I. Point-by-point response to the reviews

Review 1

General comments

The manuscript (ms) under review presents a new approach to estimate the emissions of CO2 and N2O from the various floodplains along the Amazon River during 2011 and2015. The approach combines satellite data (-> estimate of the water surface) and insitu data with an empirical assessment of the nitrate reduction rate (i.e. denitrification)in the upper soil which in turn results in production and emissions of both carbon dioxide (CO2) and nitrous oxide (N2O). Although the presented results are of interest for a wider community, I have some concerns about the approach used for NO3- reduction. Therefore, I can recommend publication only after major revisions.

On behalf of all the co-authors, we thank the referee for the review and associated comments that helped us improve the manuscript.

Specific comments

The NO3- loss in the floodplains is solely attributed to denitrification. However, NO3- loss in soils can also take place during dissimilatory nitrate reduction to ammonium (DNRA) (see e.g. Rutting et al., Biogeosci, 8, 2011). So, I am wondering whether this could affect the estimate of CO2 and N2O emissions. Please discuss. You may need to adjust the equations (1) to (4) to account for DNRA. Please replace denitrification with ‘nitrate (or NO3-) reduction’ throughout the text.

In the current study, we consider the denitrification process during flood events. In these conditions, NO3- is the limiting for both denitrification and DNRA. Moreover, the DNRA contribution to N2O emissions is about 1% (Rüttin et al., 2011 from Cole (1988)) which is negligible considering the other sources of uncertainties at this scale. The environmental conditions for DNRA occurring (e.g NO3- limiting, high redox soil and high C/N) are not met in this case, thus the contribution of DNRA should be lower. Therefore, we are confident on our choice not to address the DNRA in this study. But this may be an issue that needs to be addressed for N2O budget at global scale in non-limiting conditions.

"- The amount of N2O produced is calculated with a constant N2O/N2 ratio of 0.1. You can do so but, unfortunately, there is no reference given for it (P6L22). Moreover, it should be discussed whether this ratio is constant or variable in the Amazonian wetlands. In other words, how representative is the selected value of 0.1? This is an important point because the choice of this ratio directly determines the magnitude of the N2O emissions and the variability of this ratio determines the ‘error bar’ of the N2Oemission estimates."

We thank the reviewer for this essential comment that was discussed in the first stages of this work between co-authors. Indeed, a constant value of N2O/N2 can be argued and can be still accepted as mentioned by the referee. We actually based our estimates of this value from (Weier et al., 1992; Pérez et al., 2000) We choose to keep a 0.1 ratio for N2O/N2 production. Our spatial resolution is coarse as we consider the flooded area over a 25 km x 25 km thus we don't take into account the landscape peculiarities. N2O/N2 ratio ranges from 0.05 to 0.2 and it is likely that several different ratios should be found within one pixel. Nevertheless, without any precise measurement on the actual ratio value and the different proportions we decided to set up an effective ratio of 0.1 (which is the most common for Amazonian wetlands: Pérez et al., 2000) for the whole watershed in order to not under/over estimate the emissions. In the manuscript, we only discuss about N2O values calculated from a 0.1ratio (for better comprehension) but we added "error bars" corresponding to a 0.05 and0.2 ration in the graphs. Comments in $ 2.4.1 P6 L20 and $ 4.5 P 17-18 were added to explain these choices.

"- I am wondering why nitrification as a source of N2O under low O2 is ignored. Please discuss."

Several studies showed that under anoxic conditions denitrification is the only source ofN2O emissions (see Bollmann and Conrad 1998, Global Change Biology). The scoop of our paper is to specifically focus on denitrification and associated emissions, thus we did not take into account nitrification.

"- Title: Please note that the term 'carbon emissions' also includes emissions of methane and other C-containing gases which are not subject of the ms. Moreover,NO3- could be lost during dissimilatory nitrate reduction to ammonium (DNRA), see my comment above. To this end, I suggest to modify the title to 'Nitrate reduction and associated carbon dioxide and nitrous oxide emissions from the Amazonian wetlands'."

We suggest to the editor a tittle change to "Denitrification with associated nitrous oxide and carbon dioxide emissions from the Amazonian wetlands".

"- The central and lower panels of Figure 6 are meaningless. They show exactly the same graphs but scaled with a factor of 5 (for CO2, see equation (4)) and 0.1 (for N2O; N2O/N2=0.1). Please remove. "

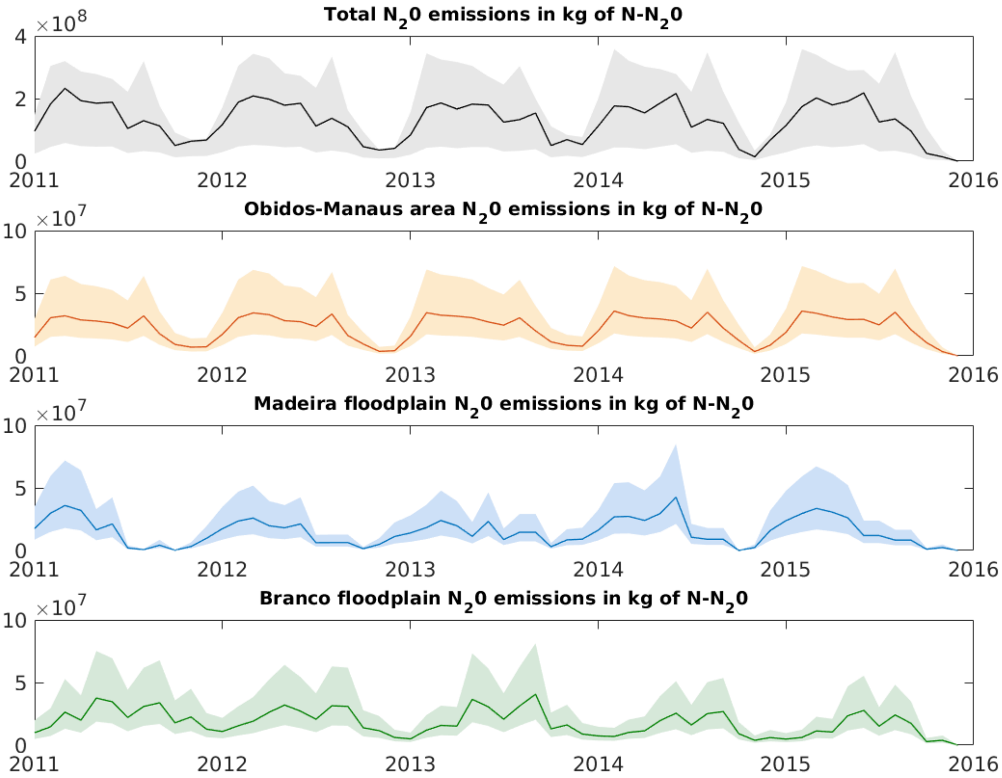

Figure 1 Monthly time series of N2O emissions over the basin, the O-M FP, the Madeira FP and the Branco FP over the period (2011-2016). The lines represent the emissions for a N2O / N2 ratio of 0.1 whereas the coloured areas refer to the potential range of the same ratio: 0.05 - 0.2. Denitrification and CO2 emissions follow the same patterns but with a scale factor of times 10 for denitrification and times 2 for CO2."

Fig.6 was changed to represent N2O emissions over the basin and the floodplains. Comments in the caption and the text P9 L6-8 were added to explain that denitrification, CO2 and N2O emission follow the same patterns with different values.

"- Please avoid using colloquial terms such as 'paramount' (see P2L11; P4L2; P18L9) or 'hot moments' (see Section 3.1). They should not be used in the context of a scientific text. "

We understand the worries of the reviewer on the potential use of colloquial terms though it was not the intention of the co-authors. Concerning the term "hot-moment": It was inspired from (McClain et al., 2003 Biogeochemical Hot spots and Hot Moments at the Interface of Terrestrial and Aquatic Ecosystems.): "A hot-moment corresponds as a short period of time with disproportionately high reaction rates relative to longer intervening time periods.". The term is also widely used in the literature. We choose to maintain it in the ms as it conveys our exact message. Concerning the choice of paramount: it has been replaced by "essential" or synonyms. Ex: During the last decade, process-based models have become key tools in estimating carbon and nitrogen budgets in the context of global multi-source changes. Future studies will concentrate in extending the current approach to other tropical basins, that local observations will be essential for the validation of such exercise and preferably over the same period of analysis.

"- Please have the text proofread by a native English speaker. There are many sentences and phrases which are odd. - There are several (annoying) typos: mole should read mol (various places throughout the text); ‘og’ should read ‘of’ in the caption of Fig.5; N20 should read N2O (Fig. 5); 3rd column/2nd line in Tab. 1: there is something wrong with the exponent; ‘anormalies’ should read ‘anomalies’(P13L15), etc. – Please replace NO3 with NO3- (in the equations as well as throughout the text and figures)"

The manuscript was thoroughly revised to improve the writing and to correct the typos.

Review 2

Guilhen et al. present a new approach to estimate denitrification rates and associated emissions of the greenhouse gases CO2 and N2O in Amazonian wetlands. Their method is based on a combination of satellite data, in situ hydrographic monitoring and remote sensing. The study is of high relevance since it aims to use the new method for providing a large-scale assessment of carbon and nitrogen cycling in the Amazonas basin. To date such an endeavour has been limited by the scarcity of available observations. Although I generally think the method used by the authors is sound, the lack of a rigorous explanation of the procedures they followed to setup their model and treat the in situ data does not allow the reader to assess if and how their method can be used to address the proposed scientific questions. The authors write that their study "aims at delivering an enhanced understanding and quantification of the denitrification process over Amazonian wetlands with their associated fluxes of N2O and CO2". Yet, based on the manuscript it is not clear at what extent the suggested drivers for denitrification in the basin are applicable in situ, and how much of the variability is explained by the model assumptions. Along these lines, I noticed that the authors use wording such as "it is supposed/assumed" several times throughout the manuscript without further substantiating their reasoning. I am aware that any model needs some assumptions; however, these need to be based on clear, comprehensible criteria. I believe authors have good reasons to adopt the assumptions they used for their model setup. However, if they are not mentioned in the manuscript, this inevitably affects its credibility. Examples of this are the selection of the N2O/N2 ratio and constant nitrate values over the entire basin during the whole annual cycle. Being nitrate a central parameter for the estimated denitrification rates, this is certainly something that has to be discussed in further detail. Unsubstantiated assumptions are also frequent during the discussion, in which processes or results shown during previous studies are generally considered as valid for the author's investigation without discussing if and what extent they are applicable. In addition to these issues, the manuscript has several flaws in terms of grammar and format consistency. I therefore strongly recommend the authors to revise these aspects on a future version.

All in all, although the manuscript by Guilhen et al. is of scientific significance for environmental sciences, there are several aspects of scientific quality and presentation that need to be addressed before it is considered for publication. Hence, in its present form I do not recommend this manuscript for publication in Biogeosciences. In the following, I list general and specific comments which, in my opinion, could improve the manuscript.

General comments

Due to the lack of clarity with respect to the model setup and how the denitrification rates and trace gas emissions were computed, it is hard to grasp whether the specific objectives of the study were successfully tackled or not. In particular, I recommend the authors to clearly differentiate between inferences that apply to natural processes and those which are derived from model-driven improvements and that only tell something about the model's performance.
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After refining the methods (see above and specific comments), I suggest the authors to more clearly formulate their discussion and conclusions in order to highlight the relevance of their study for a wider community (potentially very important in my opinion). At the end of the manuscript I would expect to have answers to the questions: were the drivers for denitrification in the Amazonian wetlands successfully identified? What is the extent of the emissions of CO2 and N2O and how they compare with global estimates? -

There are several misspellings and redaction problems throughout the manuscript, as well as inconsistent presentation of measurement units (several types used for the same variable) and acronyms (abbreviated and spelled in full throughout). I kindly suggest the authors to carry out a careful revision of these aspects to improve the scientific presentation. Also please note that chemical compounds (such as N2O and CO2) should not be italicized.

We thank the referee for the detailed review of our paper associated with very relevant comments and suggested enhancements.
The referee exposed a lack of clarity with respect to the model setup and how the denitrification rates and trace gas emissions were computed. Therefore, we revised parts of the Materials and Methods section to give more clarity on how we built our dataset, our hypothesis and the model performance. We combined sections 2.2 and 2.3 into a new Materials section. Section 2.2 “In situ data from the HyBAm observatory” was improved. We particularly detailed how we built our DOC and NO3 datasets. Descriptions on how we refined the methodology are detailed in the specific comments sections.
Our model only simulates denitrification and associate trace gas emissions (CO2 and N2O). In the manuscript, all the consideration made to build our input dataset are now presented. The considerations are linked to the soil texture map database (FAO to assess porosity - nitrogen content in soil (see comment P.8 l.7)) or in situ gauging stations of the HyBAm network (for river discharges and DOC concentrations). Overall, we improved the section 2 “Materials and methods” and the manuscript to detail how we modified the denitrification equation from Peyrard et al., (2010) for the case of the Amazon basin. We clearly separated the assumptions made for building our dataset (DOC and NO3-) and the inferences of the model. The discussion and conclusion sections have been modified to emphasize the inferences brought by our model and to show it successfully answers our stated objectives. According to the model, we identified that both the DOC concentrations and the extent of water bodies (the SWAF values) are the main drivers of the denitrification and trace gas emissions. CO2 emissions from denitrification account for 0.01% of the Amazon Carbon budget and represent a fraction of 3.5 x 10^-6 of the global CO2 emissions (natural and anthropogenic). When we compare our simulated N2O emissions to other estimations over the Amazon basin we find that our estimations are higher (+ 28%) even though we only take wetlands into account. For that reason, we discussed in the manuscript the importance of distinguishing wetlands in N2O models as those areas are significant sources of N2O emissions.
The manuscript has been carefully revised to correct all grammatical, misspelling and typo errors.
All figures have been regenerated for enhanced presentation and for some better content.
We will upload a revised manuscript in the new version as soon as we are invited to do so by the Editors.

Specific comments

Please re-check all figure captions since as they stand they are not informative and rather repeat what is already shown by the figures’ legends.

The figure captions were checked and corrected to avoid redundancy with the figure legends. Figures referencing in the text was also enhanced to emphasis on the results.

Figure 1 caption is now:
“The Amazon river basin and its main tributaries mapped over the SRTM digital elevation model.”

Figure 2 caption is now:
“Monthly averages from 2011 to 2015 of the SWAF surface water fractions over the Amazon basin based on Vertical polarization brightness temperatures (TB V) at 32.5° incidence angle acquired by the SMOS satellite.”

Figure 3 caption is now:
“Map of the spatial parameters of the denitrification model. DOC contents in mg/L mapped over each sub-basin of the main streams in January 2011 with local observation stations in blue circles (Left). NO3- contents (mol/l) of the watershed over FAO's soil types (Right).

Figure 4 has been updated to enhance visibility and caption is now:
“Spatial representation of N2O, CO2 and denitrification summed over the year 2011 to year 2015. The location of the main floodplains (hotspots) are outlined in the Denitrification map.”

Figure 5 caption is now:
“Monthly denitrification (kg-N), CO {2} (kg-C) and N2O (kg-N) emissions over the entire Amazon watershed for the period 2011 - 2016.”

Figure 6 has been updated to include impact of N2O/N2 ratio values showing only N2O emissions and caption is now:
“Monthly time series of N2O emissions over the basin, the O-M FP, the Madeira FP and the Branco FP over the period (2011-2016). The lines represent the emissions for a N2O / N2 ratio of 0.1 whereas the coloured areas refer to the potential range of the same ratio: 0.05 - 0.2. Denitrification and CO2 emissions follow the same patterns but with a scale factor of times 10 for denitrification and times 2 for CO2.”

Figure 7 has been formatted as a bar plot and caption is now:
Average monthly contribution of each floodplain to the Basin denitrification, over the Obidos - Manaus, the Madeira, Branco floodplains and total denitrification. The residual contribution from the 100 % is associated to the other wetlands in the basin.

Figure 8 caption is now:
“Monthly anomalies at the basin and main floodplains scale for denitrification throughout the period (2011-2015).”

Note that table captions where also improved.

P.1 l.6 “denitrification and trace gas emissions”

We added the term “trace gas emissions” in the sentence P1. L.6 which is now:

“Our results show that the denitrification and trace gas emissions present a strong cyclic pattern linked to the inundation processes that can be divided into three distinct phases: activation - stabilization – deactivation”

P.1 l.7 “activation-stabilization-deactivation”: This is mentioned here and then suddenly during the results. However, there is no explanation as to what is the meaning of each term. Please include a brief description.

A description was added in the result section 3.1 P.8 l.20.
“We find that the denitrification process can be separated into three phases. First the activation phase that is triggered by the increase of the flooded areas and the increase in the microbiological activities.
Second, the stabilization phase which corresponds to a maximum denitrification rate and a peak in microbiological activities. And third, the deactivation phase which corresponds to the retreat of inundation which also reduced the microbiological processes of denitrification.
Note that this conclusion is not independent of the selected model implementation and associated assumptions.”

Also, in the limitation section of the discussion the following paragraph was added on potential enhancement that can be done to better simulate the processes.
P17 L27

”Considering the dynamics of the activation-stabilization-deactivation of the denitrification, they can be more precisely assessed if variables like water surface temperatures and water depth were added in the future. These variables can inform on the speed at which the activation and deactivation of the microbiological process of denitrification are triggered.”

P.1 l.14-15 “data driven approach”: All studies are data based, please clarify whether you mean data-model-based approach.

“Data driven approach” was used to identify that the model implementation and calibration is based on data information and numerical approaches. In their book’s (Hydrological data driven approach) Introduction, https://doi.org/10.1007/978-3-319-09235-5 (Remesan & Mathew, 2015) explain that They “explore a new realm in data-based modelling with applications to hydrology.” So, we are in phase with the reviewer comment as data driven can be considered as a sub-approach to data-based-modelling. And as the term data-based-modelling can be considered as more universal then “data driven approach” it was replaced in the text by “data-base methodology”.

P.2 l.4 “(Borges et al., 2015)”: This publication deals with CO2 and CH4, not with N2O.

An additional reference for N2O was added. The sentence is now:
“This phenomenon is intimately linked to nitrous oxide (N2O) (Wu et al., 2009) and carbon dioxide (CO2) (Borges et al., 2015) emissions to the atmosphere.”

Wu, J., Zhang, J. and, J. W., Xie, H., Gu, R., Li, C., and Gao, B.: Impact of COD/N ratio on nitrous oxide emission from microcosm wetlands and their performance in removing nitrogen from wastewater, Bioresource Technology, 100,30https://doi.org/https://doi.org/10.1016/j.biortech.2009.01.056, 2009.

P.2 l.29-30 “However, considering the carbon budget (. . .)”: It seems odd to refer to
a sink here when the whole last paragraph is about sources. Perhaps this sentence
needs to be swapped with the next one.

The two sentences were combined and are now:

“In regards to the carbon budget, some studies show that the Amazon basin is more or less in balance and even acts as a small sink of carbon at the amount of 1GtC/yr (Lloyd et al., 2007).”

P.3 l.8 “provide”: Perhaps "identify" is more appropriate.

“Provide” was replaced by “to identify”.
The sentence is now:
“The specific objectives of the study are to highlight the main key factors controlling the denitrification and to identify the hot-spots and hot-moments of denitrification over wetlands.”

P.4 l.15-16 “Devol et al. (1995). . .”: This sentence is a repetition of the previous one.

The previous sentence P.3 l.13-14: “The Amazon hydrology is governed by three main sources: the Andes, the Brazilian and Guyana shields and the lowlands.” was removed.

P.4 l.2 “paramount”: The word "crucial" would be a better fit here.

The three uses of paramount were replaced in the manuscript:
P2 L11: replaced by “key tools”
P4 L2: replaced by “essential”
In conclusion: replaced by “essential”

P.4 l.10 “floodplain (O-M FP)”: replace by "floodplain (in the following O-M FP)”.

Modified, the sentence is now:

“Here we consider the three main floodplains: the Branco floodplain in the northern part, the Madeira floodplain in the southern part and the floodplain between Odidos and Manaus which is called Obidos - Manaus floodplain (in the following O-M FP)”

For the sake of homogeneity, all through the manuscript text the Branco Floodplain, Madeira floodplain and Obidos-Manaus Floodplain are referred to as Branco FP, Madeira FP and O-M FP.

A rigorous check on the use of acronyms was also done.

P.4 l.14 “In situ data and gauging stations data”: Please explain clearly which data you are referring to; i.e. which variables you used, their accuracy and spatial resolution.

The paragraph (section 2.2) concerning the used datasets was clarified as follow:

“In situ data were obtained from the HyBAm long-term monitoring network that maintains, in collaboration with the national stakeholders and local universities, 13 gauging stations in the Amazon catchment basin since 2003. For the Brazilian part of the basin, a network of eight local stations is maintained by the French Research Institute for Development (IRD) and the Amazonas Federal University (UFAM). Geochemical, sedimentary and hydrological data are available freely at www.so-hybam.org for each of the gauging stations. River discharge records are available daily while geochemical data, including DOC, are available monthly. In our study, we extracted both the daily river discharges and the monthly DOC concentrations. The list of stations we used in the study are found in Fig. 3 (left).”

P.4 l.14-15 Spell all abbreviations in full upon first usage.

Abbreviations were tracked throughout the manuscript and corrected to ensure uniformity.
For SMOS, Hybam, POC, DOC.

P.4 l.16 “with associated quality and uncertainty”: What does this mean? It seems the sentence should have ended at "rivers".

The sentence was updated as in the above answer (P4L14).

The figure caption was updated as stated above and an explanation was added to in the text to explain V-polarization: “The SMOS satellite observes the Earth surface at full polarization (Horizontal (H) and Vertical (V) polarization) with multi-incidence-angles variable incidence angles.”
More detailed information is found in Parrens et al., (2017) for the description of the SWAF product and (Al Bitar et al. 2017) for the brightness temperature angle binned brightness temperature products from SMOS.

Fig. 2 was reworked using a different set of colours to improve the visibility.

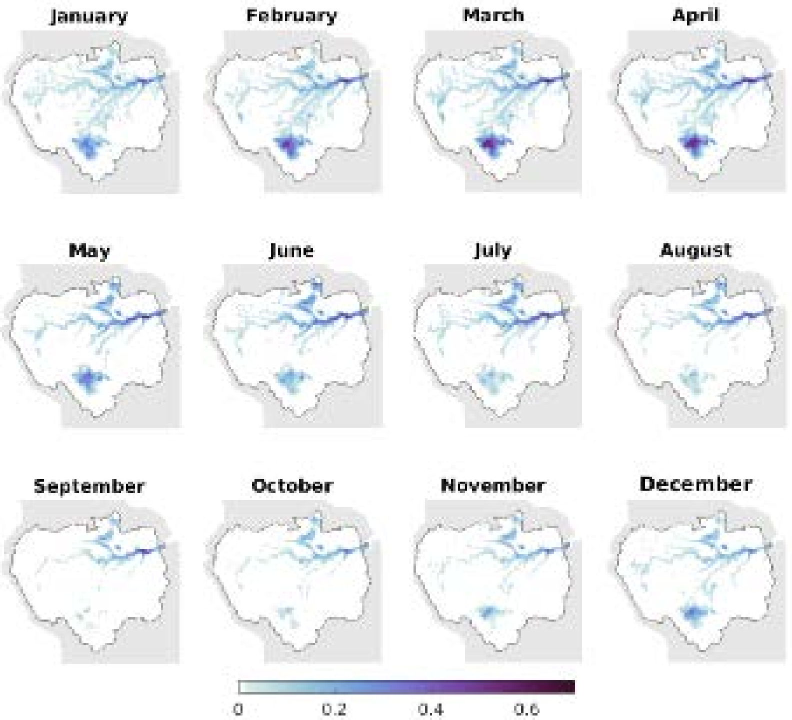

Figure 2 Monthly averages from 2011 to 2015 of the SWAF surface water fractions over the Amazon basin based on Vertical polarization brightness temperatures (TB V) at 32.5° incidence angle acquired by the SMOS satellite.

P.5 Methods: Subsections 2.2 and 2.3 should be moved to this section.

A separate Materials sub-section was added after subsection: study site in which the two paragraphs were added. Now Sub-section "2. Materials and Methods" contains a Materials subsection divided into:
2.2 Materials
2.2.1 In situ data from the HyBAm observatory
2.2.2 Water surface extents from L-Band microwave

P.5 l.3-9: Please re-check this whole paragraph since it is not clear at all.

We changed to paragraph P.5 l.3-9 to improve the clarity of our methodology. The paragraph is now:

"In this study, we modified the denitrification rate proposed by Peyrard et al. (2010) to fit tropical wetland conditions. Denitrification is the consumption of dissolved organic carbon (DOC), particulate organic carbon (POC) and nitrate (NO3-) in the soil. This process is limited by dioxygen (O2) and ammonium (NH4+) availability. Denitrification occurs during flood events when the soil has low oxygen concentrations, thus O2 concentration is not a limiting factor (Dodla et al., 2008). Furthermore, as there is only one long flood pulse in the Amazon watershed, we consider that all the ammonium is processed into nitrate between two consecutive floods. We also consider that NH+ 4 is not a limiting factor. The fact that nitrate stocks are reconstituted by nitrification under aerobic conditions, e.g when soils are no longer flooded, is a reasonable assumption in the case of the Amazon basin and more particularly for the wetland parts as shown by (Brettar et al., 2002) upper Rhine floodplain. Besides, many studies consider

denitrification as a combined consumption of nitrates and carbon (Scofield et al. (2016); Dodla et al. (2008); Goldman et al. (2017)). Taking into consideration the above statements, the denitrification rate is expressed as:”

Also do not italicize chemical compounds.

All chemical compounds are now in non-italic font throughout the manuscript. The “chemformula” package was used for the chemical equations.

Moreover, I recommend to avoid using the word “suppose” and derivatives since it gives signs of lack of accuracy in your statements.

The word “suppose” was replaced in the manuscript by “consider”.

P.6 l.25-27: If these values were taken from literature, please cite the corresponding sources. Also substantiate your choices and why they are the best for this particular study.

Concerning porosity, the following descriptions were added to the text:
“Soil Porosity (φ) is computed based on the soil texture from the FAO database at 11 km resolution and other studies (Sun et al., 2015). The porosity is averaged over the computation nodes (25x25km) using a bilinear interpolation.”

Concerning kPOC, kDOC, kNO3:
“kPOC, kDOC, kNO3 are obtained from Sun et al., (2015) who performed a study of denitrification over the Garonne catchment (temperate anthropogenic watershed). We adapted these parameters to the case of the Amazon basin. The parameters result from the best simulation. To our knowledge these parameters were never measured over the Amazon basin and the value we used are the best published estimates that we have.”

P.6 l-29-31 “On the other hand (. . .) (Sánchez-Pérez et al., 1999)”: Rephrase, it would appear as the results on that paper would be results of this study which is of course not the case.

The sentence was changed to:
“On the other hand, Sánchez-Pérez et al., (1999) showed that when denitrification is active during flooding event, nitrate pool of wetlands is provided and sustained by nitrate content coming from streams, in the case of the forested Rhine floodplain.”

P.7 l.2-3 “Dissolved organic carbon”: This was already defined as an abbreviation before in the text. For consistency keep using the abbreviations after first usage.

As mentioned above all abbreviations are now well mentioned in the manuscript.

P.7 l.3 “stable seasonality”: Seasonality implies, by definition, changes. I’m guessing the authors mean marked seasonality (i.e. that can be observed reliably every year). Also please state with respect to which parameter this seasonality is strong; is it the discharge?

The sentence is clarified as follow:

“In terms of discharge, the marked seasonality of the Amazonian streams was demonstrated by prior studies (...)”

P.7 l.5 “regarding”: Consider replacing by “according to”.

The paragraph was rewritten. Similar misuse of the word “regarding” were checked throughout the manuscript.

P.7 l.5 “main sub-basins”: Is this an operational criteria or are there any particularities to the different sub-basins? The authors state that Branco basin has differences with respect to the soil properties and therefore I wonder if and how this would affect your approach of using the same "extrapolation" uniformly.

The delineation applied in the study is based on the gauging stations used in the study. The location of the stations is in Fig.3 left below

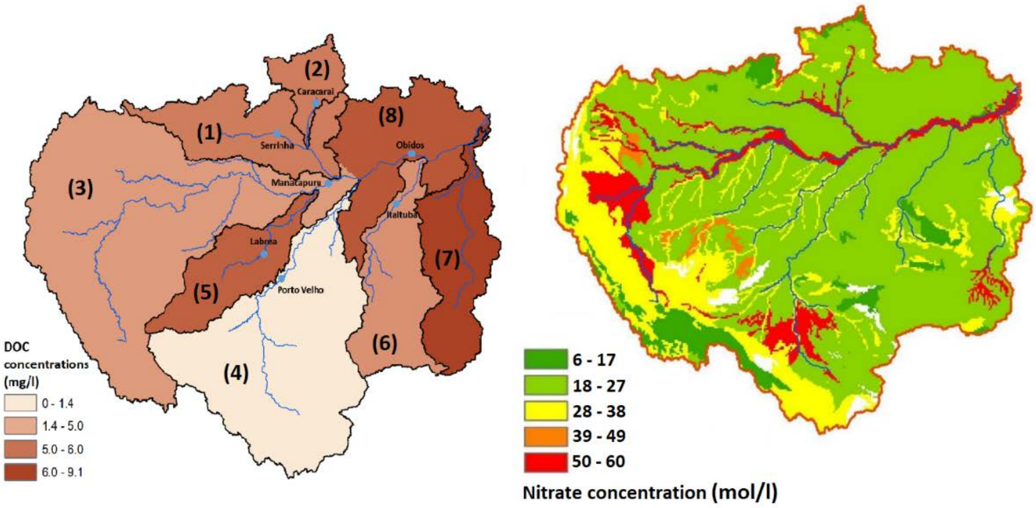

Figure 3 Map of the spatial parameters of the denitrification model. DOC contents in mg/L mapped over each sub-basin of the main streams in January 2011 with local observation stations in blue circles (Left). NO3- contents (mol/l) of the watershed over FAO's soil types (Right).

Therefore, we spatialized our data (DOC) from the gauging station to the sub-basin. The figure was replotted to better show the separation between the sub-basins.
Soil property is one particularity that is considered in the computation of the NO3- dataset. NO3- concentrations are associated with a given type of soil. The impact of soil type on Nitrate concentration is shown in fig.3 right.
In his study, Ludwig et al., (1996) demonstrated that DOC concentration was a function of discharge, soil carbon content and slope. In our study, we analysed the DOC measurements over the HyBAm stations and noticed the marked seasonality. We then used discharge to estimate spatialized DOC concentrations. Thus, this methodology draws a general trend of DOC behaviour with average values. As so, it narrows the variability of DOC concentrations for one sub basin.

P.7 l.6 “average monthly discharge”: Please show some numbers on this as well as the details of the calculation. How many stations per sub-basin were used? Are there significant differences?

Fig.3 (left) above, now displays the gauging stations used for the study. We selected the stations considering few criteria:

- **availability of DOC and discharge data**
- **location of the stations. Some stations are out of the flooded areas (shown by the SWAF data), so we decided to discard them for the study as we only consider DOC in the floodplains.**

Overall, we have one station per main sub basin.
For the average monthly discharge, we extracted the mean discharge of each month from each station. Finally, we calculated the mean average discharge for each month on the basis of daily measurements.
In order to clarify our calculation, we changed “average monthly discharge” to “the mean monthly discharge” in the section 2.4.2 (2.3.2 in the new manuscript)

P.7 l.6-7 “We then used those discharge (. . .)”: This needs to be explained. Did you use in situ data and extrapolate spatially? If so with which approach? Any caveats that should be considered? Did you grid the data? This is really important since in the current manuscript it comes as a bit of a surprise that the authors present a full map of DOC that sets the basis for some of the large-scale calculations. Without knowing the origin of this data, it is difficult to trust the model results.

The DOC data is computed on the basis of each sub-basin using the relation between DOC and discharge provided in Ludwig et al. (1996). We then associated the calculated values to the main sub basin.
For example, for the Madeira sub-basin (see new Fig.3 left) we selected only one gauging station. Discharge and DOC were extracted from the station. We then built our DOC dataset using our methodology based on the hydrology marked seasonality and the relationship between DOC and discharge. Eventually, the DOC values were extended to the whole Madeira sub basin.

The paragraph is now modified as follows:

“The daily discharge was extracted from the gauging stations used in the study (Fig. 3} (left)) from the HyBAm database (1983 – 2012). For each station, we calculated the mean monthly discharge from the daily observations. In terms of discharge, the marked seasonality of the Amazonian streams was demonstrated by prior studies (Paiva et al., 2013). For the DOC concentrations, we extracted the monthly measurements for the same stations over the same period. As the SWAF’s periods (2011 – 2015) and the DOC measurements are not concomitant, we calculated a mean average monthly DOC concentration for each station. When the information of DOC concentration was not available, our dataset was gap filled using a linear relationship between DOC concentration and discharge (Ludwig et al., 1996) based on the discharge marked seasonality of the Amazonian streams. Finally, we extended the calculated values to the associated main sub basin.”

Ludwig, W., Probst, J.-L., and Kempe, S.: Predicting the oceanic input of organic carbon by continental erosion, Global Biogeochemical Cycles, 10, 23–41, https://doi.org/10.1029/95GB02925, http://onlinelibrary.wiley.com/doi/10.1029/95GB02925/abstract, 1996.

P.7 l.7-8 “It was supposed that (. . .)”: This seems arbitrary. Is there are reason why it should not change?

In the paragraph, we state the marked seasonality in terms of discharge for the streams. Moreover, DOC concentration is linked to discharge (DOC = f(Q)) (Ludwig et al., 1996) so DOC has the same property as discharge and shows a marked seasonality. Hence, DOC concentrations change little from year to year (as discharge). Thus we considered that the monthly time series of DOC (for each sub-basin) are similar for the different years.

Overall, section 2.4.2 (now 2.3.2 in the manuscript) was changed to:
“The model parameters for the denitrification are taken from references studies and in situ measurements. The sediment porosity φ was set to 25%. It is computed based on the soil texture from the FAO database at 11 km resolution and other studies (Sun et al., 2015). The porosity is averaged over the computation nodes (25x25km) using a bilinear interpolation kPOC , kDOC and kNO3 were calibrated to 1.6 × 10−7 d −1 , 8 × 10−3 d −1 and 30 µmolL−1 respectively. They are obtained from Sun et al., (2015) who performed a study of denitrification over the Garonne catchment (temperate anthropogenic watershed). We adapted these parameters to the case of the Amazon basin. The parameters result from the best simulation. To our knowledge these parameters were never measured over the Amazon basin and the value we used are the best published estimates that we have. For P OC concentration, according to the studies performed by Moreira-Turcq et al. (2013), it was considered constant over the whole watershed and for the global period of the simulation (2011 – 2015) to 10 %.
The daily discharge was extracted from the gauging stations used in the study (Fig. 3 (left)) from the HyBAm database (1983 – 2012). For each station, we calculated the mean average discharge for each month on the basis of daily measurements. In terms of discharge, the marked seasonality of the Amazonian streams was demonstrated by prior studies (Paiva et al., 2013). For the DOC concentrations, we extracted the monthly measurements for the same stations over the same period. As the SWAF’s periods (2011 – 2015) and the DOC measurements are not concomitant, we calculated a mean average monthly DOC concentration for each station. When the information of DOC concentration was not available, our dataset was gap filled using a linear relationship between DOC concentration and discharge (Ludwig et al., 1996), based on the discharge marked seasonality of the Amazonian streams. Finally, we extended the calculated values to the associated main sub basin.

Nitrate concentrations were calculated for every type of soil given by the FAO’s classification in the upper 30 cm layer. Batjes and Dijkshoorn (1999) drew a complete description of total the nitrogen content of the soils of the Amazon region. Evaluating nitrates in the upper layer of the soils was executed adapting the mineralization rate which is based on the average temperature of the region and the proportion of both clay and limestone. For the most biologically active soils, as gleysols and fluvisols, the mineralization rate was set up to 7% of the organic nitrogen amount, which is the maximum observed value in the region. On the contrary, regosols are biologically less active soils with mineralization rates hardly reaching 2% (Legros, 2007; Sumner, 1999). Finally, we determined the nitrate concentrations by combining the nitrate content in each type of soil with the water storage capacity for each type of soil (L), deducted from the FAO soil database. Nitrate concentrations (NO3-) were considered constant over the period. On the one hand, as the Amazon is one of the most active region of the world (Legros, 2007) in term of microbial soil dynamic, it was assumed that on the one hand, during non-flooding period, mineralization of nitrogen was sufficient to compensate

nitrate loses by plant assimilation and leaching. On the other hand, Sánchez-Pérez et al., (1999) showed that when denitrification is active during flooding event, nitrate pool of wetlands is provided and sustained by nitrate content coming from streams, in the case of the forested Rhine floodplain."

P.7 Figure 3 caption: Delete "easily"

A new caption is provided (see answer to first comment).

P.7 l.11 "nitrates": Please refer to nitrate concentrations instead of nitrates. Alternatively use the chemical formula throughout the manuscript after defining it upon first usage.

The chemical formula NO3- is now used in the manuscript instead of nitrate. It was applied to all chemical compounds such as NH4+, O2, etc.

P.7 l.16: Consider rephrasing: do you mean "regardless of" instead of "regarding"?

The sentence P7 l.16: "We consider that the gases produced during the denitrification are entirely emitted to the atmosphere regarding the supersaturation of pCO2 in groundwater (Davidson et al., 2010)"

It was changed to:
"Because of the supersaturation of pCO2 in groundwater (Davidson et al., 2010), we consider that CO2 and N2O produced during denitrification are entirely emitted to the atmosphere."

P.8 l.4-5 "Soil data were determined (. . .)": The word "determined" should be replaced by "extracted", "retrieved" or other appropriate option. Also, please specify which parameters were used.

The word determined was replaced by "retrieved'.
We referred to the NO3- concentrations that were calculated for each type of soils. We added a paragraph on that statement; see comments below.

P.8 l.5-6 "The soil description file (. . .)": Consider rephrasing, this sentence is confusing. Also, does this mean that you used in situ nitrate data? If so, this information should have appeared earlier in the manuscript.

The sentence is removed and all description of the use of soil types is now assembled in the previous section.
We did not use in situ data to build our NO3- dataset as most of NO3- measurements are performed in streams and we focus on floodplain soils.

P.8 l.7 "nitrogen": Above it says you retrieved nitrate data but here you write that it was derived from the nitrogen contents. Please clarify whether the nitrate values were obtained directly or indirectly. Should the latter be the case, explain how this was done. Also, "contents" is not a precise indication of the magnitude of this variable; please refer to concentrations or other appropriate expression with the corresponding unit.

To clarify our methodology we added in section 2.4.2 a short paragraph on how we generated our nitrate dataset: "Nitrates were calculated for every type of soil given by the FAO's classification in the upper 30 cm layer. Batjes and Dijkshoorn (1999) drew a complete description of total the nitrogen content of the soils of the Amazon region. Evaluating nitrates in the upper layer of the soils was executed by correcting the mineralization rate for a given soil. For the most biologically active soils, as gleysols and fluvisols, the mineralization rate was set up to 7% of the organic nitrogen. On the contrary, regosols are biologically less active soils with mineralization rates hardly reaching 2% (Legros, 2007; Sumner, 1999). Finally, we determined the nitrate concentrations by combining the nitrate content in each type of soil with the water storage capacity for each type of soil (L), deducted from the FAO soil database."

From P8 l.3 to P8 l.11: the paragraph was reworked to : "where DNO3 is the net denitrification in mol/month, RNO3 is the denitrification rate in mol/month/L, SWAF is the fraction of land covered with open waters and Qwa is the water storage capacity for each type of soil (L), deducted from the FAO soil database. In summary the model requires the inputs and parameters for : (1) the nitrate concentration for each type of soil (mol/L), (2) the DOC concentrations of the streams that overflow, extended to the associated sub-basin and (3) the extent of inundated surfaces. The model was applied at monthly scale from January 1st 2011 to December 31th 2015 and monthly maps were then generated. Note that in order to assess the denitrification only occurring in wetlands, the minimum SWAF value recorded during the period (2011 - 2015) is subtracted to each month simulation, as it accounts as a residual artefact of streams."

P.8 l.28-29 "The mean annual denitrification (. . .)": It is not clear to me what is meant with this sentence. Which trends?

Here we refer to the average general trend of denitrification observed over one year for the whole basin (e.g Fig. 7 black line). It shows the three different phases (activation - stabilization - deactivation). For more clarity, we added few lines at the beginning of the paragraph:

"The average monthly denitrification over the basin for the period 2011 - 2015 (depicted in Fig. 7 as the black line) represents the main trend observed over the Amazonian watershed. We find that the denitrification process can be separated into three phases activation – stabilization - deactivation. First the activation phase that is triggered by the increase of the flooded areas and the increase in the microbiological activities. Second, the stabilization phase which corresponds to a maximum denitrification rate and a reach of microbiological activities
And third, the deactivation phase which corresponds to the retreat of inundation which also reduced the microbiological processes of denitrification."

P.8. l.29: "Hot moments": In the author's response to the comments of reviewer #1 I saw that this term seems to be widely used in the community and because of this they would prefer to keep it. However the journal has a wide readership and therefore it is appropriate to briefly explain what is meant by this.

The definition and the reference for the expression "hot moment" were added in the paragraph P.8 l.29 before detailing them: "A hot-moment corresponds to a short period of time with disproportionately high reaction rates relative to longer intervening time periods (McClain et al., 2003)."

P.9 Figure 4: Having a border on the same color as one of the categories of the color bar is not appropriate. Also the image quality does not allow distinguishing the features described in the text.

The figure was changed to avoid confusions with the different colours and to improve the quality of the image.

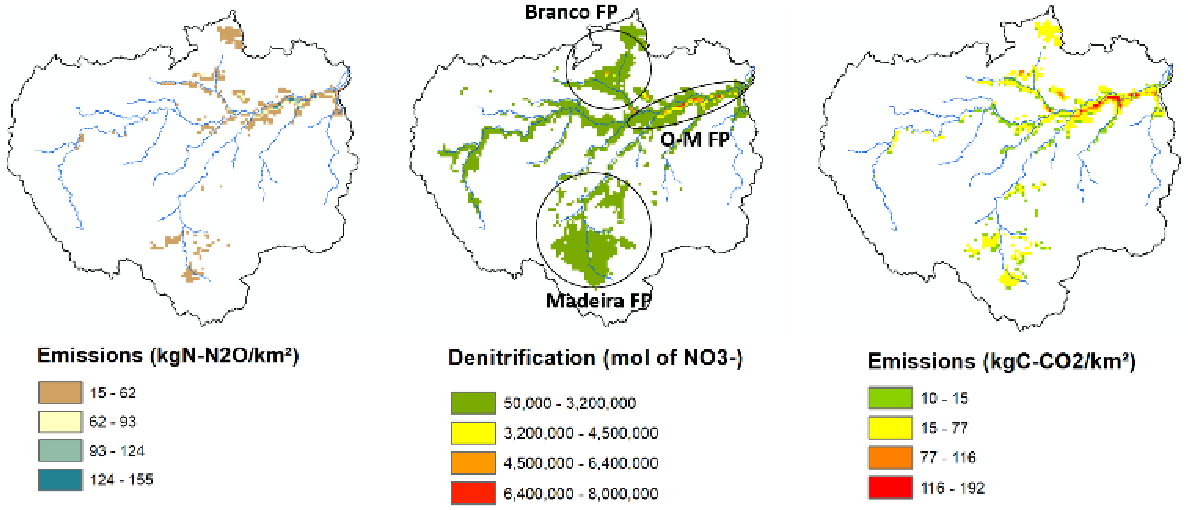

Figure 4 Spatial representation of N2O, CO2 and denitrification summed over the year 2011 to year 2015. The location of the main floodplains (hotspots) are outlined in the Denitrification map.

P.9 Section 3.2: Reconsider this subtitle since as it stands is not informative as to which is its content.

Changed to : "Denitrification, CO2 and N2O emissions: focus on the three main Amazon floodplains"

P.9 l.7: "The following comments can be given:": At this stage I would prefer to talk about results, observations, inferences based on data, or similar, but not "comments".
Please consider a different option. Also, using an active voice rather than a passive one would improve the text here and in similar instances. I kindly invite the authors to check for this.

The sentence was replaced by "the results of the model provide the following inferences:". Moreover, we corrected the manuscript to avoid the use of the passive way.

P.9. l.8 "global trend": Probably you mean "overall trend"; using the word "global" here can be misleading because this statement refers to the basin, not the globe.

The word "global" was replaced by "overall" when relevant.

P.11. Figure 6: Bar plots (e.g. stacked bars) would convey much better the relative contribution of each floodplain to the total denitrification and the emissions of CO2 and N2O.

We understand that the reviewer is mentioning figure 7 bar plots; we answer the question related to it in the corresponding comment. Concerning figure 6 it has also been updated to include the impact of the physical extent values of the NO2/N ratio. Also only N2O emissions are shown now.

P.11 l.3: Again, global should be replaced by total, overall or similar in this context.

Answered above.

P.11 l.6-8 "While the O-M floodplain (. . .)": This sentence is confusing. Is the main message here that most of the variability in denitrification and emissions of CO2 and N2O can be explained by the O-M FP and that this result is statistically significant? If so with which level of confidence? What are then the exact values or percentages of the contributions? It is not enough to say that one floodplain is the main source if this is not supported by numbers. I strongly suggest to rephrase and substantiate this statement.

In this section we tried to determine if the three floodplains have a different or similar contribution to the denitrification / emissions. To do so, we run an ANalysis Of VAriance (ANOVA) on our complete time series (monthly value from 2011 to 2015) with a level of confidence alpha = 5%. The results indicate that the FP have indeed an impact on the processes (p.value = 1.35 x 10^-8). We then ranked the three FP by applying a post-hoc analysis (same alpha and p.value). The analysis revealed 2 separated groups: group A = the O-M FP, group B = the Madeira FP and the Branco FP. On the one hand, we found that the O-M FP is the main source of emissions; on average it provides 38% of the emissions. On the other hand, we found that the Branco and the Madeira floodplains contribute similarly to the processes (on average 25% and 21% respectively).

In the manuscript P.11 l.6-8 was changed to :
"We then run an ANOVA and a post-hoc analysis to determine the contribution to the basin denitrification of each floodplain. The results return two different groups (p.value = 1.35 x 10^-8, alpha = 5%). The first group is constituted by the O-M FP which is the main source of denitrification for the basin and provides 38% of the process on average. The second group is constituted by the Branco and the Madeira floodplains. They contribute similarly to the processes (on average 25% and 21% respectively)."

P.12 Figure 7: Change "Denetrification" by "Denitrification" on the y-label axis. Also in this case stacked bars might improve visualization. As for the caption, it contains an unnecessary repetition of information already contained in the plot itself.

The y-label was corrected to "Denitrification". Fig.7 was replotted as stacked bars with an updated caption.

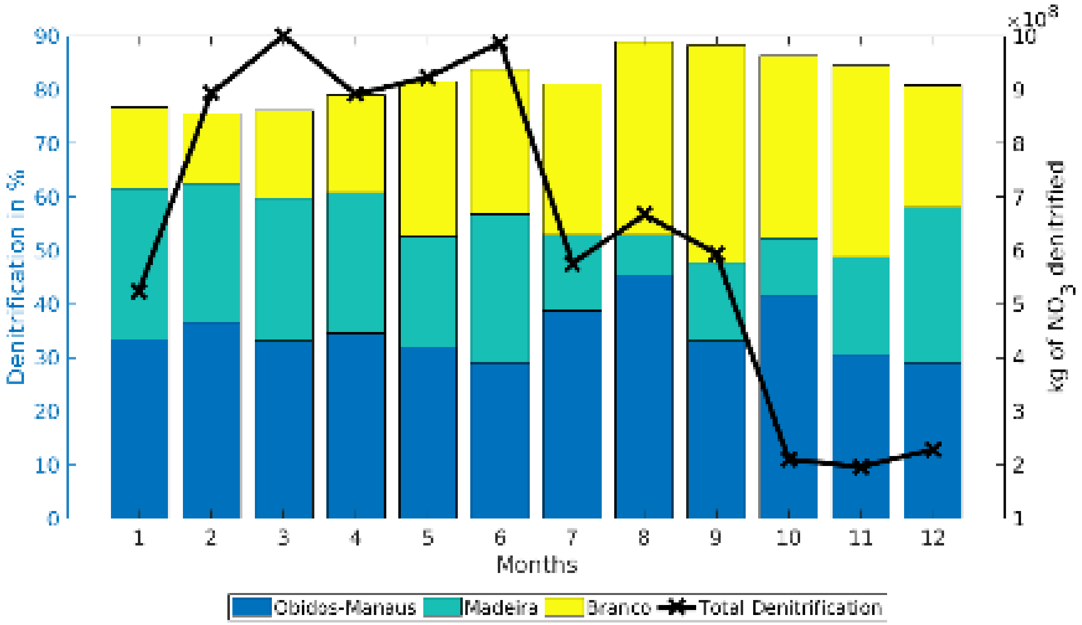

Figure 5 : Average monthly contribution of each floodplain to the Basin denitrification, over the Obidos - Manaus, the Madeira, Branco floodplains and total denitrification. The residual contribution from the 100\% is associated to the other wetlands in the basin.

P.12 l.2 “are twice as much higher”: Based on the numbers in the table I would say the authors mean two orders of magnitude higher rather than twice as much. Please check.

Corrected in Review 1.

P.12. l.2 “Averagely”: Replace by "In average" or similar.

The correction was made and replaced by “on average”. No other use of “averagely” was found in the manuscript.

P.12 Table 1: The exponent notation on the emissions of CO2 and N2 for the Amazon basin should read “x 1010” and not “x 1010”. Also, I believe the table captions should go on top of them. Please check the journal’s style guidelines.

Exponents were corrected.

P.13 l.1-2: “Over the whole basin (. . .)”: I am assuming this means no significant trend. If this is correct please state it with a more clear formulation and substantiate with numbers/plots.

Indented, we observed no significant differences of yearly emissions at watershed scale during the period for both CO2 and N2O emissions.
In the manuscprit we changed from P.12 l1.3 to P.13 l.1-2 to :

“Table 1 depicts the yearly emissions of CO2 and N2O over the Amazon basin and the three main floodplains. Emissions of CO2 from denitrification are twice as much higher than N2O emissions over the basin. The total yearly emissions of CO2 and N2O over the Amazon basin are significantly identical from 2011 to 2015 (Kruskal-Wallis p.value = 0.9929). On average, flooded areas produce 2.76 × 109 kg C-CO2 per year and 1.03 × 109 kg N-N2O per year by denitrification from the natural NO3- pool of the watershed.”

P.13 Section 3.2: Replace “gazes emissions” by “trace gas emissions” or “CO2 and N2O emissions”.

The title was change to “Denitrification and trace gas emissions anomalies”

P.13 l.8-9: “la Niña year”: Citation is needed and at best provide an index.

A reference was added that details el Nino and la Nina events on the Amazon basin. “On the one hand, year 2011 was a “la Niña year” (Moura et al. 2019).

Moura, M., Rosa dos Santos, A., Pezzopane, J., Alexandre, R., Ferreira da Silva, S., Marques Pimentel, S., Santos de Andrade, M., Gimenes495 Rodrigues Silva, F., Figueira Branco, E., Rizzo Moreira, T., Gomes da Silva, R., and de Carvalho, J.: Relation of El Niño and La Niña phenomena to precipitation, evapotranspiration and temperature in the Amazon basin, Science of The Total Environment, 651, 1693 – 1651, https://doi.org/https://doi.org/10.1016/j.scitotenv.2018.09.242., 2019.

P.13 l.15: Replace “anormalies” by “anomalies” here and subsequent instances. Also, the study covers 2011-2015, not 2010-2015.

Modified.

P.13 l.16: “were calculated by (. . .)”: I suggest rephrasing this sentence. If I understand this correctly, you took the mean of a given month across the years 2011-2015 and then subtract it from each month in the time series to calculate the anomaly. However this does not easily comes across in the text.

The calculation explanation was changed P13 l15 -16 to:
“Anomalies were determined by first calculating the mean value for each month across the period 2011 - 2015. This mean value was then subtracted from each corresponding average month in the series.”

P.13 l.18: What is the exact number for "the most"?

We substantiated our inferences with more results in the manuscript P.13 l.18:
“(...) during La Niña year and the heavy precipitations period, most of the anomalies are positive especially for the first months (66% - 66% for the total denitrification, 16% - 83% for the O-M FP, 25% - 33% for the Madeira FP and 100% - 50% for the Branco FP respectively).”

P.13. l.19 “However”: This word implies contradiction, which in this case does not exist because the second sentence is not related to the first one. Please check.

Agreed. The sentence P.13 l.19 starts now as : “During el Nino episode (…)”

P.13 l.20 “significant effect on (. . .)”: Please state precisely what is meant here. How is an effect measured? Is it the denitrification rate? With significant do you mean a statistically significant difference?

Here we performed an ANOVA on our time series (monthly values from 2011 to 2015) to assess if a meteorological event had an impact on the processes. We associated each month to an event; el Nino, la Nina, heavy rainfall or regular (as factor). The results show that only El Nino has an effect on the denitrification/emissions. To evaluate this difference, we compared the value simulated during the months el Nino to the average value of this given month. For example, Dec 2015 was under el Nino conditions. So, we compared the simulated value of Dec 2015 to the mean value of all the Dec during 2011 - 2015. On average, we find that during el Nino conditions denitrification / emissions are 27% lower than the expected mean values.

P.13. l.22: “It appears”: This does not appear but rather it is exactly what is shown in Fig. 8. On the other hand, I do not see necessary to plot all years if only 2011 and 2015 are compared. The other years in between only distract the reader. That being said, it is interesting to see that the responses of the Madeira and Branco floodplains are decoupled and completely change sign during La Niña and El Niño years, whereas between 2012 and 2014 they seem to be coupled. A discussion as to why this is the case would argue in favour of keeping the plot as it is.

The sentence P.13 l.22 now starts as: “extreme meteorological events do not have an uniform impact on the whole basin.”

We included all the years in our analysis (ANOVA). Moreover, heavy precipitations were recorded from October 2013 to March 2014. We think that it is important to notice that la Nina and heavy rainfall lead to wetter conditions but have no impact on the denitrification and the emissions. Two conclusions are made here. First, only el Nino event has an impact on the processes; all the anomalies are all negative. Second, the other events (la Nina and heavy precipitations) have no impact on the processes. Moreover, no clear general trends for the anomalies were found during those events.
The referee’s comments are correct and interesting nevertheless we believe that no conclusion can be made regarding the fact that only one la Nina and el Nino events are recorded over the study time span.

P.13 l.25-26: “As so, it can be (. . .)”: Before it was stated that there were no significant trends; therefore "assuming" here is speculative and contradicts your results.

(Table 2) We indeed found no significant trend at a yearly time step for the whole basin in general. When we focus on the three floodplains: the emissions of the OM FP and the Madeira FP increase but with a small statistical significance whereas for the Branco FP it decreases and denitrification is reduced by a factor 2 from 2011 to 2015.
We associated the drying of the Branco FP as a reason of the decrease of its denitrification. This is consistent with our model design, the decrease is attributed to the decrease of the inundated surfaces of the Branco FP.

we revised the manuscript accordinglyP.13 l.24-26
"The average denitrification rate for the whole basin shows little inter annual variations. However, in 2015 simulated denitrification for the Branco FP was twice as low than for the year 2011. As so, it can be assumed that this floodplain has been drying off during the 2011 - 2015 period and thus is much more sensitive to drier conditions than other parts of the watershed"

Was modified to:

"The average yearly denitrification rates for the whole basin, the O-M FP and the Madeira FP show no clear trend between 2011 and 2015. For the Branco FP, a decreasing trend was identified during the study period. From 2011 to 2015 the simulated average yearly denitrification for the Branco FP drops by a factor two."

P.14 l.7: "analysed analytically": Redundant, but beyond that, what does it mean?

Corrected, that was a redundant mistake. We meant analysed

P.14 l.9-10 "Overall, the denitrification (. . .)": This sentence is an example of how the variables important for the model and the variables that are key for the processes in situ cannot be clearly distinguished. Please clarify.

We refer here to the variables that are important to the model. We further clarified our statement by changing P.14 l.10 to:

"DOC and SWAF are the main driving variables of the denitrification model."

P.14 l.14: "processing": It is not clear what this means here.

Here we wanted to emphasize on the biogeochemical processing potential of wetlands. To clarify our statement. In the manuscript we completed the sentence P.14 l.14 as :

"The denitrification values show that all the three floodplains are particularly active systems in terms of ecological services for processing organic matter and NO3-. "

P.15. l.2: "natural ecosystems": Which ecosystems? References?

This statement was a loose sentence. The section P.15 l1-2 "The Branco floodplain, which is the bottom value of the set with an average potential of 38.8 kgN/ha/yr, has values at least twice as much higher than natural ecosystems." was removed from the text as it confuses the reader and it is not of interest considering the paragraph.

P.15. l.7: "sensing waterbodies": Probably here it is meant to say: "(. . .) conducting remote sensing–based monitoring of water bodies".

The sentence was changed to: "This result strengthens the importance of Earth Observation (EO) based monitoring of water bodies for determining inundated surfaces patterns and intensities and their impact on biochemical processes."

P.15 l.12 "(equation 1)": Please check the journal's style regulations but I believe here an abbreviation (Eq. 1 or similar) should suffice.

All equations are references as Eq. X in the updated manuscript.

P.15 l-14-15: Spell all abbreviations in full.

The model's abbreviations are now spelled in full:
N2O Model Inter-comparison Project (NMIP)
Dynamic Land Ecosystem Model (DLEM)
Vegetation Integrative SImulator for Trace gases (VISIT)
Organising Carbon and Hydrology In Dynamic Ecosystems - Carbon Nitrogen (ORCHIDEE-CN)

P.15 l.19: "kPOC and kDOC": These parameters were taken from the literature. Hence, a reader that is not familiar with the cited work won't understand how temperature, water saturation of the soil, nitrogen contents, soil pH and micro-organisms activity are accounted for. Please clarify.

We added a brief description to explicitly explain how temperature and others are accounted for in kPOC and kDOC.
"kPOC and kDOC are the mineralization rate parameters. They describe the kinetic processing of organic matter into POC and DOC respectively. The organic matter processing is performed by microbial communities. Therefore, environmental conditions such as temperature and soil pH have a direct influence on the bacterial activity and turnover. The cumulated impact of temperature, soil pH and micro-organisms activity, is accounted indirectly for in our approach through the parameters kPOC and kDOC and the mineralisation rate describe in Eq. 1 ((Peyrard et al., 2010; 20 Sun et al., 2017)."

P.15 l.22-23: How can it be that the N2O emissions from the wetlands only are higher than for the whole basin in which they are included? Please check.

The results are correct. The difference is due to the spatial extent that is considered. There is one total amount of N2O for the whole basin that originates from the flooded areas. But it can be weighted by the basin area or the wetlands area. So we have 2 different values of weighted emissions: the wetland is higher because associated to the smaller area.

P.15 l.23: "global": See comments above with respect to this term.

Answered above

P.16 l.1 “We consider it as being produced (. . .)”: This is another statement that is not substantiated at all and leaves open questions as to what the model does. It is crucial for the reader to know this right on the methods section.

This consideration is made when building the NO3 database. Our model only simulates denitrification along with CO2 and N2O emissions. The new section 2.3.2 (2.4.2 in the non revised ms) is clearer on how we built our NO3 dataset and details the considerations with relevant references (see answers above) and removes any confusion.

P.16 l.12 “simulation node”: This is the first time this term appears in the manuscript.
Please mention its meaning in the methods section.

For clarification, we refer to the computation over nodes and not pixels as we use the EASEv2 25km grid, which has rectangular nodes that conserve surface but not dimensions over latitudes.

We changed P.8 l.11:

“The model was applied at daily scale from January 1st 2011 to December 31th 2015 and monthly maps were then generated.”

to:

“The model simulations were applied over the EASEv2 nodes at daily scale from January 1st 2011 to December 31th 2015 and monthly maps were then generated. “

P.16 l.15 "critically": Replace by "considerably" or similar.

We changed P.14 l.15:
“Our wetlands estimations are critically lower (10^4) than integrated ecosystem observations.”
To:
“Our wetlands estimations are considerably lower (10^4) than integrated ecosystem observations.”
No other use of the word “critically” was found in the text

P.16 l.19 "participate to": Replace by "contribute with".

The sentence P.16 l.19: “Overall, CO2 emissions from denitrification over the whole Amazon basin participate to 0.01% of the carbon emissions of the watershed.”

Was change to:
“Overall, CO2 emissions from denitrification over the whole Amazon basin contribute with 0.01% of the carbon emissions of the watershed.”
No other use of the word “participate” was found in the text

P.16 l.21-22 “even a small change (. . .)”: This statement is confusing. The authors argue that even small changes could drastically modify the carbon budget. However I would expect this to be supported by a disproportionately high share to the total emissions. Hence, I wonder whether 0.01% is such a high contribution. Should this be the case, I invite the authors to substantiate the statement.

Actually, the comment confirms our statement, but we need to clarify it.
Our point is that wetlands contributes little in terms of emissions so if the wetland area is converted to, lets say, crop land or managed forests this change will drastically impact the emissions budget as the crop land for example will have a higher contribution. Thus, a small change in the natural wetlands cover to an anthropogenic non-inundated area has a big impact on the emissions budget. This change can also be due to climatic events like dry El-Nino events. In order to reflect our statement we rephrased the sentence.
The following sentence:

“Most of the CO2 emissions over the Amazon are attributed to processes such as organic matter respiration from biomass. Confirming previous studies, this result means that even a small change in the distribution of wetlands cover over the Amazonian basin may drastically modify the carbon budget.”
Was changed to:
“Most of the CO2 emissions over the Amazon are attributed to processes such as organic matter respiration from biomass and little contributions from wetlands. Previous study from Vicari et al. 2011 showed that the change of wetlands into forested area can increase the carbon emissions drastically. In this context and in light of the results obtained in this paper one can conclude that in case of very dry natural events or intense anthorpogenisation of the land-cover the carbon budget of the once wetland areas and now non-inundated surfaces will greatly increase.”

Vicari, R., Kandus, P., Pratolongo, P., and Burghi, M.: Carbon budget alteration due to landcover-landuse change in wetlands: the case of afforestation in the Lower Delta of the Parana River marshes (Argentina), WATER AND ENVIRONMENT JOURNAL, 25, 378–386, https://doi.org/10.1111/j.1747-6593.2010.00233.x, 2011.

P.16 l.22: “It constitutes (. . .)”: This seems to be a loose sentence here, please check.

We believe that regarding the current context (land use change / deforestation) over the Amazon basin, it’s important to highlight practices that impact C and N balance.
The sentence was modified to:
“This constitutes an important topical subject for the Amazonian basin.”

P.16. Table 4: Replace “gaz” by “gas”. Also, the units can be added to the caption and the last column of the table can be removed.

“Gaz” was replaced by “gas”. The last column of the table was removed and the units were moved to the legend.

P.17. l.4: “close”: Consider replacing by “similar” / “alike” / “comparable”.

We changed P.17 l.4 “The N2O emissions from the Amazon and the Congo basins are close”
To:
“The N2O emissions from the Amazon and the Congo basins are comparable”

We also changed the term “close” in P.8 l.26 : “Values registered in September are lower than in August, and yet in year 2011, 2012 and 2015, these were similar.”
P.1 l.12-13 : “(…) we found that the Amazonian wetlands have similar emissions of N2O to the tropical Congo wetlands”
P18 l.6: “Overall, the results appear alike to other large scale models; especially for N2O emissions.”

P.17 l.19-20 “we may”: This expression sounds doubtful and does not reflect confidence in your results. Please consider replacing it.

In the revised manuscript, we corrected all the sentence that sounded doubtful and rephrased them when necessary.

P.17 l19-20: Moreover, our results show that the Òbidos - Manaus floodplain possesses the same denitrification potential as a nitrate polluted temperate ecosystem.”
P.13 l.23 “Overall denitrification may not be impacted at watershed scale”
Changed to:
“Extreme meteorological events do not impact the denitrification and trace gases emissions at the basin scale.”
P14 l.8-9 “NO3- is a non-limiting factor for the denitrification In the Amazon basin”.
P.15 l.11-12 “Overall, the denitrification rate (Eq. 1) shall be considered as a combination of a potential rate function (provided by DOC and POC) and limitation functions provided by the peculiar environmental conditions.”
P.18 l.5-6: “Each floodplain possesses its own functioning that depends on rainfalls and the hydrology of the floodplain’s river.”

P.18 l.4 “transpires”: This word does not seem correct here. Please check.

We understand the concerns of the Referee on using the correct words. According to the Oxford Dictionary, “transpire” means “Prove to be the case / Occur, Happen” which reflects the wanted message.

P.18. l.6 “(. . .) depends on rainfalls (. . .)”: Yet, no plot showing discharge is presented.

Denitrification depends on rainfall and inundation by construction of the model (constrained by SWAF). But, the following graph shows that denitrification is triggered a few weeks before the flooding and is maximum during that period. It indicates that precipitations and flooding both have a key role in the denitrification process.

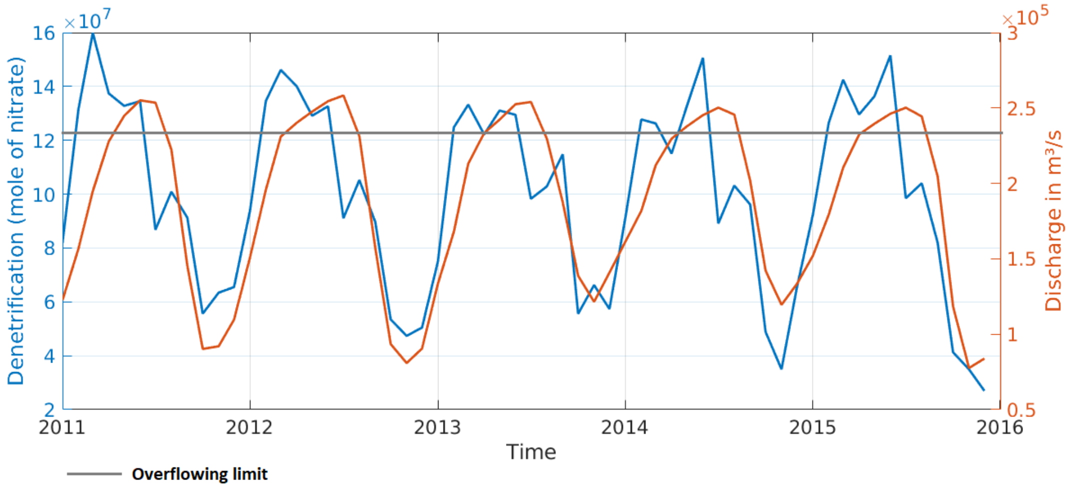

Figure 6 Evolution of denitrification of the O-M FP and the discharge at Obidos. The black horizontal line shows the discharge limit when the river overflow. It depicts that denitrification becomes active a few weeks before the inundation.

II. Relevant changes in the manuscript

P.3 L.9 Introduction and definition of hot spot and hot moment:

"A hot spot represents an area that shows disproportionately high reaction rates relative to the surrounding and hot moment corresponds to a short period of time with disproportionately high reaction rate relative to longer intervening time periods (McClain et al., 2003)"

Paragraph 2.2 In situ data from the HyBAm observatory was updated to :

"In situ data were obtained from the Hidro-geoquímica da Bacia Amazônica (HyBAm) long-term monitoring network that maintains, in collaboration with the national stakeholders and local universities, 13 gauging stations in the Amazon catchment basin since 2003. For the Brazilian part of the basin, a network of eight local stations is maintained by the French Research Institute for Development (IRD) and the Amazonas Federal University (UFAM). Geochemical, sedimentary and hydrological data are available freely at www.so-hybam.org for each of the gauging stations. River discharge records are available daily while geochemical data, including Dissolved Organic Carbon (DOC), are available monthly. In our study we extracted both the daily river discharges and the monthly DOC concentrations. The name and the location of the stations we used in the study are found in Fig. 3 (left)."

P.4 L.30 – 32 changed and updates to :

"The SWAF data were averaged each month over the sampling period (2011-2015) within the Amazon basin. The SMOS satellite observes the Earth surface at full polarization (Horizontal - H, Vertical - V and cross-polarization - HV) at multi incidence angles. In this paper, the SWAF product was generated from the SMOS TB data at 32.5° and V-polarization. Fig.2 outlines the common hydrological patterns observed in the Amazon basin as well as the dynamic of the inundations for the different floodplains. The contrasted seasonal peaks in flooded areas between the Northern and Southern floodplains are well depicted."

P.5 L 3-10 updated:

"Denitrification is the consumption of DOC, Particulate Organic Carbon (POC) and (NO_3^-) in the soil. This process is limited by dioxygen (O_2) and ammonium (NH_4^+) availability. Denitrification occurs during flood events when the soil has low O_2 concentrations, thus O_2 concentration is not a limiting factor (Dodla et al., 2008). Furthermore, as there is only one long flood pulse in the Amazon watershed, we consider that all the NH_4^+ is processed into NO_3^- between two consecutive floods. We also consider that NH_4^+ is not a limiting factor. The fact that NO_3^- stocks are reconstituted by nitrification under aerobic conditions, e.g when soils are no longer flooded, is a reasonable assumption in the case of the Amazon basin and more

particularly for the wetland parts as shown by (Brettar et al., 2002) on the upper Rhine floodplain.”

P.6 L.21:

“Finally, N2O production is indirectly estimated as a result of N2 formation. Production of N2O from N2 during denitrification commonly ranges from a factor 0.05 to 0.2 (Pérez et al., 2000). Nevertheless, with no precise field measurements an average N2O / N2 ratio of 0.1 (Weier et al., 1992) applied in the study”

Paragraph **2.4.2 Parametrization of dissolved/particulate organic carbon and nitrate concentrations** was changed to :

“The model’s parameters for the denitrification are taken from references studies and in situ measurements. The sediment porosity φ was set to 25%. It is computed based on the soil texture from the Food and Agricultural Organization (FAO) database at 11 km resolution. The porosity is averaged over the computation nodes (25x25km) using a bilinear interpolation. kPOC, kDOC and kNO3 were set to 1.6×10−7 d−1, 8.0×10−3 d−1 and 30 µmolL−1 respectively. They are adapted from (Sun et al., 2017) who performed a study of denitrification over the Garonne catchment (temperate anthropogenic watershed). To our knowledge these parameters were never measured over the Amazon basin and the values we used are the best published estimates that we have. For POC concentration, according to the studies performed by Moreira-Turcq et al. (2013), it was considered constant over the whole watershed and for the entire period of the simulation (2011 – 2015) to 10%. The daily discharge was extracted from the gauging stations used in the study (Fig.3) from the HyBAm database (1983–2012). For each station, we calculated the mean monthly discharge from the daily observations. In terms of discharge, the marked seasonality of the Amazonian streams was demonstrated by prior studies (Paiva et al., 2013). For the DOC concentrations, we extracted the monthly measurements for the same stations over the same period. As the SWAF’s periods (2011 – 2015) and the DOC measurements are not concomitant, we calculated a mean average monthly DOC concentration for each station. When the information of DOC concentration was not available, our dataset was gap filled using a linear relationship between DOC concentration and discharge (Ludwig et al., 1996), based on the discharge marked seasonality of the Amazonian streams. Finally, we extended the calculated values to the associated main sub-basin of the gauging station.

NO3- concentrations were calculated for every type of soil given by the FAO’s classification in the upper 30 cm layer (Fig. 3). Batjes and Dijkshoorn (1999) drew a complete description of the total nitrogen content of the soils of the Amazon region. Evaluating NO3- in the upper layer of the soils was executed adapting the mineralization rate which is based on the average160 temperature of the region and the proportion of both clay and limestone. For the most biologically active soils, as gleysols and fluvisols, the mineralization rate was set up to 7% of the organic nitrogen amount, which is the maximum observed value in the region. On the contrary, regosols are biologically less active soils with mineralization rates hardly reaching 2% (Legros, 2007;Sumner,1999). Finally,we determined the NO3- concentrations by combining the NO3- content in each type of soil with the water storage capacity for each type of soil, retrieved from the FAO soil database. NO3- concentrations were considered165 constant over the period. On one hand, as the Amazon is one of the most active region of the world (Legros, 2007) in

term of microbial soil dynamic, during non-flooding period, mineralization of nitrogen was sufficient to compensate NO3- loses by plant assimilation and leaching. On the other hand, Sánchez-Perez et al. (1999) showed that when denitrification is active during flood events, NO3- pool of wetlands is provided and sustained by NO3- content coming from streams, in the case of the forested Rhine floodplain.”

P.8 L.7-10 updated to:

“In summary the model requires the inputs and parameters for : (1) the NO3- concentration for each type of soil (mol/L), (2) the DOC concentrations of the streams that overflow, extended to the associated sub-basin and (3) the extent of inundated surfaces. The model simulations were applied over the Equal-Area Scalable Earth Grids version 2 (EASEv2)185 nodes at daily scale from January 1st 2011 to December 31th 2015 and monthly maps were then generated”

P.8 L.28 added:

“The average monthly denitrification over the basin for the period 2011-2015 (depicted in Fig. 7 as the black line) represents the main trend observed over the Amazonian watershed. We find that the denitrification process can be separated into three205 phases. First the activation phase that is triggered by the increase of the flooded areas and the increase in the microbiological activities. Second, a stabilization phase which corresponds to a maximum denitrification rate and a peak in microbiological activities. And third, a deactivation phase which corresponds to the retreat of the inundation which also reduced the microbiological processes of denitrification. Note that this conclusion is not independent of the selected model implementation and associated assumptions.”

P.11 L.8 added:

“We then ran an ANalysis Of VAriance (ANOVA) and a post-hoc analysis to determine the contribution to the basin denitrification of each floodplain. The results showed two different groups (p.value = 1.35×10−8, alpha = 5%). The first group is constituted by the O-M FP which is the main source of denitrification for the basin and provides 38%250 of the processes on average. The second group is constituted by the Branco FP and the Madeira FP. They contribute similarly to the processes (on average 25% and 21% respectively) The same conclusions can be made for the CO2 and N2O emissions.”

P.13 L.1-2 changed to:

“The yearly emissions of CO2 from 2011 to 2015 over the Amazon basin show significant low interannual differences (Kruskal-Wallis p.value = 0.9929). The same conclusion is drawn for the yearly N2O emissions. On average, flooded areas emits 2.20×109 kg C-CO2 per year and 1.03×109 kg N-N2O per year by denitrification from the natural NO3- pool of the watershed.”

P13 L.15-16 changed to:

“Anomalies were determined by first calculating the mean value for each month across the period 2011-2015. This mean value was then subtracted from each corresponding month in the series.”

P.13 L.19 added:

“Examining the anomalies of the watershed and the floodplains shows that during La Niña year and the heavy precipitations period, most of the anomalies are positive especially for the first months (66% - 66% for the basin denitrification, 16% - 83% for the O-M FP, 25% - 33% for the Madeira FP and 100% - 50% for the Branco FP respectively).”

P.13 L.24-16 changed to:

“The average yearly denitrification rates for the whole basin, the O-M FP and the Madeira FP show no clear trend between 2011 and 2015. For the Branco FP, a decreasing trend was identified during the study period. From 2011 to 2015 the simulated average yearly denitrification for the Branco FP drops by a factor two.”

P.15 L.17-20 updated to:

“In our case, kPOC and kDOC are the mineralization rate parameters. They describe the kinetic processing of organic matter into POC and DOC respectively. The organic matter processing is performed by microbial communities. Therefore, environmental conditions such as temperature and soil pH have a direct influence on the bacterial activity and turnover. The cumulated impact of temperature, soil pH and microorganisms activity, is accounted indirectly for in our approach through the parameters kPOC and kDOC described in Eq. 1 (Peyrard et al., 2010; Sun et al., 2017).”

P.16 L.20-22 changed to:

“Previous study from (Vicari et al., 2011) showed that the change of wetlands into forested area can increase the carbon emissions drastically. In this context and in light of the results obtained in this paper one can conclude that in case of very dry natural events or intense anthorpogenisation of the land-cover the carbon budget of the once wetland areas and now non-inundated surfaces will greatly increase.”

P.17 L.25 and L.27 added:

“Third, an average N_2O / N_2 ratio of 0.1 was set up for the study. It varies depending on several conditions as soil properties, land cover, temperature and more. Thus a precise and spatial estimation of the ratio was not relevant due to the low resolution of our input data and the lack of in field measurements.”

“Fifth, considering the dynamics of the activation-stabilization-deactivation of the denitrification, they can be more precisely assessed if variables like water surface temperatures and water depth were added in the future. These variables can inform on

the speed at which the activation and deactivation of the microbiological process of denitrification are triggered."

Conclusion. P18. L.7 added:

"CO2 emissions from denitrification account for 0.01% of the Amazon carbon budget and represent a fraction of 3.5×10−6 of the global CO2 emissions (natural and anthropogenic). When we compare our simulated N2O emissions from Amazonian wetlands to other estimations over the Amazon basin we find that our estimations are higher (+ 28%). For that reason, we emphasize on the importance of distinguishing wetlands in nitrogen models as those areas are significant sources of N2O emissions."

"From our model design perspective, we find that the denitrification for the Amazon wetlands is driven by first the extent of the flooded areas, which constrain the process) and second by the DOC content in the soil solution, which determine the maximum denitrification potential."

Figures modified. In order (2, 3, 4, 6, 7):

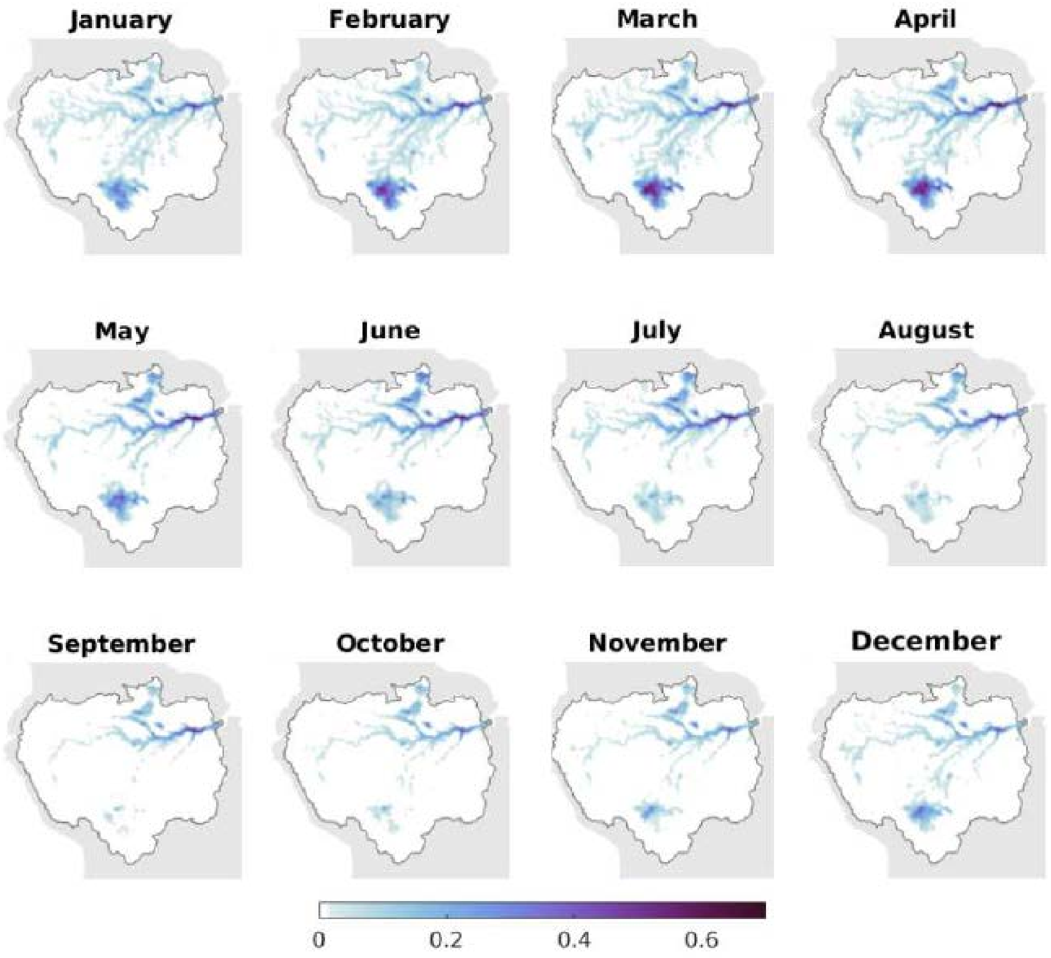

Figure 2

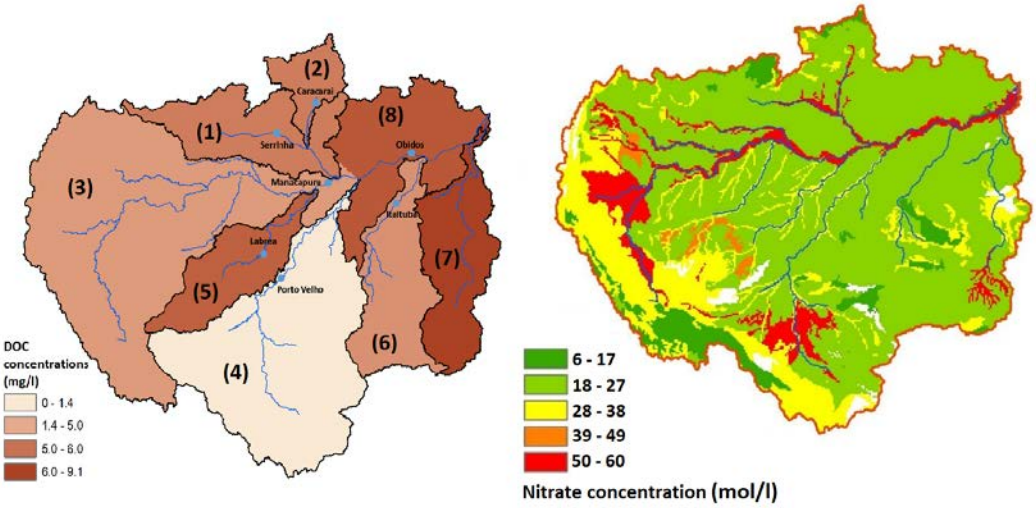

Figure 3

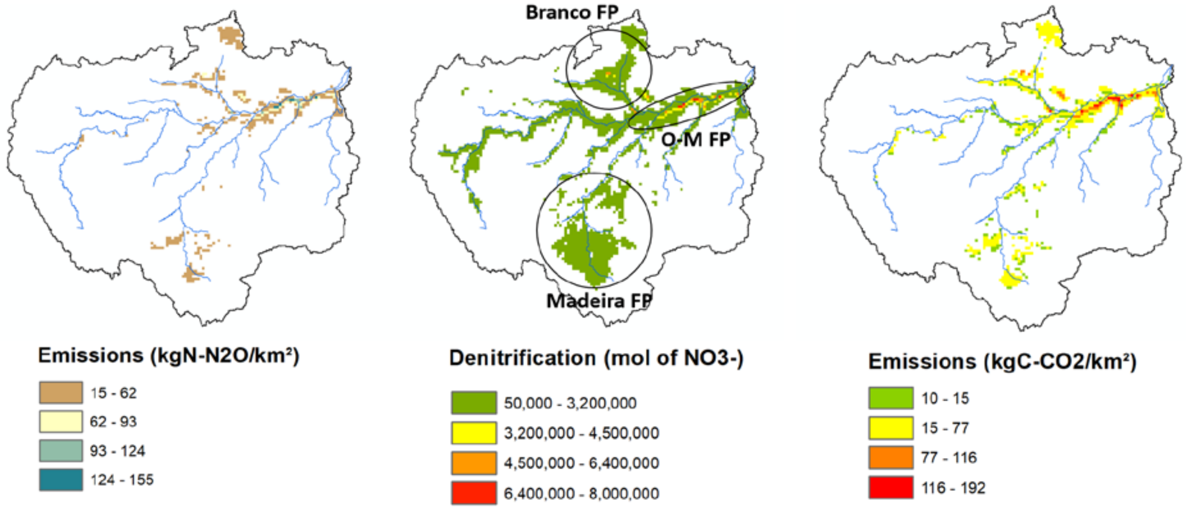

Figure 4

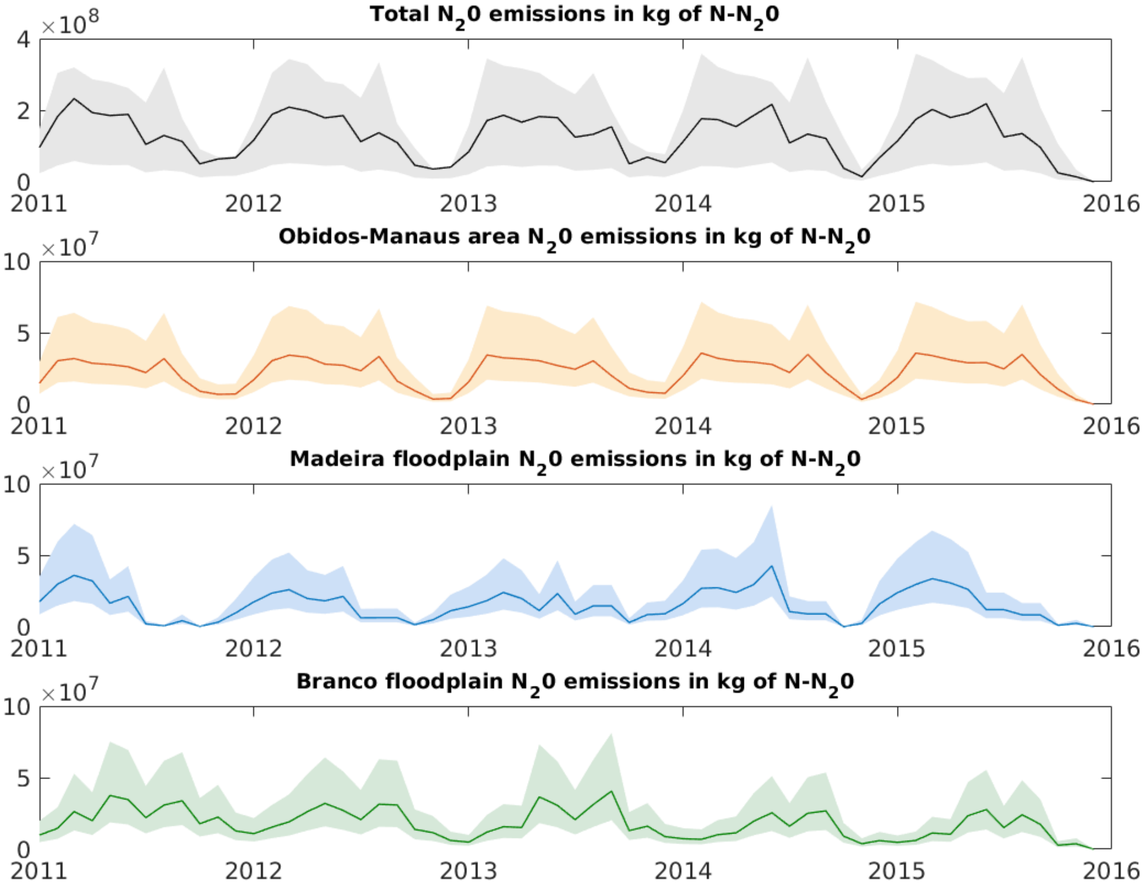

Figure 6

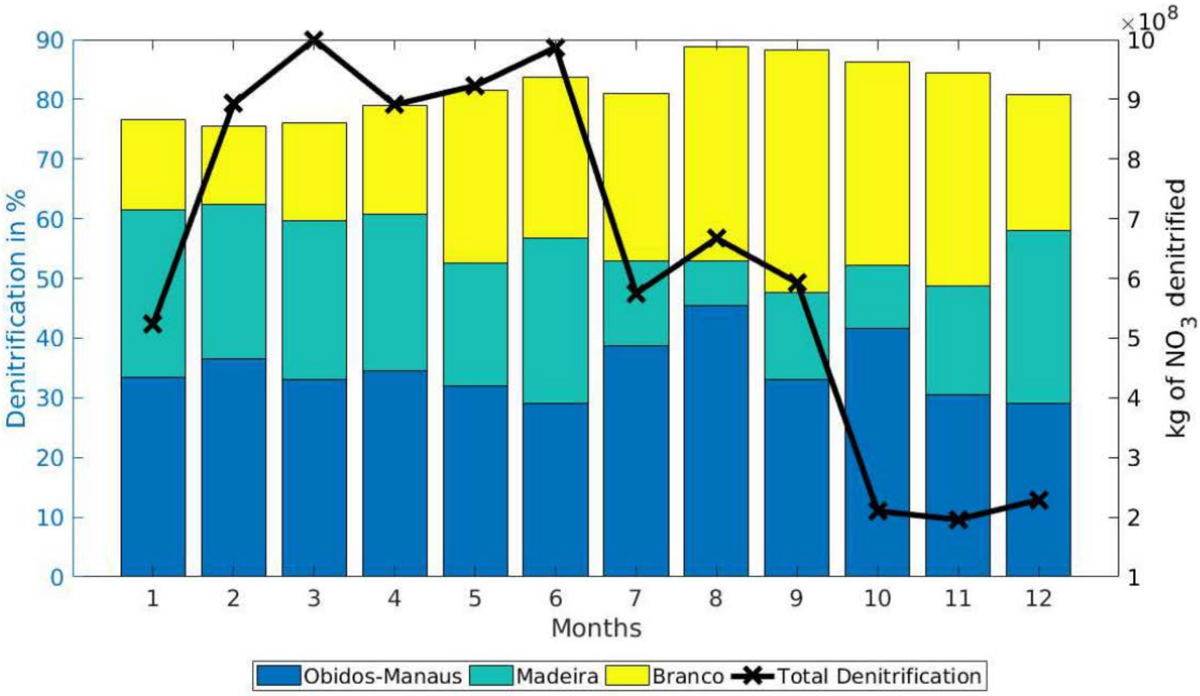

Figure 7

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Denitrification and associated nitrous oxide and carbon dioxide emissions from the Amazonian wetlands

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Abstract. In this paper, we quantify the CO_2 and N_2O emissions from the denitrification over the Amazonian wetlands. The study concerns the entire Amazonian wetland ecosystem with a specific focus on three floodplain (FP) locations: the Branco FP, the Madeira FP and the FP alongside the Amazon River. We adapted a simple denitrification model to the case of tropical wetlands and forced it by open water surface extent products from the Soil Moisture and Ocean Salinity (SMOS) satellite. A priori model parameters were provided by in situ observations and gauging stations from the HyBAm observatory. Our results show that the denitrification and the trace gas emissions present a strong cyclic pattern linked to the inundation processes that can be divided into three distinct phases: activation - stabilization - deactivation. We quantify the average yearly denitrification and associated emissions of CO_2 and N_2O over the entire watershed at 17.8 kgN/ha/yr, 0.37 gC-CO_2/m^2/yr and 0.18 gN-N_2O/m^2/yr respectively for the period 2011-2015. When compared to local observations, it was found that the CO_2 emissions accounted for 0.01% of the integrated ecosystem, which emphasizes the fact that minor changes to the land cover may induce strong impacts to the Amazonian carbon budget. Our results are consistent with the state of the art of global nitrogen models with a positive bias of 28%. When compared to other wetlands in different pedo-climatic environments we found that the Amazonian wetlands have similar emissions of N_2O with the Congo tropical wetlands and lower emissions than the temperate and tropical anthropogenic wetlands of the Garonne river (France), the Rhine river (Europe), and south-eastern Asia rice paddies. In summary our paper shows that a data-model-based approach can be successfully applied to quantify N_2O and CO_2 fluxes associated with denitrification over the Amazon basin. In the future, the use of higher resolution remote sensing product from sensor fusion or new sensors like the Surface Water Ocean Topography Mission (SWOT) mission will permit the transposition of the approach to other large scale watersheds in tropical environment.

1 Introduction

Inland waters play a crucial role in the carbon and nitrogen cycle. In particular, wetlands sequester the atmospheric and fluvial carbon (Abril and Borges, 2018). This phenomenon is intimately linked to nitrous oxide (N_2O) (Wu et al., 2009) and carbon dioxide (CO_2) emissions to the atmosphere (Borges et al., 2015). In wetlands, during inundation periods denitrification processes nitrates (NO_3^-) into atmospheric dinitrogen (N_2). These processes are controlled by biogeochemical reactions linked to microorganisms activity and pedoclimatic conditions (soil characteristics, nutrients availability and water content). Moreover the alternations between terrestrial and aquatic phases in wetlands promotes carbon and nitrogen mineralization and denitrification in soils (Koschorreck and Darwich, 2003). Our understanding and capacity to quantify the mechanisms involved in N_2O and CO_2 emissions over wetlands are limited and leads to uncertainties in estimating them at large scales.

During the last decade, process-based models have become key tools in estimating carbon and nitrogen budgets in the context of global multi-source changes. Recent studies presenting a review of existing models capable of quantifying N_2O and CO_2 fluxes over continental ecosystems (Tian et al., 2018; Lauerwald et al., 2017) show that they are mainly used to characterize the part of greenhouse gases (GHGs) emissions due to natural and anthropogenic/agricultural activities at different spatialtemporal scales. The estimation of N_2O emissions from natural sources are still subject to large uncertainties (Ciais and Coauthors., 2013) while N_2O emissions from anthropogenic activities are under investigations. Assessing N_2O budget for wetlands at large scale currently constitutes a knowledge gap. In terms of denitrification, the relatively sparse and shot-term observations limit our capability to estimate the carbon and nitrogen recycling in terrestrial ecosystems, especially over wetlands. Since in situ measurements constitute the main source of data, few studies assess N_2O and CO_2 emissions from denitrification at large scale and are usually limited to field scale or small scale watersheds (Russell et al., 2019; Johnson et al., 2019; Korol et al., 2019).

In the case of the Amazon basin, the total amount of CO_2 emission reaches 0.3 PgC/yr for both natural and agricultural sources. Scofield et al. (2016) pointed out over the Amazonian wetlands that the disproportionally high CO_2 out-gassing may be explained by the abundant amount of podzols for the Negro Basin. Podzols slow the organic matter decomposition and increase the leaching of humus. Over the Amazon basin, floodplain soils are mainly Gleysols (Legros, 2007) which are characterized by a high microbiological activity. CO_2 emissions from the river are mainly due to organic matter respiration as well as exports from the wetland system. In wetland, root respiration and microbial activities are a major source of CO_2 emissions (Abril et al., 2014). Ultimately CO_2 outgassed from the Amazon River is about 145 ± 40 TgC/yr (de Fatima F. L. Rasera et al., 2008) and tops at 470 TgC/yr when extrapolated to the whole basin (Richey et al., 2002). In regards to the carbon budget, some studies show that the Amazon basin is more or less in balance and even acts as a small sink of carbon at the amount of 1GtC/yr (Lloyd et al., 2007).

Remote sensing has emerged as a major tool for GHGs quantification, either via assimilation into physically-based models (Engelen et al., 2009) or as a direct observation (Bréon and Ciais, 2010). For wetlands the monitoring of water extents is crucial for the denitrification processes. Water surface monitoring has been done with a variety of spectral bands (Martinez and Le Toan, 2007; Pekel et al., 2016; Birkett et al., 2002) in active and passive remote sensing. Recently L-Band microwave remote sensing showed advanced capabilities to monitor water surfaces in tropical environment because of all-weather capabilities, providing soil signal under vegetation (Parrens et al., 2017).

This study aims to deliver an enhanced understanding and quantification of the denitrification process over Amazonian wetlands with their associated fluxes of N_2O and CO_2 using modelling and microwave remote sensing. We constrained and adapted a denitrification process-based set of equations by L-Band microwave water surface extents from the Soil Moisture and Ocean Salinity (SMOS) satellite and a priori information from in situ. The specific objectives of the study are to highlight the main key factors controlling the denitrification and to identify the hot spots and hot moments of denitrification over wetlands. A hot spot represent an area that shows disproportionately high reaction rates relative to the surrounding and hot moment corresponds to a short period of time with disproportionately high reaction rates relative to longer intervening time periods (McClain et al., 2003).

2 Materials and methods

2.1 Study area

The Amazon basin (Fig.1) is the world largest drainage basin with an area of $5.50 \times 10^6\ \mathrm{km}^2$ and an average water discharge of $208\,000\ \mathrm{m}^3\,\mathrm{s}^{-1}$ (Callode et al., 2010) representing 20% of all surface freshwaters transported to the ocean. The watershed spans across Bolivia, Colombia, Ecuador, French Guiana, Peru, Suriname, and Guyana and 68% of the basin pertains to Brazil.

Devol et al. (1995) described the hydrology of the main stream as the aggregation of the water originating from Andean regions, from the main tributaries and from “local sources” corresponding to smaller streams draining local lowlands. The contribution of each water body differs in time. For example from November to May the contribution of Andean waters reaches 60% and declines during the dry season to 30%. Wetlands are essential in the watershed functioning : 30% of the Amazon discharge has once passed through the floodplain distributed along a 2010 km reach between São Paulo de Olivença and Òbidos (Richey et al., 1990). The Amazon watershed is be divided into 8 major sub-basins: (1) the Negro basin, (2) the Branco basin, (3) the Solimoes River and its tributaries, (4) the Madeira basin, (5) the Purus basin, (6) the Tapajos basin, (7) the Xingu basin and (8) the section between Manaus and the mouth of the Amazon River. This delineation was used in the denitrification model (Fig. 3 left).

The Amazon basin contains several floodplains (FP). Here we consider three main floodplains: the Branco FP in the northern part, the Madeira FP in the southern part and the floodplain between Odidos and Manaus which is called Obidos-Manaus floodplain (in the following O-M FP). The O-M FP covers an area of $2.50 \times 10^5\ \mathrm{km}^2$ whereas the Madeira FP covers 3.70×10^5 km^2. The Branco FP is the widest of the three floodplains with a covered area of $6.70 \times 10^5\ \mathrm{km}^2$.

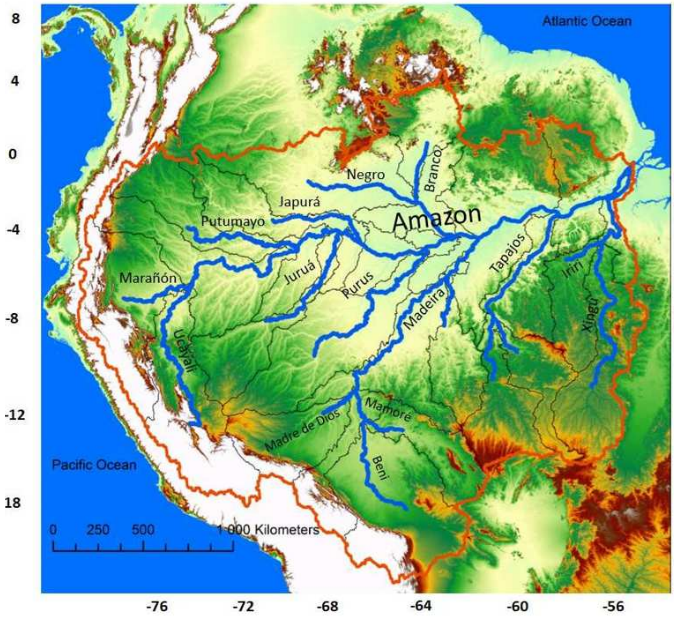

Figure 1. The Amazon river basin and its main tributaries mapped over the SRTM (Shuttle Radar topography Mission - 500 m) digital elevation model.

2.2 Materials

2.2.1 In situ data from the HyBAm observatory

In situ data were obtained from the Hidro-geoquímica da Bacia Amazônica (HyBAm) long-term monitoring network that maintains, in collaboration with the national stakeholders and local universities, 13 gauging stations in the Amazon catchment basin since 2003. For the Brazilian part of the basin, a network of eight local stations is maintained by the French Research Institute for Development (IRD) and the Amazonas Federal University (UFAM). Geochemical, sedimentary and hydrological data are available freely at www.so-hybam.org for each of the gauging stations. River discharge records are available daily while geochemical data, including Dissolved Organic Carbon (DOC), are available monthly. In our study we extracted both the daily river discharges and the monthly DOC concentrations. The name and the location of the stations we used in the study are found in Fig. 3 (left).

2.2.2 Water surface extents from L-Band microwave

The Soil WAter Fraction (SWAF) retrieved from L-Band microwave is used to determine the open water surfaces (Parrens et al., 2017). SWAF is obtained using a contextual model to the SMOS angle binned brightness temperatures (MIRCLF3TA) data (Al Bitar et al., 2017). SMOS was launched in November 2009 by the European Space Agency (ESA) and is the first satellite dedicated to map soil moisture. SMOS is a passive microwave 2-D interferometric radiometer operating in L-band

(1.413 GHz, 21 cm wavelength) (Kerr et al., 2010). SMOS orbits at a 757 km altitude and provides Brightness Temperature (TB) emitted from the Earth over a range of incidence angles (0° to 55°) with a spatial resolution of 35 to 50 km. Parrens et al. (2017) showed the capability of SMOS to retrieve the water fraction under dense forests over the Amazon basin. One of the main upsides of SMOS is its sensitivity to soil signal under vegetation in all-weather conditions thanks to the L-Band frequency. The SWAF data were averaged each month over the sampling period (2011-2015) within the Amazon basin. The SMOS satellite observes the Earth surface at full polarization (Horizontal - H, Vertical - V and cross-polarization - HV) at multi incidence angles. In this paper, the SWAF product was generated from the SMOS TB data at 32.5° and V-polarization. Fig.2 outlines the common hydrological patterns observed in the Amazon basin as well as the dynamic of the inundations for the different floodplains. The contrasted seasonal peaks in flooded areas between the Northern and Southern floodplains are well depicted.

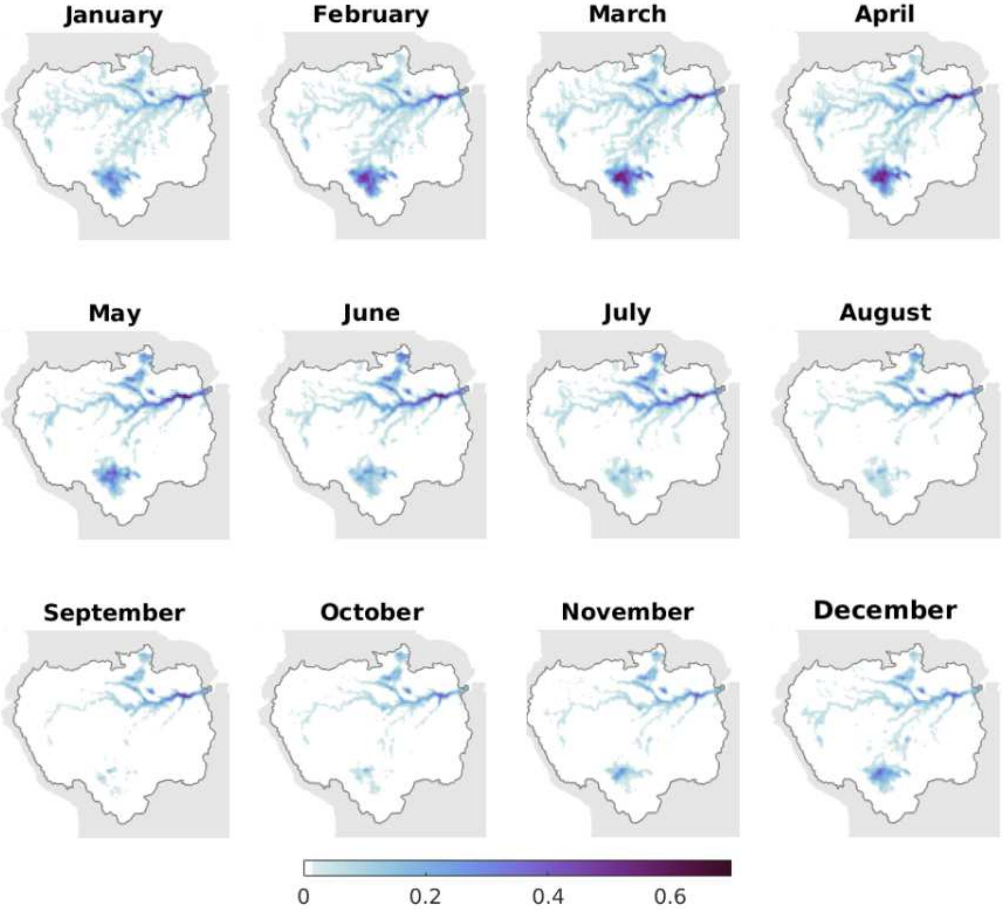

Figure 2. Monthly averages from 2011 to 2015 of the SWAF surface water fractions over the Amazon basin based on Vertical polarization Brightness Temperatures (TB V) at 32.5° incidence angle acquired by the SMOS satellite.

2.3 Methods

2.3.1 Assessing denitrification and emissions

In this study, we modified the denitrification rate proposed by Peyrard et al. (2010) to fit tropical wetland conditions. Denitrification is the consumption of DOC, Particulate Organic Carbon (POC) and (NO_3^-) in the soil. This process is limited by dioxygen (O_2) and ammonium (NH_4^+) availability. Denitrification occurs during flood events when the soil has low O_2 concentrations, thus O_2 concentration is not a limiting factor (Dodla et al., 2008). Furthermore, as there is only one long flood pulse in the Amazon watershed, we consider that all the NH_4^+ is processed into NO_3^- between two consecutive floods. We also consider that NH_4^+ is not a limiting factor. The fact that NO_3^- stocks are reconstituted by nitrification under aerobic conditions, e.g when soils are no longer flooded, is a reasonable assumption in the case of the Amazon basin and more particularly for the wetland parts as shown by (Brettar et al., 2002) on the upper Rhine floodplain. Besides, many studies consider denitrification as a combine consumption of NO_3^- and carbon (Scofield et al., 2016; Dodla et al., 2008; Goldman et al., 2017). Taking into consideration the above statements, the denitrification rate is expressed as:

$$R_{\mathrm{NO_3}} = -0.8 \cdot alpha \cdot (\rho \cdot \frac{1-\phi}{\phi} \cdot k_{POC} \cdot [POC] \cdot \frac{10^6}{M_C} + k_{DOC} \cdot [DOC]) \cdot \frac{[\mathrm{NO_3}^-]}{[k_{\mathrm{NO_3}} + \mathrm{NO_3}^-]} \qquad (1)$$

where $R_{\mathrm{NO_3}}$ is the denitrification rate in $\mu\mathrm{mol\,L^{-1}\,d^{-1}}$, $0.8 \cdot alpha$ represent the stoichiometric proportion of NO_3^- consumed in denitrification compared to the organic matter used with $alpha = 5$ as mentioned in Peyrard et al. (2010) , ρ is the dry sediment density $\mathrm{kg\,dm^{-3}}$, ϕ is the sediment porosity, k_{POC} is mineralization rate constant of POC (d^{-1}), POC refers to the POC in the soil and the aquifer sediment (1 per thousand), M_C is the carbon molar mass $\mathrm{g\,mol^{-1}}$, DOC refres to the DOC in the aquifer water $\mu\mathrm{mol\,L^{-1}}$, k_{DOC} is the mineralization rate constant of DOC (d^{-1}), $k_{\mathrm{NO_3}}$ is the half-saturation for NO_3^- limitation in $\mu\mathrm{mol\,L^{-1}}$ and NO_3^- is the nitrate concentration in the aquifer in $\mu\mathrm{mol\,L^{-1}}$.

Estimation of CO_2 emissions is based on the denitrification equation where gaseous CO_2 is formed. We consider that neither NO_3^- nor organic matter are limiting factors for the reaction which is considered total (Eq. 2) (de Freitas et al., 2001). Abril and Frankignoulle (2001) showed that denitrification tends to raise the alkalinity. In order to take into account this phenomenon, the formation of HCO_3^- from dissolved CO_2 (Eq. 3) was coupled to the denitrification (Eq. 2).

$$4\,\mathrm{NO_3^-} + 5\,\mathrm{CH_2O} + 4\,\mathrm{H^+} \longrightarrow 2\,\mathrm{N_2} + 5\,\mathrm{CO_2} + 7\,\mathrm{H_2O} \qquad (2)$$

$$\mathrm{CO_2} + \mathrm{H_2O} \longrightarrow \mathrm{HCO_3^-} + \mathrm{H^+} \qquad (3)$$

Overall, in this study, denitrification was modelled using:

$$4\,\mathrm{NO_3^-} + 5\,\mathrm{CH_2O} \longrightarrow 2\,\mathrm{N_2} + \mathrm{CO_2} + 4\,\mathrm{HCO_3^-} + 3\,\mathrm{H_2O} \qquad (4)$$

The equation of the chemical reaction of denitrification (Eq. 4) is used to determine the generated amount of CO_2 by relating it to the amount of NO_3^- denitrified. Finally, N_2O production is indirectly estimated as a result of N_2 formation. Production of N_2O from N_2 during denitrification commonly ranges from a factor 0.05 to 0.2 (Pérez et al., 2000). Nevertheless, with no precise field measurements an average N_2O / N_2 ratio of 0.1 (Weier et al., 1992) applied in the study.

2.3.2 Parametrization of dissolved/particulate organic carbon and nitrate concentrations

The model's parameters for the denitrification are taken from references studies and in situ measurements. The sediment porosity ϕ was set to 25%. It is computed based on the soil texture from the Food and Agricultural Organization (FAO) database at 11 km resolution. The porosity is averaged over the computation nodes (25x25km) using a bilinear interpolation. k_{POC}, k_{DOC} and $k_{\mathrm{NO_3}}$ were set to $1.6 \times 10^{-7}\ \mathrm{d^{-1}}$, $8.0 \times 10^{-3}\ \mathrm{d^{-1}}$ and 30 $\mathrm{\mu mol\,L^{-1}}$ respectively. They are adapted from (Sun et al., 2017) who performed a study of denitrification over the Garonne catchment (temperate anthropogenic watershed). To our knowledge these parameters were never measured over the Amazon basin and the values we used are the best published estimates that we have. For POC concentration, according to the studies performed by Moreira-Turcq et al. (2013), it was considered constant over the whole watershed and for the entire period of the simulation (2011 – 2015) to 10%. The daily discharge was extracted from the gauging stations used in the study (Fig. 3) from the HyBAm database (1983 – 2012). For each station, we calculated the mean monthly discharge from the daily observations. In terms of discharge, the marked seasonality of the Amazonian streams was demonstrated by prior studies (Paiva et al., 2013). For the DOC concentrations, we extracted the monthly measurements for the same stations over the same period. As the SWAF's periods (2011 – 2015) and the DOC measurements are not concomitant, we calculated a mean average monthly DOC concentration for each station. When the information of DOC concentration was not available, our dataset was gap filled using a linear relationship between DOC concentration and discharge (Ludwig et al., 1996), based on the discharge marked seasonality of the Amazonian streams. Finally, we extended the calculated values to the associated main sub-basin of the gauging station.

NO_3^- concentrations were calculated for every type of soil given by the FAO's classification in the upper 30 cm layer (Fig. 3). Batjes and Dijkshoorn (1999) drew a complete description of the total nitrogen content of the soils of the Amazon region. Evaluating NO_3^- in the upper layer of the soils was executed adapting the mineralization rate which is based on the average temperature of the region and the proportion of both clay and limestone. For the most biologically active soils, as gleysols and fluvisols, the mineralization rate was set up to 7% of the organic nitrogen amount, which is the maximum observed value in the region. On the contrary, regosols are biologically less active soils with mineralization rates hardly reaching 2% (Legros, 2007; Sumner, 1999). Finally, we determined the NO_3^- concentrations by combining the NO_3^- content in each type of soil with the water storage capacity for each type of soil, retrieved from the FAO soil database. NO_3^- concentrations were considered constant over the period. On one hand, as the Amazon is one of the most active region of the world (Legros, 2007) in term of microbial soil dynamic, during non-flooding period, mineralization of nitrogen was sufficient to compensate NO_3^- loses by plant assimilation and leaching. On the other hand, Sánchez-Perez et al. (1999) showed that when denitrification is active during flood events, NO_3^- pool of wetlands is provided and sustained by NO_3^- content coming from streams, in the case of the forested Rhine floodplain.

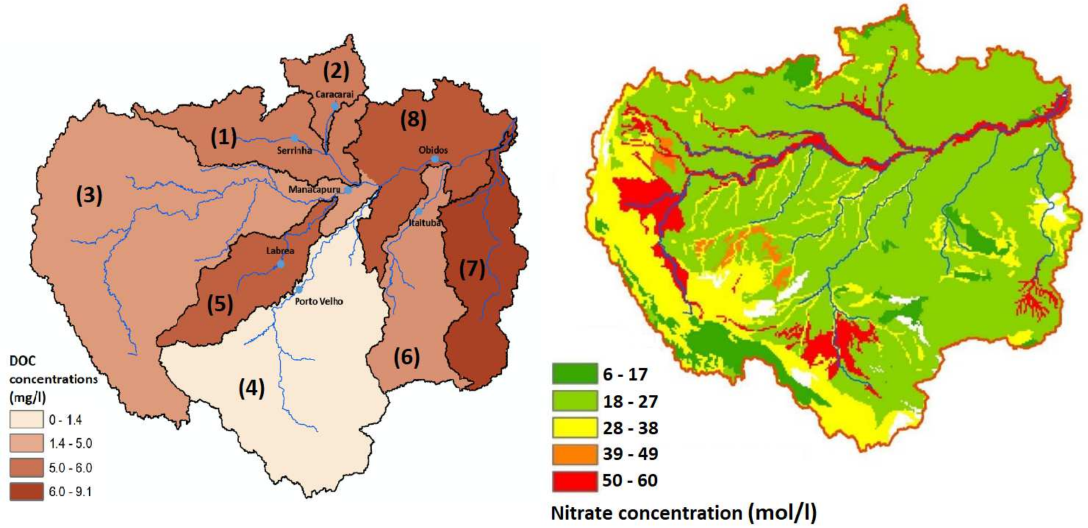

Figure 3. Map of the spatial inputs of the denitrification model. DOC contents in mg/L mapped over each sub-basin of the main streams (January) with local observation gauging stations in blue circles (Left). NO_3^- contents (mol/l) of the watershed over FAO's types of soils (Right).

2.3.3 Denitrification computation

The methodology focuses on modelling the denitrification process that occurs in the first 30 cm of water-saturated soils in wetlands. Thereby, only the NO_3^- included in that layer were considered undergoing denitrification. NO_3^- brought by streams are supposed not to modify significantly the amount of NO_3^- contained in the soil solution. Indeed, the concentration of NO_3^- in the river is negligible to the concentration of riverine aquifers (Sánchez-Pérez et al., 2003). We consider that the DOC in the soil is directly brought by streams so the amount of DOC included in soils is set up to the streams values. Most of the organic carbon is transported from alluvial sediments or brought by streams during flooding events (Peter et al., 2012). Because of the supersaturation of $p_{\mathrm{CO_2}}$ in groundwater (Davidson et al., 2010), we consider that the gases produced during the denitrification are entirely emitted to the atmosphere . Overall, denitrification was calculated as:

$$D_{\mathrm{NO_3}} = R_{\mathrm{NO_3}} \cdot SWAF \cdot Q_{wa} \tag{5}$$

where $D_{\mathrm{NO_3}}$ is the net denitrification in mol month^{-1}, $R_{\mathrm{NO_3}}$ is the denitrification rate in mol month^{-1} L^{-1}, SWAF is the fraction of land covered with open waters and Q_{wa} is the water storage capacity for each type of soil (L) retrieved from the FAO soil database. In summary the model requires the inputs and parameters for : (1) the NO_3^- concentration for each type of soil (mol/L), (2) the DOC concentrations of the streams that overflow, extended to the associated sub-basin and (3) the extent of inundated surfaces. The model simulations were applied over the Equal-Area Scalable Earth Grids version 2 (EASEv2) nodes at daily scale from January 1st 2011 to December 31th 2015 and monthly maps were then generated. Note that in order to assess the denitrification only occurring in wetlands, the minimum SWAF value recorded during the period (2011-2015) is subtracted to each month simulation, as it accounts as a residual artefact of streams.

3 Results

3.1 Spatial and temporal patterns of denitrification over the Amazon basin

Denitrification and emissions of CO_2, N_2O and N_2 are simulated for each months from 2011 to 2015. Figure 4 shows the yearly average maps of denitrification, CO_2 and N_2O emissions over the Amazon basin. The three major hot spots which correspond to the major floodplains of the Amazon Basin are identified.

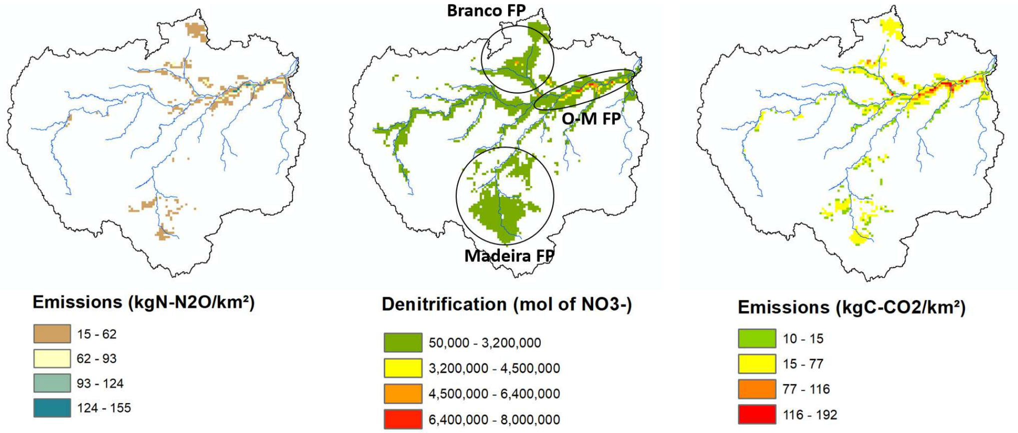

Figure 4. Spatial representation of N_2O emissions (kgN-N_2O/km²), denitrification (mol of NO_3) and CO_2 emissions (kgC-CO_2/km²) summed over the year 2013. The location of the main floodplains (hot spots) are outlined in the denitrification map.

Denitrification time series over the entire Amazon basin (Fig. 5) show that the denitrification process leads to similar temporal patterns of CO_2 and N_2O emissions at the basin scale. From November to March denitrification and emissions become active with the increase of NO_3^- denitrification in the basin. During the first months, until December, the activation is slow and mild. It then increases in the following months and peaks in March at 1.16×10^9 kg of N-NO_3^- denitrified, 2.15×10^8 kg of C-CO_2, 1.00×10^8 kg of N-N_2O. Between March and June, denitrification and emissions are steady and fluctuate respectively around 9.51×10^8 kg of N-NO_3^- denitrified, 2.04×10^8 kg of C-CO_2, 9.51×10^7 kg of N-N_2O. Finally it is observed from June to October that the processes inactivates at a slower rate (-33%) than activation. Subsequently, the decreasing trend shifts and tops in August. Values registered in September are lower than in August, and yet in year 2011, 2012 and 2015, these were similar. The decreasing trend reaches eventually a minimum peak in November at 1.96×10^8 kg of N-NO_3^- denitrified, 4.20×10^7 kg of C-CO_2, 1.96×10^7 kg of N-N_2O.

The average monthly denitrification over the basin for the period 2011-2015 (depicted in Fig. 7 as the black line) represents the main trend observed over the Amazonian watershed. We find that the denitrification process can be separated into three phases. First the activation phase that is triggered by the increase of the flooded areas and the increase in the microbiological activities. Second, a stabilization phase which corresponds to a maximum denitrification rate and a peak in microbiological activities. And third, a deactivation phase which corresponds to the retreat of the inundation which also reduced the microbiological processes of denitrification. Note that this conclusion is not independent of the selected model implementation and associated assumptions. Additionally, it shows more precisely three hot moments in March, June and August of each year. The first two hot moments, in March and June, are maximum area peaks. During these months, in spite of observing a low activity over the watershed (below 8.70×10^5 kg of N-NO_3^- denitrified per pixel), the extent of surfaces undergoing denitrification is the highest. On the contrary, the August hot moment is mainly due to a particularly strong denitrification between Obidos and Manaus with peaks of 6.16 and 7.20×10^6 kg of N-NO_3^- denitrified. CO_2 emissions average 1.75×10^8 kg of C-CO_2 per month over the basin. N_2O emissions fluctuate around 6.52×10^7 kg of N-N_2O per month from the watershed.

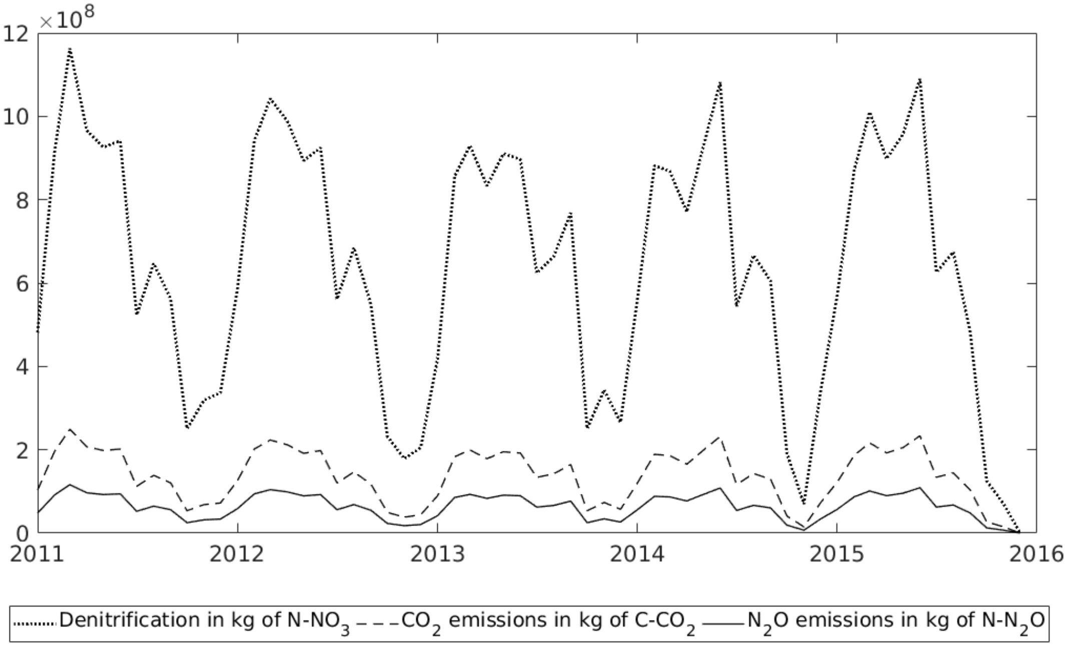

Figure 5. Monthly denitrification (kgN-NO_3), CO_2 (kgC-CO_2)and N_2O (kgN-N_2O) emissions over the entire Amazon watershed for the period 2011 - 2015.

3.2 Denitrification, CO_2 and N_2O emissions: focus on the three main Amazon floodplains

The temporal patterns of the processes over the entire basin and throughout the whole period are unique in each floodplain. In fact, the three floodplains do not become active/ inactive at the same time and do not reach their maximum potential activity at the same moment either. Figure 6 shows the monthly behaviour of N_2O emissions over the basin and for each floodplain together. The denitrification, the CO_2 and N_2O emissions follow the same patterns but on different proportions. The results of the model provide the following inferences:

- The O-M FP follows the same pattern as the overall trend and is mainly active between March and June but it never becomes totally inactive during the October – December period. It undergoes an average denitrification of 2.20×10^8 kg of N-NO_3^- and emissions of 4.78×10^7 kg of C-CO_2 and 2.23×10^7 kg of N-N_2O.
- The Madeira FP follows the same pattern as the O-M FP. However, it becomes active in October and reaches on average its maximum emissions in March with 2.93×10^8 kg of N-NO_3^- denitrified, 6.28×10^7 kg of C-CO_2, 2.93×10^7 kg of N-N_2O. The intensity of the processes decreases rapidly after. A maximum peak is usually observed afterwards in June with 3.03×10^8 kg of NO_3^- denitrified, 6.49×10^7 kg of C-CO_2 and 3.03×10^7 kg of N-N_2O. The Madeira FP denitrification is almost inactive between July and October with emissions below 5.17×10^7 kg of N-NO_3^- denitrified, 1.11×10^7 kg of C-CO_2 and 5.17×10^6 kg of N-N_2O.
- The Branco FP emissions are the least constant of the three floodplains even though a general pattern can be observed. The floodplain becomes active in January but the activation is slow and the denitrification is low until April (less than 1.70×10^8 kg of N-NO_3^-) as well as the emissions (4.00×10^7 kg of C-CO_2 and 1.70×10^7 kg of N-N_2O). Afterwards, the processes intensity increases and tops in May (2011, 2012, 2013) / June (2014 and 2015) and September 2013 at 4.06×10^8 kg of N-NO_3^-, 8.71×10^7 kg of C-CO_2, 4.06×10^7 kg of N-N_2O. The floodplain is the least active from October to February/March with denitrification and emissions barely reaching 1.20×10^8 kg of N-NO_3^- and 2.50×10^7 kg of C-CO_2, 1.20×10^7 kg of N-N_2O respectively.

The detailed functioning of each floodplain explains the general pattern observed for the processes. The O-M FP drives the general trends of the total denitrification, CO_2 and N_2O emissions of the watershed and the three different phases: activation, stabilization and deactivation. The March peak is mainly due to the Madeira FP reaching a maximum of activity. The June peak is also attributed to the Madeira floodplain in years 2011, 2012 and 2013. The peak in 2014 is due to the combined contributions of the Branco FP and the Madeira FP topping activities, whereas in 2015 only the Branco FP is contributing. The August peak is again due to the rising of the O-M FP and the Branco FP activity.

Figure 7 shows the monthly contribution of each floodplain to the total denitrification. Overall, the three floodplains contribute to 80% of the basin denitrification. From January to March it is mainly supported by the O-M FP and the Madeira FP, whereas from July to November it is due to the O-M FP and the Branco FP activity. In April, May, June and December the involvement of the floodplains is similar. We then ran an ANalysis Of VAriance (ANOVA) and a post-hoc analysis to determine the contribution to the basin denitrification of each floodplain. The results showed two different groups (p.value = 1.35×10^{-8}, alpha = 5%). The first group is constituted by the O-M FP which is the main source of denitrification for the basin and provides 38% of the processes on average. The second group is constituted by the Branco FP and the Madeira FP. They contribute similarly to the processes (on average 25% and 21% respectively) The same conclusions can be made for the CO_2 and N_2O emissions.

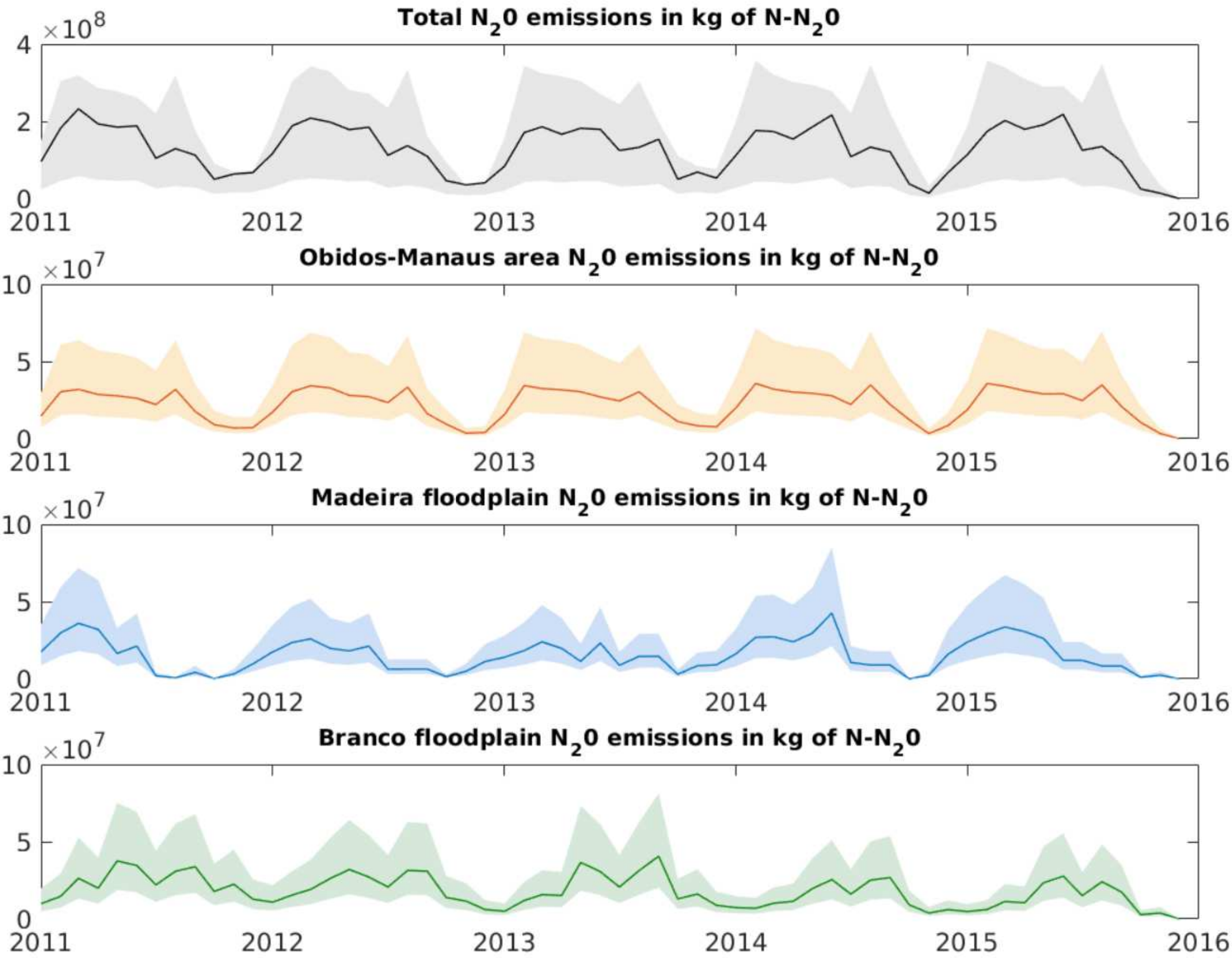

Figure 6. Monthly time series of N_2O emissions over the basin (black), for the O-M FP (yellow), for the Madeira FP (blue) and for the Branco FP (green) over the period (2011-2015). The lines represent the emissions for a N_2O / N_2 of 0.1 whereas the colored areas refer to the potential range of the ratio (0.05 - 0.2). Denitrification and CO_2 emissions follow the same patterns but with a scale factor of times 10 for denitrification and times 2 for CO_2.

3.3 Greenhouse gases emissions from the Amazonian wetlands

Table 1 depicts the yearly emissions of CO_2 and N_2O over the Amazon basin and the three main floodplains. Emissions of CO_2 from denitrification are twice as much higher than N_2O emissions over the basin. The yearly emissions of CO_2 from 2011 to 2015 over the Amazon basin show significant low interannual differences (Kruskal-Wallis p.value = 0.9929). The same con-

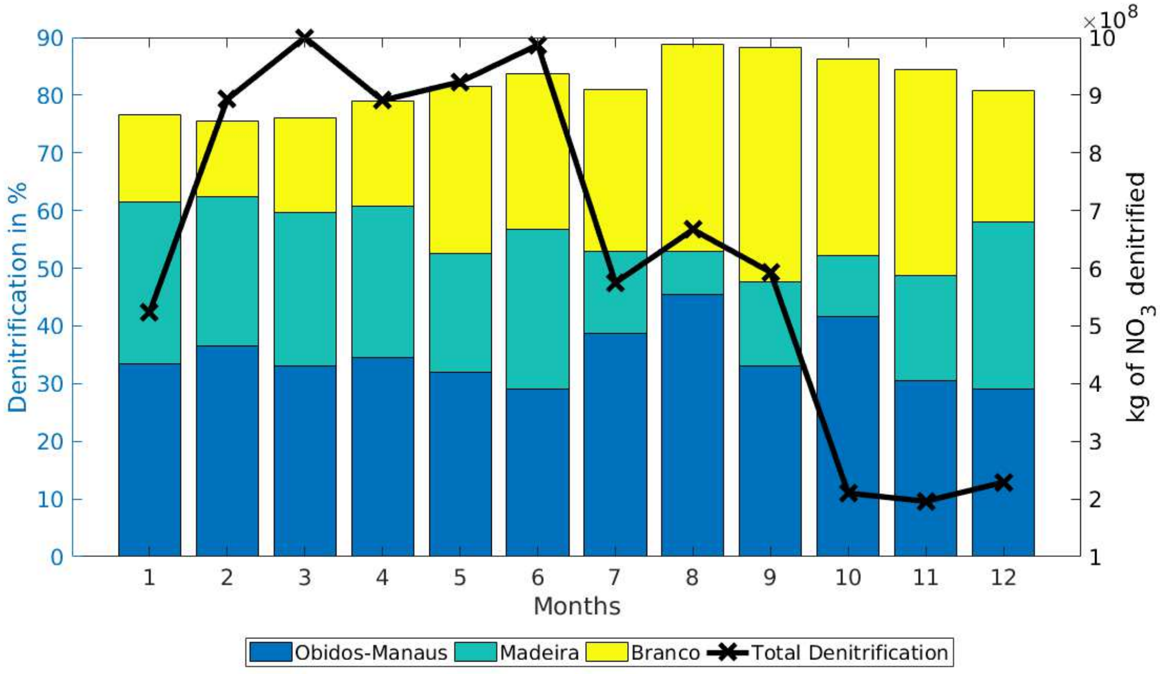

Figure 7. Average monthly contribution of each floodplain: the O-M FP, the Madeira FP, Branco FP to the Amazon total denitrification. The residual contribution from the 100% is associated to the other wetlands in the basin.

clusion is drawn for the yearly N_2O emissions. On average, flooded areas emits 2.20×10^9 kg C-CO_2 per year and 1.03×10^9 kg N-N_2O per year by denitrification from the natural NO_3^- pool of the watershed.

Table 1. Average yearly CO_2 emissions in kgC-CO_2, N_2O emissions in kgN-N_2O and N_2 emissions in kgN for the Amazon basin and the three main floodplains. The value are calculated for a N_2O / N_2 ratio of 0.1.

Wetland	Area (ha)	CO_2 (kgC)	N_2O (kgN)	N_2 (kgN)
Amazon basin	5.7×10^8	$2.20 \times 10^9 \pm 2.75 \times 10^8$	$1.03 \times 10^9 \pm 2.57 \times 10^7$	$9.26 \times 10^9 \pm 2.57 \times 10^8$
Obidos - Manaus FP	2.5×10^7	$7.63 \times 10^8 \pm 9.94 \times 10^7$	$3.56 \times 10^8 \pm 9.28 \times 10^6$	$3.21 \times 10^9 \pm 9.28 \times 10^7$
Madeira FP	3.7×10^7	$4.79 \times 10^8 \pm 2.65 \times 10^8$	$2.24 \times 10^8 \pm 2.47 \times 10^7$	$2.01 \times 10^9 \pm 2.47 \times 10^8$
Branco FP	6.78×10^7	$5.57 \times 10^8 \pm 6.17 \times 10^8$	$2.6 \times 10^8 \pm 5.75 \times 10^7$	$2.34 \times 10^9 \pm 5.75 \times 10^8$

During that period, the O-M FP is the floodplain which contributes the most to the emissions for the two gases. The dynamics of the Madeira FP and the Branco FP changed in 2014. Indeed from 2011 to 2013, the Branco FP roughly emitted twice as much gases than the Madeira FP. This trend shifted in 2014 with the involvement of the Madeira FP becoming more important in term of emissions than the Branco FP. At a yearly basis, the whole Amazon basin undergoes a denitrification of about 1.03×10^{10} kgN/ha/yr.

3.4 Denitrification and trace gas emissions anomalies

During the period of the study, major meteorological events were recorded over the Amazon basin. On the one hand, the year 2011 was a year influenced by La Niña (Moura et al., 2019). La Niña periods lead to wetter weather conditions in South America. From October 2013 to March 2014, heavy rainfalls were documented on the Madeira regions and caused extreme flooding in this region and nearby Obidos. On the other hand, September 2015 marked the begging of an "El Niño" episode. In South America and the Amazon, El Niño produces drier weather conditions.

Fig.8 shows the monthly anomalies of denitrification observed over the Amazon watershed from 2011 to 2015. Anomalies were determined by first calculating the mean value for each month across the period 2011-2015. This mean value was then subtracted from each corresponding month in the series. Positive anomalies show an intense denitrification whereas negative anomalies show a denitrification lower than the average. Examining the anomalies of the watershed and the floodplains shows that during La Niña year and the heavy precipitations period, most of the anomalies are positive especially for the first months (66% - 66% for the basin denitrification, 16% - 83% for the O-M FP, 25% - 33% for the Madeira FP and 100% - 50% for the Branco FP respectively). During El Niño episode, all the anomalies are negative. Nevertheless el Niño is the only meteorological event that has a significant effect on the processes (p.value= 4.40×10^{-3}). Moreover it impacts the three floodplains (p.value= 3.43×10^{-4}). Months undergoing the El Niño episode show a reduction of 27.7% from the average values.

Extreme events do not have a consistant impact on the whole basin. Table 2 sums up the spatial denitrification for the Amazon basin and the three floodplains at a yearly scale. Extreme meteorological events do not impact the denitrification and trace gases emissions at the basin scale. The average yearly denitrification rates for the whole basin, the O-M FP and the Madeira FP show no clear trend between 2011 and 2015. For the Branco FP, a decreasing trend was identified during the study period. From 2011 to 2015 the simulated average yearly denitrification for the Branco FP drops by a factor two.

Table 2. Yearly denitrification in kgN/ha/yr for the whole basin and the three major floodplains from year 2011 to 2015.

Denitrification (kgN/ha/yr)	**2011**	**2012**	**2013**	**2014**	**2015**
Basin	18.4	18.0	17.9	17.5	17.2
O-M FP	137.3	140.6	144.9	146.9	142.7
Madeira FP	57.4	56.3	53.3	67.4	67.7
Branco FP	48.5	43.0	43.0	31.4	28.3

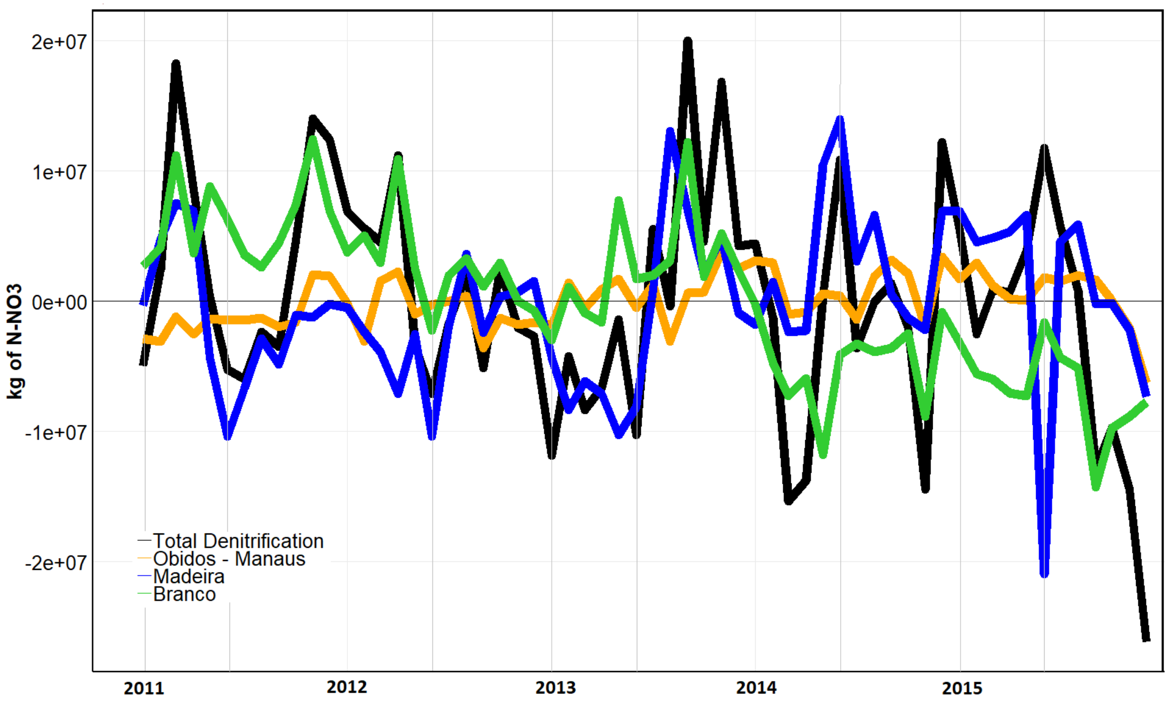

Figure 8. Monthly anomalies at the basin and main floodplains scale for denitrification throughout the period (2011-2015).

4 Discussion

4.1 Determining key factors of the denitrification

A sensitivity analysis of the parameters of the denitrification Eq. (1) was performed. k_{POC} can range from 0.15×10^{-6} to 1.10×10^{-4} which leads to a yearly denitrification 46% lower and 18% higher than the initial values respectively. k_{DOC} range from 1.00×10^{-4} to 1.22 which leads to values of denitrification 94% lower and 130 000% higher respectively. It follows that for the Amazon Basin k_{DOC} is evaluated as more sensitive than k_{POC}. Also, the NO_3^- related part of the denitrification equation was analysed. NO_3^- are relatively abundant in the watershed's soils and it is noticeable that k_{NO_3} is negligible compared to NO_3^- though $\lim_{NO_3^- \to \infty} \frac{[NO_3^-]}{[k_{NO_3} + NO_3^-]} = 1$. NO_3^- is a non-limiting factor of denitrification for the Amazon basin. Overall, the denitrification equation currently depends on four variables: POC, DOC, NO_3^- and SWAF. Overall, the main driving variables of the denitrification model are SWAF and DOC.

Table 3 depicts for the O-M FP, Madeira FP and Branco FP the effective denitrification over the 2011-2015 period in kgN/ha/yr as well as the average and standard deviation values of DOC concentration in mg/L and SWAF index. The denitrification values show that all the three floodplains are particularly active systems in term of processing organic matter and NO_3^-. The O-M FP is an active floodplain in term of denitrification potential with an average annual intensity of 142.5 kgN/ha/yr. The DOC show that the Branco FP is the highest floodplain in terms of DOC concentration with an average of 8.93 ± 2.87

Table 3. Overall denitrification in kgN/ha/yr, mean and standard deviation of the SWAF and DOC (mg/L) values for the three floodplains

Floodplain	**Denitrification**	**DOC**		**SWAF**	
		Mean	Standard deviation	Mean	Standard deviation
O-M FP	142.5 kgN/ha/yr	5.65 mg/L	2.45 mg/L	3.3%	0.12%
Branco FP	38.8 kgN/ha/yr	8.93 mg/L	2.87 mg/L	1.4%	0.27%
Madeira FP	60.4 kgN/ha/yr	2.26 mg/L	2.45 mg/L	1.7%	0.17%

mg/L, followed by the O-M FP with 5.65 ± 2.45 mg/L and the Madeira FP 2.26 ± 2.45 mg/L. Similar to the DOC, the average and standard deviation of the SWAF values were extracted from the daily observations over the 2011-2015 period. The ranked order of the floodplains for the SWAF component is similar to the denitrification one. This result strengthens the importance of Earth Observation (EO) based monitoring of water bodies for determining inundated surfaces patterns and intensities and their impact on biochemical processes. Eventually, the differences of denitrification intensity observed for the three floodplains are the combined effect of the variations of the DOC concentrations and the SWAF. As a matter of facts, DOC assesses the average maximum denitrification rate of a floodplain. Whereas the SWAF value is the main driving factor of the model which reveals the actual denitrification. Overall, the denitrification rate (Eq. 1) should be considered as a combination of a potential rate function (provided by DOC and POC) and limitation functions provided by the peculiar environmental conditions.

4.2 Comparing to physically-based models

The N_2O emissions at large scale are compared to results of the N_2O Model Inter-comparison Project (NMIP) project (Tian et al., 2018) model, more particularly the Dynamic Land Ecosystem Model (DLEM) (Xu et al., 2017), the Vegetation Integrative SImulator for Trace gases (VISIT) (Ito and Inatomi, 2012) and the Organising Carbon and Hydrology In Dynamic Ecosystems - Carbon Nitrogen (ORCHIDEE-CN) (Zaehle and Friend, 2010) models. These models consider the N_2O emissions from nitrification and denitrification, where in our case only denitrification during flooding is considered. In our case, k_{POC} and k_{DOC} are the mineralization rate parameters. They describe the kinetic processing of organic matter into POC and DOC respectively. The organic matter processing is performed by microbial communities. Therefore, environmental conditions such as temperature and soil pH have a direct influence on the bacterial activity and turnover. The cumulated impact of temperature, soil pH and microorganisms activity, is accounted indirectly for in our approach through the parameters k_{POC} and k_{DOC} described in Eq. 1 (Peyrard et al., 2010; Sun et al., 2017).

During the period 2011-2015 those models evaluated emissions of N_2O from the Amazon basin at about 0.14 gN/m²/yr. Our model simulates emissions of N_2O at roughly 0.18 ± 4.4 x 10^{-3} gN/m²/yr over the basin. The peculiar emission of the 1.3 x 10^{11} m² wetlands system represent 0.81 ± 0.02 gN/m²/yr. We can observe that our model gets a total higher estimation of the emissions of N_2O at a rate of 28% than the other models with 80% of them (0.14 gN/m²/yr) originates from the three main floodplains; the O-M FP, the Madeira FP and the Branco FP. In term of input data, our model as well as DLEM, VISIT and O-CN use climate data, soil types and inundated fractions/surfaces. A divergent point is how nitrogen pool is calculated. We consider it as being produced by the organic matter mineralization and a maximum nitrification, whereas the other models compute it from nitrogen deposition. Moreover, they also take natural vegetation, swamps delineation (O-CN) and land cover as input data while we only focus on wetland types. These models assess N_2O emissions based on the processes of the nitrogen cycle such as denitrification. Our model apprehends denitrification as a function of carbon and nitrate contents (DOC, POC and NO_3^-) and inundated surfaces (SWAF). As a result, these models do not fully distinguish the alluvial floodplain from other lands (Xu et al., 2017) and underestimate its effects (Ito and Inatomi, 2012). Thus our results bring us to conclude that current physically-based N_2O emissions models are likely to slightly underestimate the contribution of wetlands in the global budget.

4.3 Wetlands and integrated ecosystem emissions

In this section, our model outputs for wetlands emissions are compared to local in situ measurements of the N_2O and CO_2 ecosystem emissions. Table 4 summarizes the different results from in situ measurements for N_2O and CO_2 and the closest simulation node from our simulation. When comparing the N_2O with in situ campaigns performed by (Koschorreck, 2005) and (Keller et al., 2005) at Manaus plateau and Santarem, the wetlands emissions from our study are roughly 1/200 of the integrated ecosystem observed emisisons. CO_2 emissions at local in situ measurements (Keller et al., 2005) as well as to broader measurements (Richey et al., 2002) are compared to our models outputs. Our wetlands estimations are considerably lower (10^4) than integrated ecosystem observations. As expected, even though CO_2 emissions from wetland denitrification are about 2.16×10^9 kgC-CO_2 per year over the Amazon basin, these emissions are negligible when compared to the full ecosystem carbon emissisons (Cole et al., 2007; Davidson et al., 2010). Overall, CO_2 emissions from denitrification over the whole Amazon basin contribute with 0.01% of the carbon emissions of the watershed. Most of the CO_2 emissions over the Amazon are attributed to processes such as organic matter respiration from biomass and little contributions from wetlands. Previous study from (Vicari et al., 2011) showed that the change of wetlands into forested area can increase the carbon emissions drastically. In this context and in light of the results obtained in this paper one can conclude that in case of very dry natural events or intense anthorpogenisation of the land-cover the carbon budget of the once wetland areas and now non-inundated surfaces will greatly increase.

Table 4. Comparison of the values estimated by our study and the literature from the emissions of CO_2 (gC/km²/yr) and N_2O (gN/km²/yr).

Paper	Gas measured	Site	Ecosystem in situ obs.	Modeled wetlands
Koschorreck (2005)	N_2O	Manaus plateau	$5 \pm 7.5 \times 10^6$	$2.4 \pm 1.1 \times 10^4$
Keller et al. (2005)	N_2O	Santarem	$8.6 \pm 0.7 \times 10^6$	$5.2 \pm 0.9 \times 10^4$
Richey et al. (2002)	CO_2	Amazon River wetlands	$6 \pm 0.3 \times 10^7$	$4.4 \pm 2.5 \times 10^3$
Keller et al. (2005)	CO_2	Santarem	$5.7 \pm 0.6 \times 10^7$	$1.6 \pm 0.9 \times 10^3$

4.4 The Amazonian wetlands emissions versus Tropical and temperate wetlands

We put in perspective the Amazonian wetlands emisisons to a variety of wetland ecosystems such as the Congo basin, rice paddies of south-eastern Asia, the Garonne (France) and the Rhine (Europe) rivers with each possessing peculiar features. The Congo basin can be considered, like the Amazon, as a pristine ecosystem regarding agricultural nitrogen inputs. On the contrary, rice paddies regions are territories with intensive agricultural activities, high NO_3^- fertilization and undergo several flood events per year. Both the Congo basin and the rice paddies regions are part of the tropical region, like the Amazon basin. The N_2O emissions from the Amazon and the Congo basins are comparable. Our results for the Amazon and the ones exposed in Tian et al. (2018) for the Congo show emissions of 0.18 gN/m²/yr. The two watersheds are pristine from agricultural nitrogen inputs and located toward the same latitudes, so relatively similar emissions of N_2O are expected. On the contrary, rice paddies shoot up with emissions of about 0.28 gN/m²/yr. This is explained by the impacts of agricultural inputs and successive flooding on wetland ecosystems that increase the amount of greenhouse gases. The Garonne and the Rhine rivers catchments are in temperate regions under high agricultural pressures. The Garonne river, one of the main fluvial systems in France, is 525 km long draining a 55 000 km² area into the Atlantic Ocean. The large range of altitudes and slopes within the watershed leads to a diversity of hydrological behaviours. The typical alluvial plain starts from its middle section and is about 4 km wide. The riparian forest and poplar plantations cover the first 50-200 m from the riverbank, beyond which lies agricultural land that accounts for 75% of the total area. The Rhine river, one of the main fluvial systems in Germany, is 1,233 km long draining a 198 000 km² area from Switzerland to the North sea. The average denitrification reaches 132.52 ± 3.9 kgN/ha/yr Sun et al. (2017) and 653 kgN/ha/yr Sánchez-Perez et al. (1999) for the Garonne's and Rhine's floodplains respectively. The average rate of denitrification for the Amazon basin is 17.8 ± 0.4 kgN/ha/yr which is far less than values observed in European catchments. As a comparison the Òbidos - Manaus floodplain (table 2) denitrification potential is equivalent to the Garonne river. Overall, the Amazon wetland ecosystem can be regarded as a not-very active greenhouse gases emitting system compared to other ecosystems of the tropical region. Moreover, our results show that the O-M FP possesses the same denitrification potential as a NO_3^- polluted temperate ecosystem.

4.5 Limitations of the current approach

The findings of this study have to be seen in light of some limitations. First, the sampling resolution of input data can induce bias. The SWAF product tends to underestimate water surface extents variability and land cover identification due to the coarse resolution of 25 km x 25 km. Second, the use of uniform k_{POC} and k_{DOC} values limits the capabilities of the model to fully consider the impact of the spatial variability of both geophysical and biological variables. Third, an average N_2O / N_2 ratio of 0.1 was set up for the study. It varies depending on several conditions as soil properties, land cover, temperature and more. Thus a precise and spatial estimation of the ratio was not relevant due to the low resolution of our input data and the lack of in field measurements. Fourth, as highlighted by the present study, the lack of in situ measurements of N_2O emissions over tropical wetlands specifically increases the uncertainties and equifinalities for the calibration of model parameters and validation. Fifth, considering the dynamics of the activation-stabilization-deactivation of the denitrification, they can be more precisely assessed if variables like water surface temperatures and water depth were added in the future. These variables can inform on the speed at which the activation and deactivation of the microbiological process of denitrification are triggered. Future studies should concentrate on: adding more remotely sensed geophysical variables at the adapted spatial resolution (Parrens et al., 2019), taking into account the fact that flooding actually sustains the different processes.

5 Conclusions

The main objective of the study is to quantify and assess CO_2 and N_2O emissions over the Amazonian wetlands during flooding periods. To achieve these goals we design a data-based methodology that relies on modelling and remote-sensing products. It aims to estimate emissions linked to denitrification at large scale. The model parametrisation was justified by results from several published papers. It appears that denitrification mainly relies on DOC contents in the watershed. The study also contributes to better understand the functioning of the major floodplains of the Amazon Basin and their respective involvement in the Amazon Carbon and Nitrogen budget. It transpires that the most active floodplain is the Òbidos-Manaus, which is responsible for the majority of processes. Each floodplain possesses its own functioning that depends on rainfalls and the hydrology of the floodplain's river. Overall, the results appear quite alike to other large scale models; especially for N_2O emissions. CO_2 emissions from denitrification account for 0.01% of the Amazon carbon budget and represent a fraction of 3.5×10^{-6} of the global CO_2 emissions (natural and anthropogenic). When we compare our simulated N_2O emissions from Amazonian wetlands to other estimations over the Amazon basin we find that our estimations are higher (+ 28%). For that reason, we emphasize on the importance of distinguishing wetlands in nitrogen models as those areas are significant sources of N_2O emissions. Key factors of the denitrification for the Amazon basin were identified in the study. From our model design perspective, we find that the denitrification for the Amazon wetlands is driven by first the extent of the flooded areas, which constrain the process) and second by the DOC content in the soil solution, which determine the maximum denitrification potential. Future studies will concentrate in extending the current approach to other tropical basins, needless to say that local observations will be essential for the validation of such exercise and preferably over the same period of analysis. Data from future missions like SWOT will deliver water heights at 21 days global coverage, which will improve the results of such studies through the integration of surfaces and volume information.

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