 2008; Teh et al., 2014). No clear temporal trend could be detected during the study period and no clear pattern linked CH_4 fluxes with surface soil humidity (Supplementary Figure 1), but as for CO_2, longer time series covering at least a full year are needed to explore the seasonal and diurnal variability of fluxes. As highlighted previously in French Guiana (Courtois et al., 2018), spatial variability of CH4 emission was high, even at a small spatial scale (Figure 5, Figure 6). Interestingly, some spots clearly display high CH_4 emission during all the study period (Figure 5, Figure 6).

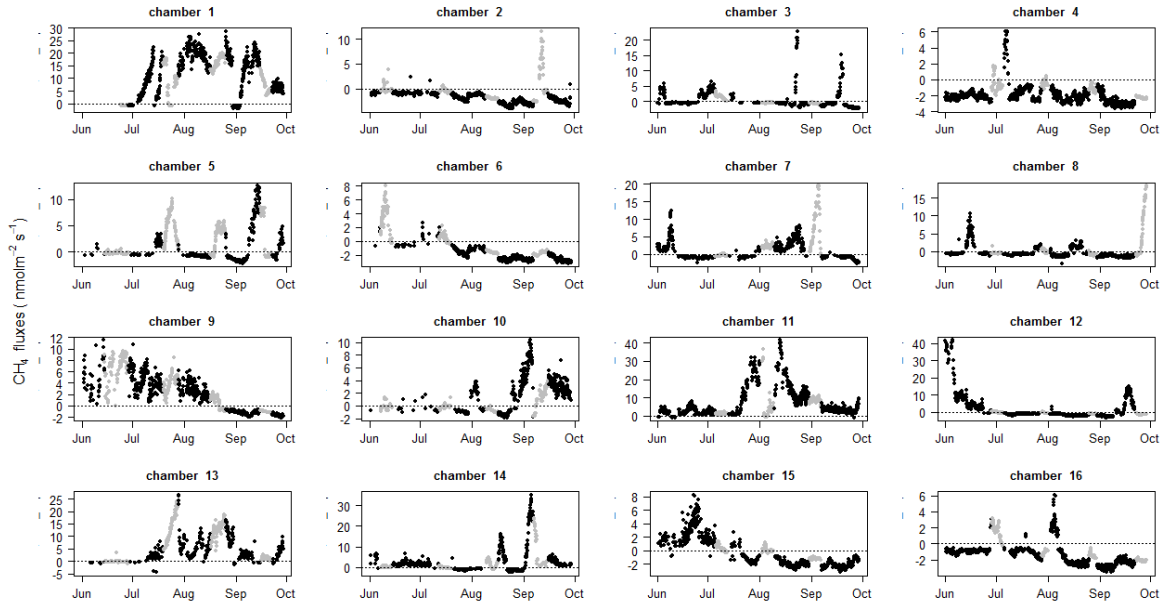

Figure 64: CH_4 fluxes through time: CH_4 fluxes for each chamber (1 to 16) over the study period with fluxes estimated with SHORT (2 minutes) closure time in black and fluxes estimated with LONG (25 minutes) closure time in grey. The dotted line displays the zero flux line. All panels have the same limits on the y axis (from -5 to 30 nmol m^{-2} s^{-1})

3.3. N_2O fluxes

Additionally to the 343 fluxes than were removed after the firsts steps of quality check procedure, N_2O fluxes estimations were also discarded because of (1) problems with Picarro files (12 measurements), (2) application of the MDF criterion (1594 measurements), (3) application of the

R^2 criterion for SHORT closure time (11643 measurements, i.e. 28% of the SHORT measurements) (4) detection of anomalous values (364 measurements). In total, 3998 N_2O fluxes over 17592 (22.7%, 140 measurements with the SHORT and 3858 measurements with the LONG closure time) can be used over the four month period. 94.1% of fluxes measured with the LONG closure times were retained after our quality control data processing over the four-month study period. ~~N_2O fluxes were on average 0.038 ± 0.537 nmol m^{-2} s^{-1} with a high variability among chambers (Table 2). Most N_2O fluxes (85.6%) with the LONG closure time were above or below MDF (± 0.002 nmol m^{-2} s^{-1}, Table 1) and varied between -2 to 2 nmol m^{-2} s^{-1} (Figure 2).~~ When measured over 25 minutes, N_2O fluxes in our site could therefore be considered as reliable. Using the SHORT closure time, most flux estimations had to be discarded because they led to unreliable flux estimations (~~Supplementary F~~Figure 2). ~~Only 7.9% of the measurements using the SHORT closure time were retained after our quality control checks for the N_2O flux data.~~ Nonetheless, ~~the high frequency of~~ the SHORT closure times~~s~~ still allowed the detection of ~~one~~ high N_2O emission or consumption events ~~(up to 15 nmol m^{-2} s^{-1})~~ that were~~as~~ detected during the study period (Figure ~~5, chamber 7~~5 and 7).

N_2O fluxes were on average 0.1 ± 0.2 nmol m^{-2} s^{-1} with a high variability among chambers (Table 2). At the same chamber, N2O flux can shift from consumption to emission with 28% of fluxes indicating a sink and 72% a source for N_2O (Figure 3). The high variability in N_2O fluxes that we detected over four months with our automated system are in agreement with the typical high variability in N_2O fluxes measured from tropical soils over space and time using static chambers (Arias-Navarro et al., 2017; Courtois et al., 2018). Moreover, N_2O fluxes didn't show any relationship with surface soil humidity (Supplementary Figure 1), which underline the complexity of the biological process underlying these fluxes. In a previous study in the same environment

(Courtois et al., 2018), we estimated that the minimum detectable fluxes using Gas Chromatography analysis of four discrete gas samples over 30 minutes for N_2O was ± 8.3 µg N m^{-2} h^{-1}. MDF estimated in the present study using high frequency measurement was 0.002 nmol m^{-2} s^{-1} or 0.2 µg N m^{-2} h^{-1} for N_2O which is therefore ~ 40 times lower. Such result indicates that this long-term system is well-adapted to capture and estimate the low N_2O fluxes occurring in this ecosystem.

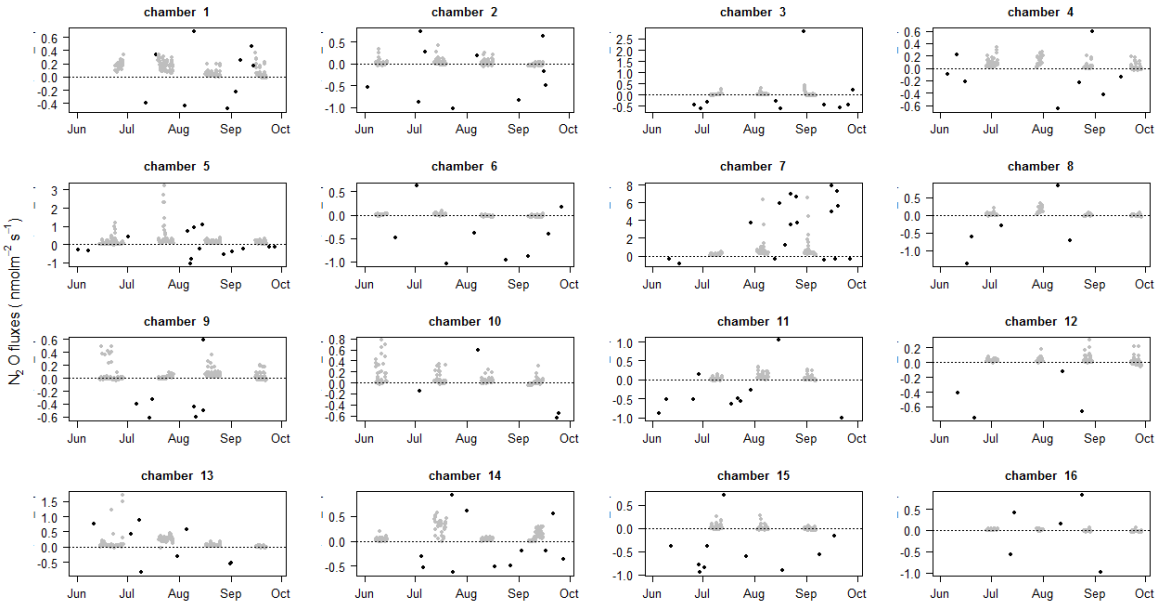

Figure 57: N_2O fluxes through time: N_2O fluxes for each chamber (1 to 16) over the study period with fluxes estimated with the SHORT (2 minutes) closure time in black and fluxes estimated with the LONG (25 minutes) closure time in grey. The dotted line displays the zero flux line. Due to the high differences among chambers, each panel has specific limit on the y axis.

4. Conclusions

Our ~~unique~~ system coupled a Li8100 CO_2 analyzer and multiplexor with a Picarro G2308 CH_4 and N_2O analyzer to sample 16 automated soil flux chambers with a rotation of SHORT and LONG closure times for the accurate monitoring of three GHG fluxes over four months with high spatial and temporal resolution. The sampling system of SHORT and LONG closure times with a weekly

rotation presented here has three major advantages, which ultimately can provide high confidence in the estimation of annual the full GHG budgets of tropical soils: (1) the LONG closure time allows a reliable estimation of the low N_2O fluxes in this ecosystem, which was clearly not achieved using a shorter closure time, (2) the number of data points per day are sufficiently high (9 to 10 measurements per day) to capture potential diurnal variation (Nicolini et al., 2013; Rubio and Detto, 2017) of the three gases with good spatial replication (16 chambers), (3) periodic extreme events of high N_2O fluxes can still be detected with the SHORT closure time period, which occurs at higher frequency than the LONG closure measurements. Our study underlines the importance of appropriate closure time for each GHG gas for accurate estimation of GHG budgets. We demonstrate here that the combination of a commercial soil GHG chamber system – the LI-8100A Automated Soil CO_2 Flux System – running in line with a Picarro G2308, enables the continuous, long-term measurement of CO_2, CH_4, and N_2O simultaneously under tropical conditions. Similar configurations have been recently implemented in temperate climate (Petrakis et al., 2017b, 2017a), but to our knowledge, this is the first time that this experimental set up is fully described and tested under tropical field conditions for the measurement of the three soil GHG fluxes simultaneously . Additionally, our study determined the optimal chamber closure time for each GHG. This information is crucial for the calculation of accurate soil fluxes at diurnal timesteps and for the estimation of annual GHG budgets. This combination of automated closed dynamic chambers and advanced GHG analyzers allows for, (1) accounting of short-term variability in GHG fluxes while taking into account spatial variability, (2) estimating annual GHG budgets at these locations, (3) tracking the variability in GHG fluxes along hours, days, seasons and years, and (4) studying the impact of climatic change on soil GHG budgets.

Author contribution. JVB and NA designed the experiments and EAC, CS, BB and DB carried them out. EAC and CS prepared the manuscript with contributions from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

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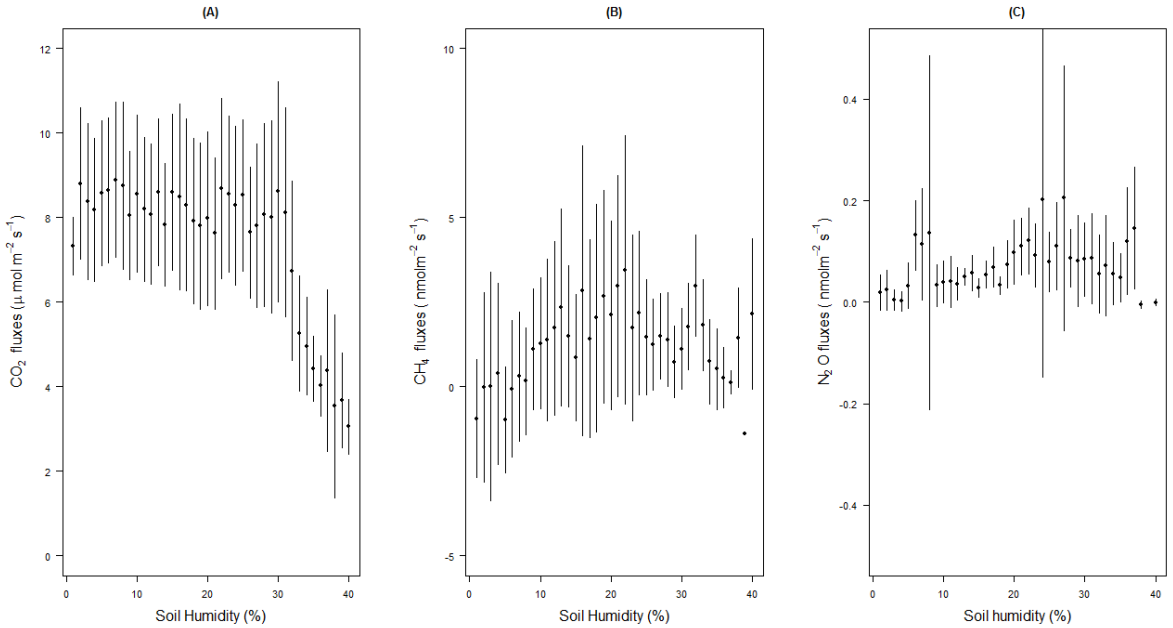
Supplementary File 1: R code for merging Picarro files to include them in Soil Flux pro

```
## to list all the days in a given directory (Picarro makes one directory per day)
ListDay<-list.files()
Pfile<-list()
## to concatenate all the hourly file in one file per day
for (j in 1:length(ListDay))
{
print(j)
ListFilesPicarro<-list.files(ListDay[j])
Data<-read.table(paste(ListDay[j],"/",ListFilesPicarro[1],sep=""))
for (i in 2:length(ListFilesPicarro))
{
temp<-read.table(paste(ListDay[j],"/",ListFilesPicarro[i],sep=""))
Data<-rbind(Data, temp)
print(i)
}
Pfile[[j]]<-Data
}
## to concatenante all days and make just one file will all data
MasterData<-Pfile[[1]]
for (k in 2:length(Pfile))
{
MasterData<-rbind(MasterData,Pfile[[k]])
print(k)
}
## to write the table in a way that SFP can read it
write.table(MasterData, "MasterData.dat", quote=F)
```

Supplementary Figure 1: Relationship between soil surface humidity and (A) CO_2, (B) CH_4 and (C) N_2O fluxes over the study period.



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