Point-by-point response

Review 1

Comment on:

"Denitrification, carbon and nitrogen emissions over the Amazonian wetlands"

In an earlier review of this manuscript I expressed the potential relevance of the study albeit my concerns with respect to the lack of clarity on the approach used to reach the conclusions postulated by the authors. Having read the revised version submitted by the authors, it is my opinion that the issues raised (both of content and format) were satisfactorily addressed. Hence, after addressing the technical corrections listed below, I do recommend this manuscript for publication in Biogeosciences.

Technical corrections

Note that these corrections are referred to the file named:

"bg-2020-3-author_response-version1.pdf"

P.1 l.3 "from the denitrification": delete "the"

The sentence P.1 L.3 "In this paper, we quantify the CO2 and N2O emissions from the denitrification over the Amazonian wetlands." was changed to:

"In this paper, we quantify the CO2 and N2O emissions from denitrification over the Amazonian wetlands"

P.2 l.41 (...) pointed out that over the Amazonian wetlands disproportionally (...)

The sentence P.2 L.41 "Scofield et al. (2016) pointed out over the Amazonian wetlands that the disproportionally high CO2 out-gassing may be explained by the amount of podzols for the Negro Basin" was changed to:

"Scofield et al. (2016) pointed out that over the Amazonian wetlands disproportionally high CO2 out-gassing may be explained by the amount of podzols for the Negro Basin"

P.3 l.59 (...) a priori in situ information (...)

The sentence P.3 L.59 "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" was modified to:

"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 in situ information"

P.6 l.113 Replace "dioxygen" by "oxygen"

The sentence P.6 L.113 was changed to "This process is limited by oxygen (O2) and ammonium (NH4+) availability

P.7 l.144 "(25x25km)": Add space between the numbers and the unit of measure.

P.7 L.144 the unit of measure was replaced to (25 km x 25 km)

P.7 l.148 Replace "For PCO" by "The" and delete "it" from the sentence "(…) it was considered (…)"

The sentence P.7 L.148 "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%" was changed to:

"According to the studies performed by Moreira-Turcq et al . (2013), the POC concentration was considered constant over the whole watershed and for the entire period of the simulation (2011-2015) to 10%"

P.11 l.221 "Denitrification as well as the CO2 and N2O emissions (...)"

The sentence P.11 L.221 "The Denitrification, the CO2 and N2O emissions follow the pattern" was changed to:

"Denitrification as well as the CO2 and N2O emissions follow the same pattern"

P.11 l.248 "We then ran": Delete "then"

P.11 L.248 "We ran an Analysis of Variance (ANOVA) and a post-hoc analysis (…)"

P.12 l.257 Replace "p.value" by "p-value"

p.value was checked and replaced by p-value throughout the manuscript.

P.16 l.309 Replace "facts" by "fact" and "assesses" by "determines" or similar.

Corrected

P.16 l.310 Replace "(…) floodplains. Whereas (…)" by "floodplains, whereas".

The sentence P.16 L.309-310 "As a matter of facts, DOC assesses the average maximum denitrification rate of a floodplain. Whereas the SWAF value is the main driven factor of the model which reveals the actual denitrification" were changed to:

"As a matter of fact, DOC determines the average maximum denitrification rate of a floodplain, whereas the SWAF value is the main driven factor of the model which reveals the actual denitrification"

P.16 l.314 Replace "are compared" by "were compared".

The sentence P.16 L.314 "The N2O emissions at large scale are compared to the results of N2O models (…)" was changed to:

"The N2O emissions at large scale were compared to the results of N2O models (…)"

P.16 l.322 "accounted for indirectly"

P.16 L.322 "The cumulated impact of temperature, soil pH and microorganisms activity, is accounted indirectly for in our approach (…)" was changed to:

"The cumulated impact of temperature, soil pH and microorganisms activity is accounted for indirectly in our approach (…)"

P.17 l.349-350 Consider replacing "Previous study from (…)" by "The study by Viocari et al. (2011) (...)".

P.17 L.349-350 the sentence now starts as "Vicary at al. (2011) showed that (…)"

P.19 l.389 Delete ":"

Corrected

P.19 l.406 Replace ")" by a comma.

P.19 L389 & P.19 L.406 Typo mistakes were checked throughout the manuscript and corrected. No other occurrences were found.

P.19 l.397 "Carbon" and "Nitrogen" should be written as "carbon" and "nitrogen" here

P.19 L.397 "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" was replaced by:

"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"

P.19 l.403 "(…) emphasize the importance of (…)"

P.19 L.403 "We emphasize on the importance of (…)" was changed to "We emphasize the importance of (…)"

Review 2

Comments on 'Denitrification and associated nitrous oxide and carbon dioxide emissions from the Amazonian wetlands,

ms by Guilhen et al. re-submitted to Biogeosci Discuss; ms# bg-2020-3.

The manuscript (ms) under review is significantly revised compared to the previous version. Although I note that most of my and rev#2's comments have been addressed, I still have severe concerns about the presented approach of estimating the NO3- loss and the associated emissions. In brief, I think it is not reasonable to ignore DNRA and nitrification. Moreover, there are too many typos and the English writing still needs a critical revision by a native speaker. Therefore, I cannot recommend publication of the ms in its present form.

We understand that the reviewer has comments on the non-inclusion of the DNRA and nitrification processes and we provide here solid justifications for not adding them during flood periods in the wetlands of the Amazon basin and added in the discussion the need to considering DNRA in other ecosystems.

General Comments

By narrowing their view on denitrification, the authors are missing the opportunity to get a comprehensive idea about the major processes and parameters relevant for N2O an CO2 emissions during the flooding events. There is no word on potentially missing processes and the resulting associated uncertainties in the discussion of the shortcomings of their approach in section 4.5 'Limitation of the current approach'.

We kindly remind the reviewer that the aim of our study is to focus on heterotrophic denitrification that is the only processes involved in N2 production (Hu et al., 2015) and to assess the part of denitrification in N2O and CO2 emissions at large scale over flooded areas. While only denitrification is considered, efforts have been invested in providing a methodology to compute it at the whole Amazonian basin scale using remote sensing datasets.

During the review process additional information were added on the impact of uncertainties in the parameters (figure 6) to answer the reviewer's comments. Also, we have in the discussion section a specific paragraph on the limitation of the study with respect to the stated objectives.

Nevertheless, for future more comprehensive studies, the discussion section is now extended to the issue of DNRA and the need to consider it in other environments than the one considered in this study when the approach is extrapolated to other regions. Also, we added a comment on the opportunities to complexify the proposed methodology by integrating additional physical processes (DNRA, nitrification) in order to consider non-flooded periods and other ecosystems.

Hu et al., (2015) (https://doi.org/10.1093/femsre/fuv021)

Specific comments:

- I would like to point out again, that DNRA can be a significant (anoxic) loss process for NO3-. When looking at Table 1 in Rutting et al. (BG, 2011) I find that 12-50% of the overall NO3- loss can be attributed to DNRA, e.g. in a Brazilian forest lowland. I agree that N2O emissions from DNRA might be as low as 1%. However, when assuming that a significant fraction of the NO3- loss is happening via the denitrification channel but instead via the DNRA channel, the total N2O emissions will be reduced significantly as well. So, you may need to modify your approach (equations 1-4) and include DNRA.

In the current study, we quantify denitrification during flood events. We showed in section (4.1) that NO3- in soil solution is a non-limiting factor for the process. In this case, denitrification and DNRA are not competing on the NO3- pool.

Rutting et al. (2011) states in the conclusion that: "we conclude that DNRA is a significant, or even dominant, NO3 consumption process in some ecosystems (Table 1)." And the list of the ecosystems related to this statement can be identified in Table 1. This statement is then followed by: « As Burgin and Hamilton (2007) concluded for aquatic systems, more work is also needed to understand the importance of DNRA in various terrestrial ecosystems.". Our study addresses terrestrial aquatic ecosystems as we provide denitrification during flood events in wetlands. Thus, we conclude that in the current status of knowledge there is no strong scientific justification to take into consideration DNRA in our conditions. Also, if we consider the DNRA it would be very difficult to justify the parameter values to control it. Again, while in Rutting et al. (2011) it is stated that: "However, under NO3- limiting and strongly reducing conditions, a shortage of electron acceptors is most likely limiting microbial growth. Under these conditions DNRA has the advantage over denitrification since more electrons can be transferred per mole NO3- (Tiedje et al., 1982)". There is no mention for the NO3- non-limiting conditions with high microbial activity.

Moreover the result of Rutting et al., (2011) shows the estimations of the DNRA rate for Brazilian lowland from Sotta et al., (2008). In the latter study, the authors performed a local measurement in the Caxiuana, National Forest. The study concerned two types of soils (sandy – clay Oxisol). And measurements were performed during wet and dry seasons but not during flooding. We made a google earth snap shot of the location.

Considering all of the elements brought above, we added the following text to the discussion section:

P.19 L.390 : "Sixth, denitrification and dissimilatory nitrate reduction to ammonium (DNRA) are two natural processes for NO3- reduction. In their, review Rutting et al. (2011) states that DNRA competition for NO3- should be considered for some ecosystems which did not include aquatic ecosystems. They added that more studies are needed for terrestrial aquatic ecosystems based on Burgin and Hamilton (2007). Tiedje et al., (1982) showed that under NO3- limiting and strongly reducing conditions, DNRA has the advantage over denitrification. Sotta et al., (2008) estimated at 12-50% the reduction of NO3- from DNRA in low land Brazilian forest but in non-flooded periods. In

our case, NO_3^- is non-limiting, thus we do not need to take into account the impact of NO_3^- loss from DNRA. Moreover, since estimates of the DNRA direct contribution to N_2O emissions is about 1% (Cole et al., 1988) and considering the uncertainty and errors linked to the modelling of denitrification in the wetlands of the whole Amazon basin the DNRA processes were not considered. Finally, in our study we focused on denitrification solemnly. In order to provide a complete nitrogen budget for the whole Amazon basin, future studies will need to complexify the proposed methodology by integrating additional biogeochemical processes (DNRA, nitrification,…) and physically relative datasets (soil temperature, soil moisture,…) in order to extend the approach to non-flooded periods and other ecosystems. "

Rutting et al. (2011) (10.5194/bg-8-1779-2011)

Burgin and Hamilton (2007) (https://doi.org/10.1890/1540-9295(2007)5[89:HWOTRO]2.0.CO;2)

Tiedje et al., (1982) (https://doi.org/10.1007/BF00399542, 1982.)

Sotta et al., (2008) (https://doi.org/10.1016/j.soilbio.2007.10.009)

Cole et al., (1988) (Assimilatory and dissimilatory reduction of nitrate to ammonia: in The Nitrogen and Sulphur Cycles)

- I still wondering why nitrification as a source of N_2O under low O_2 during the flooding events is ignored. Nitrification does not take place in anoxic conditions (here I agree with the authors) but it can occur along the O_2 gradients in the overlying water or along the O_2 gradients the upper soils. N_2O emissions from nitrification are enhanced when O_2 concentrations are approaching anoxic conditions. This will lead to an additional source of N_2O. This additional N_2O source via nitrification should be mentioned or even included in Eq 1-4. The missing N_2O from nitrification may be one of the reasons for the discrepancy between the model results and the measurements (see Table 4). I see that this line of argumentation in contrast to the authors' assumption that nitrification is not taking place during the flooding events, see P6L115-118: '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 flood plain.' however, I do not think that this is a reasonable assumption, because the overlying water is in contact with atmosphere, so there is a O_2 gradient towards the soil surface (or in shallow well-mixed waters in the upper soil) allowing nitrification to take place. Moreover, Brettar et al. (2002) is not a suitable reference to justify the authors' statement because it deals only with denitrification in flooded soils and nitrification is not mentioned in the publication at all.

We agree with the statements of the reviewer on nitrification, but we kindly remind the reviewer that the aim of our study is to focus on N_2O and CO_2 emissions due to denitrification under flood conditions. We added in the discussion the potential interest of apply such methodology in future studies that combines parsimonious physical modelling to remote sensing to address other processes like nitrification.

For the missing N_2O please see next comment.

On our statement: *'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'*. In inundated areas in the Amazon Basin, the intensity of the flood that can last few weeks supports the fact that soils are in anoxic conditions.

The study of Brettar at al. (2002) gives information on the dynamic of the redox potential in soil which is a proxy of nitrification / heterotrophic denitrification. In another work in the groundwater of the alluvial floodplain of the Garonne river, Iribar et al., 2015 showed that denitrification is the principal way to produce N2 via heterotrophic denitrification and quantify the NosZ genes involved in the heterotrophic denitrification. We understand the worries of the reviewer therefore, for a complete description of the nitrogen dynamic in the Upper Rhine forest, the reference in the manuscript was changed to Sánchez-Pérez and Trémolières (2003)

In the case of assessing the part of denitrification, DNRA and nitrification on N2O emissions, we agreed with the reviewer on the fact that measurements on the bacteria communities should be performed to assess the part of denitrification/nitrification/DNRA to improve those kinds of study.

Further answers concerning the N2O emissions are provided in the next answer.

Sánchez-Pérez and Trémolières (2003) (https://doi.org/10.1016/S0022-1694(02)00293-7)

Iribar et al., (2015) (https://doi.org/10.1016/j.ecoleng.2015.02.002)

- An important reference about N2O emissions has been overlooked: Liengaard et al., Hot moments of N2O transformation and emission in tropical soils from the Pantanal and the Amazon (Brazil); Soil Biol. Biochem., 75, 26-36, 2014.

The study presented by Lienggard et al., (2014) aims at detailing the production of N2O during hot moments of N2O emission from both Pantanal and Amazon wetland soils following controlled waterlogging of the soil matrix. We included a reference to this study in section 4.3 'Wetlands and integrated ecosystem emissions'.

We extracted the average simulated values of N2O emissions (from 2011 to 2015) from the closest simulation nodes (25 x 25 km) to the in-situ measurements of Lienggard et al. (2014). Comparing our simulations to the study of Liengaard et al., (2014) draws the same results (section 4.3 P.17 L.342; e.g our simulations are lower of a factor 1/100). But looking closely to Liengaard et al., (2014) the measurement of the N2O emission are occurring "in the best conditions" (e.g maximum inundation, optimal temperature, etc). To reproduce these "best conditions" we looked for a simulation node with maximum flooding. The highest pixel in our simulation is located in the O-M FP for August 2015.

We find that this specific value is in range with the average measurements of Liengaard et al., (2014) (4.9×107 gN/km²/yr while our highest simulation value estimated an emission of about 2.6 ± 1.3 x 107 gN/km²/yr."). This comforts us with our previous comments and the same conclusions (section 4.5) when comparing to local in-situ data that over a 25 x 25 km area the amount of flooded area from monthly data is much lesser than the representative flooded area of the hourly in-situ data.

P.17 L.340 was changed to :

"We extracted the average simulated value of the period from the simulation node. When comparing the N2O with in situ campaigns performed by Koschorreck (2005), Keller et al. (2005) and Liengaard et al. (2014) at the different locations, the wetlands emissions from our study are roughly lower from a factor 10+2 of the integrated ecosystem observed emissions. This difference comes from different spatial and temporal scales for both the in situ measurements and our model. To verify this explanation, we extracted the maximal pixel value simulated during the period of the study. On average, in situ measurements return emissions of about 4.9×107 gN/km²/yr while our highest simulation value estimated an emission of about 2.6 ± 1.3 x 107 gN/km²/yr."

Minor comments

P2L27: What do you mean with '… alternations between terrestrial and aquatic phases in wetlands …'? Do you mean the dry and wet seasons?

P.2 L.27 was changed to "(…) alternations between dry and wet periods in wetlands (…)"

P2L43: What do you mean with ' … is more or less in balance and even acts as a small sink …' ? Is it a sink or not?

Current knowledge on the CO2 budget of the Amazon Basin is that it is more or less in balance considering the uncertainties in the estimates. Some studies consider that it acts as a small sink.

We consider the statement clear and we also add that answering the question about the total carbon balance of the Amazonian basin while of utter importance is not the objective of our paper.

Lloyd, J., Kolle, O., Fritsch, H., De Freitas, S. R., Silva Dias, M. A. F., Artaxo, P., Nobre, A. D., De Araojo, A. C., Kruijt, B., Sogacheva, L., Fisch, G., Thielmann, A., Kuhn, U., and Andreae, M. O.: An airborne regional carbon balance for Central Amazonia, Biogeosciences, 4, 759–768, https://hal.archives-ouvertes.fr/hal-00297719, 2007.

P3L79: Fig 3 is referenced before Fig 2

P9L204: Fig 7 is referenced before Fig 6

Following the modifications during the review process the referencing was impacted. The Figures appear now in order in the text.

P6L125: typo 'refres'

P.6 L.125 typo corrected to refers

P7L140: 'Nevertheless, with no precise field measurements an average N2O/N2 ratio of 0.1 (Weieretal.,1992) applied in the study.' I guess 'was' is missing before 'applied'.

P.7 L.140 is now "Nevertheless, with no precise field measurements an average N2O/N2 of 0.1 (Weier et al.,1992) was applied in the study."

P7L147/148: ' … are the best published estimates that we have …' How do you know that these are the best, because they are the only ones? (which is not a good argument)

P.7 L.147 was changed to"… are the only published estimates that we have"

P17L352: What do you mean with 'anthropogenisation'? I do not think that this term is commonly used and I do not understand it in this context.

P.17 L.352 The term "anthropogenisation" does exist. Still we replaced it with a more communly used term: "anthropogenic changes" to mention changes induced by human activities.

P17L349: 'Previous study …' It must read 'A previous study … 'or 'The previous study …'.

P.17 L.349 changed to "Vicari et al., (2011) showed that (…)"

P18L370: It must read 'North Sea'

Corrected

P18L385: 'equifinalities'? What do you mean with this? I do not think that this term is commonly used and I do not understand it in this context. According to Wikipedia 'equifinality' means: The principle that in open systems a given end state can be reached by many potential means, viz. "All roads lead to Rome," or "There's more than one way to skin a cat."

Actually, equifinality is a very commonly used term to mention compensation effects in parameter identification: (e.g. the same solution (flux values of N2) can be obtained with several sets of parameter values (surface of inundated area / rate of micro-biological activity).

For example this highly cited paper by Prof. Been K. in hydrological modelling.

Beven, K. (2006). A manifesto for the equifinality thesis. Journal of hydrology, 320(1-2), 18-36.

Also the term is commonly used in other papers

"equifinality" and "geochemistry":

https://scholar.google.fr/scholar?hl=fr&as_sdt=0,5&q=equifinality+geochemistry

"equifinality" and "hydrology":

https://scholar.google.fr/scholar?hl=fr&as_sdt=0%2C5&q=equifinality+hydrology&btnG=

P19L397: It must read 'carbon and nitrogen'.

Typos were corrected and checked throughout the ms.

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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 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 dry and wet periods 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 that over the Amazonian wetlands 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 in situ information. 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 5.50×10^6 km^2 and an average water discharge of $208\,000$ m^3 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 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 2.50×10^5 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 6.70×10^5 km^2.

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

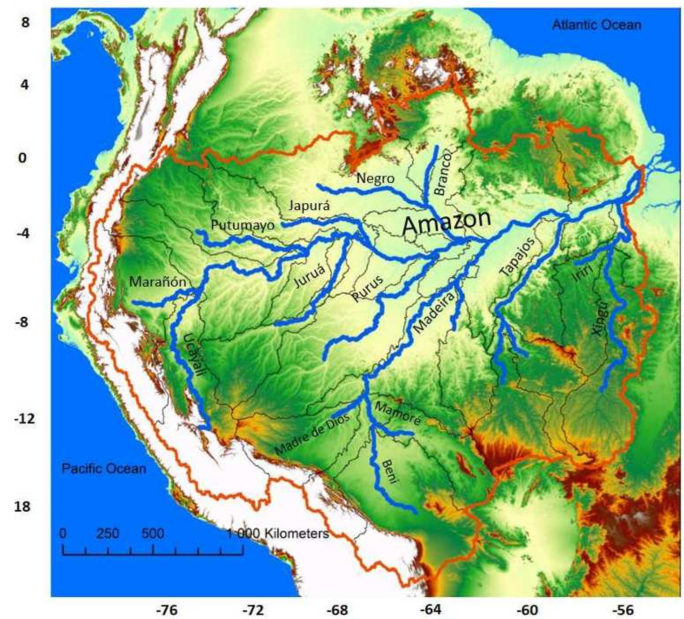

Figure 1. The Amazon river basin and its main tributaries mapped over the SRTM (Shuttle Radar topography Mission - 500 m) digital elevation model.

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.

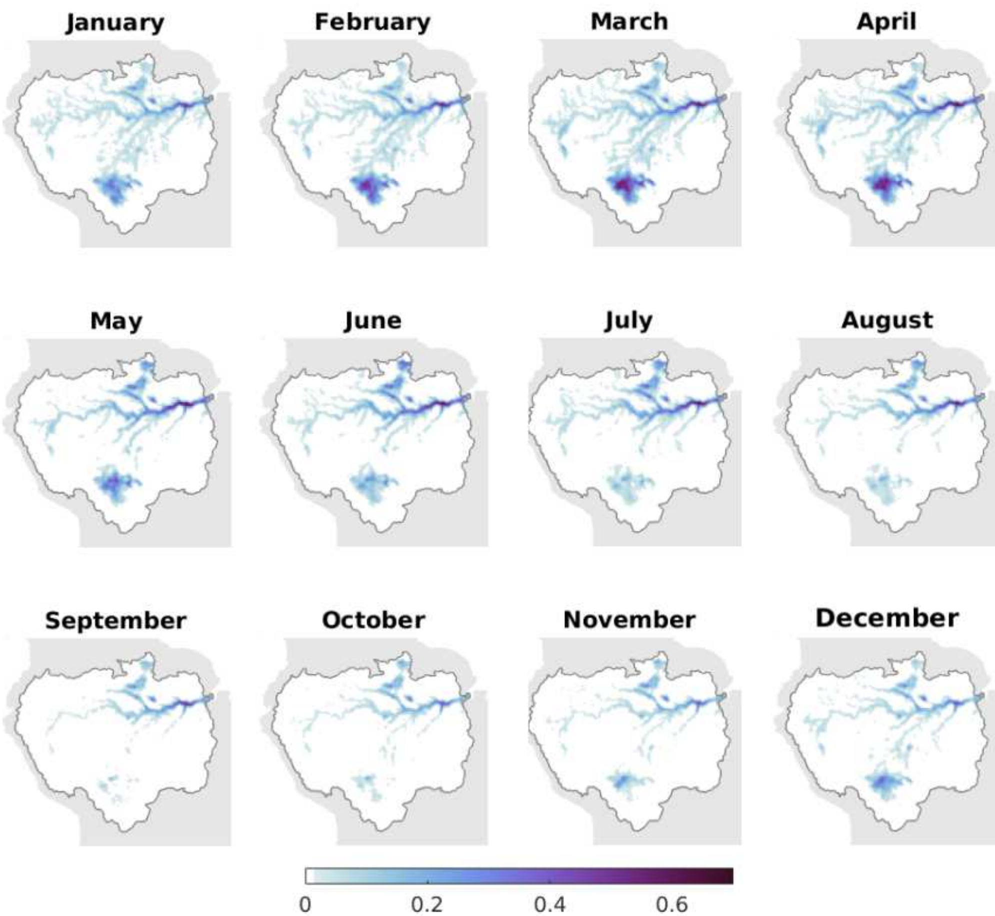

Figure 2. Monthly averages from 2011 to 2015 of the SWAF surface water fractions over the Amazon basin based on Vertical polarization Brightness Temperatures (TB V) at 32.5° incidence angle acquired by the SMOS satellite.

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 oxygen

(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 Sánchez-Pérez and Trémolières (2003) on the upper Rhine floodplain. In another work, on the groundwater of the alluvial floodplain of the Garonne river, Iribar et al. (2015) showed that denitrification is the main process that produces N_2 and quantified the Nosz involved in heterotrophic denitrification. 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 refers 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) was 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 (25 km x 25 km) 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 only published estimates that we have. According to the studies performed by Moreira-Turcq et al. (2013), the POC concentration 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.

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

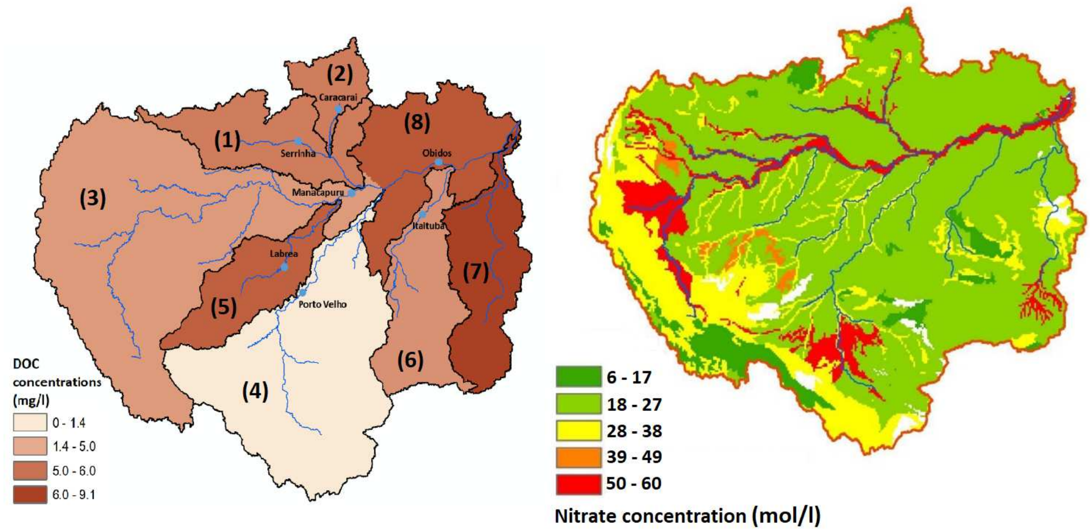

Figure 3. Map of the spatial inputs of the denitrification model. DOC contents in mg/L mapped over each sub-basin of the main streams (January) with local observation gauging stations in blue circles (Left). The Amazon watershed is be divided into 8 major sub-basins: (1) the Negro basin, (2) the Branco 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. NO_3^- contents (mol/l) of the watershed over FAO's types of soils (Right).

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.

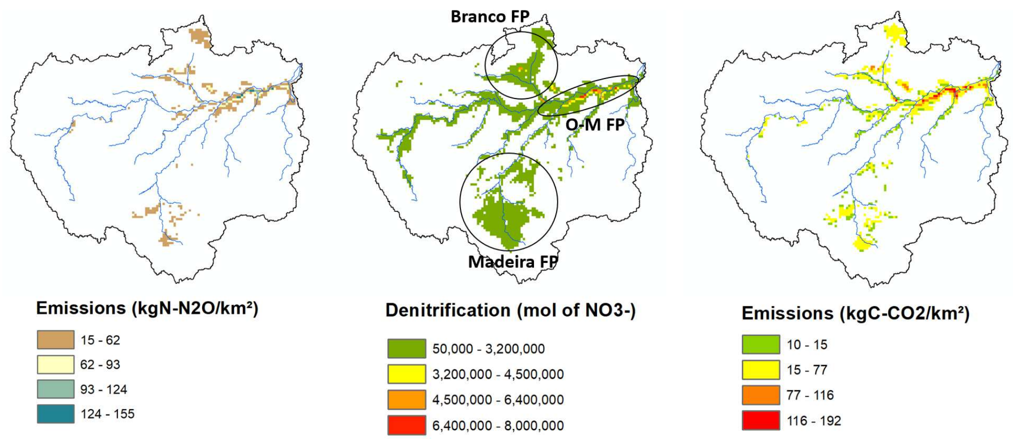

Figure 4. Spatial representation of N_2O emissions (kgN-N_2O/km²), denitrification (mol of NO_3) and CO_2 emissions (kgC-CO_2/km²) summed over the year 2013. The location of the main floodplains (hot spots) are outlined in the denitrification map.

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 same pattern of denitrification repeats every year during the period of the study (2011-2015). 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.

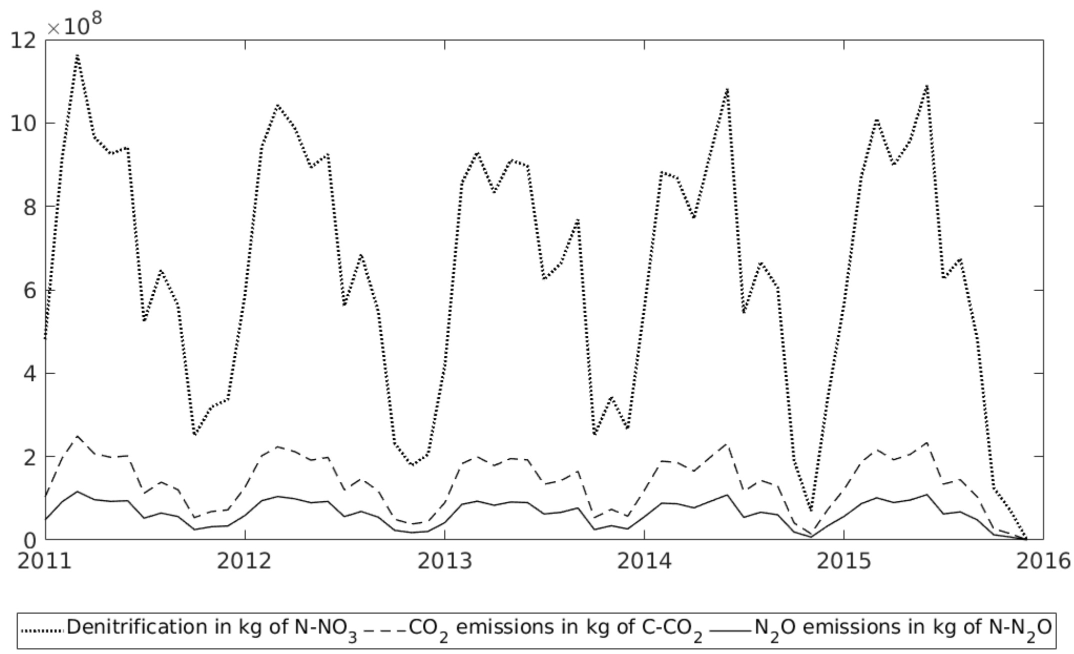

Figure 5. Monthly denitrification (kgN-NO_3), CO_2 (kgC-CO_2)and N_2O (kgN-N_2O) emissions over the entire Amazon watershed for the period 2011 - 2015.

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. Denitrification as well as 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 as well as the average monthly denitrification over the basin for the period 2011-2015. 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 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.

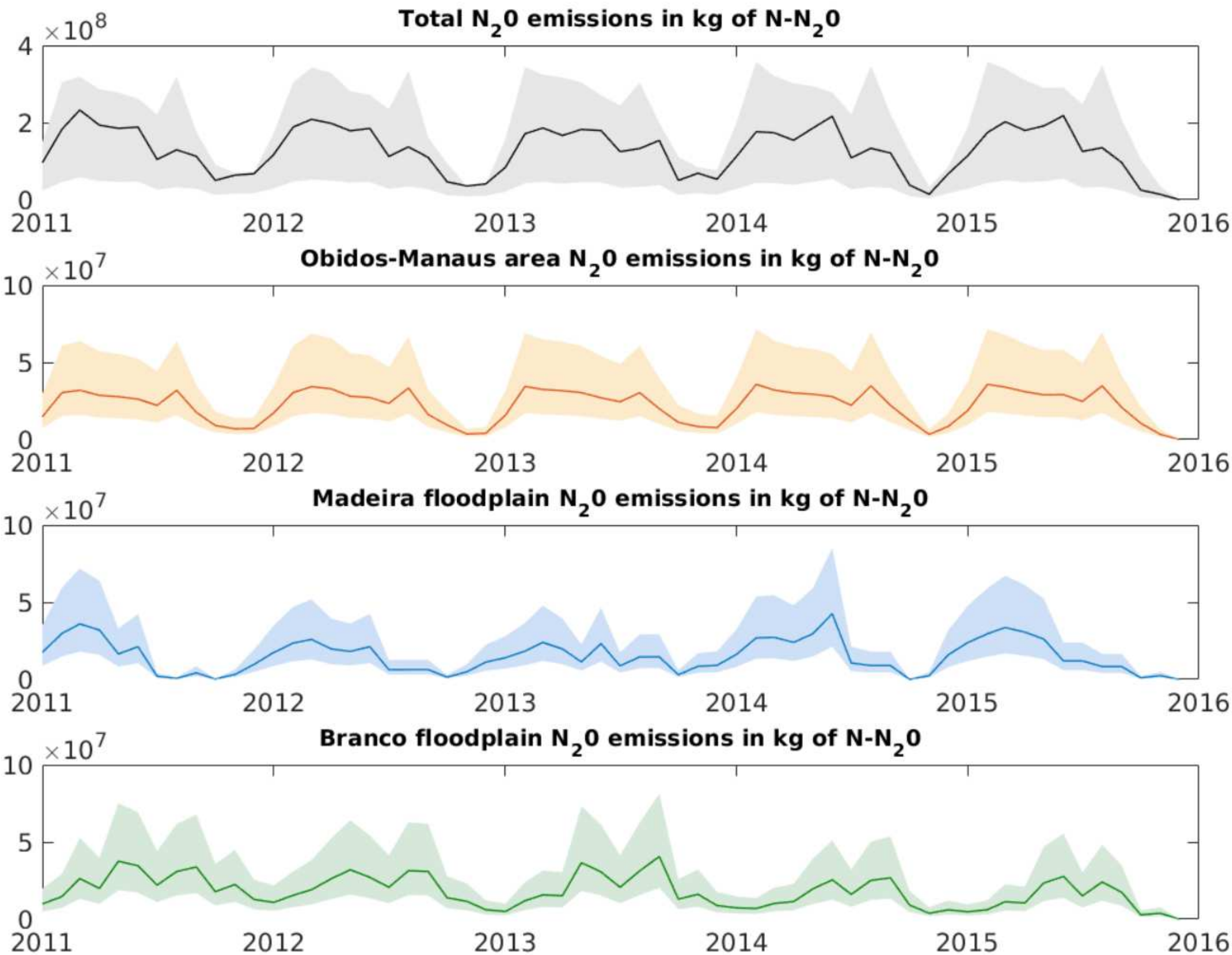

Figure 6. Monthly time series of N_2O emissions over the basin (black), for the O-M FP (yellow), for the Madeira FP (blue) and for the Branco FP (green) over the period (2011-2015). The lines represent the emissions for a N_2O / N_2 of 0.1 whereas the colored areas refer to the potential range of the 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-

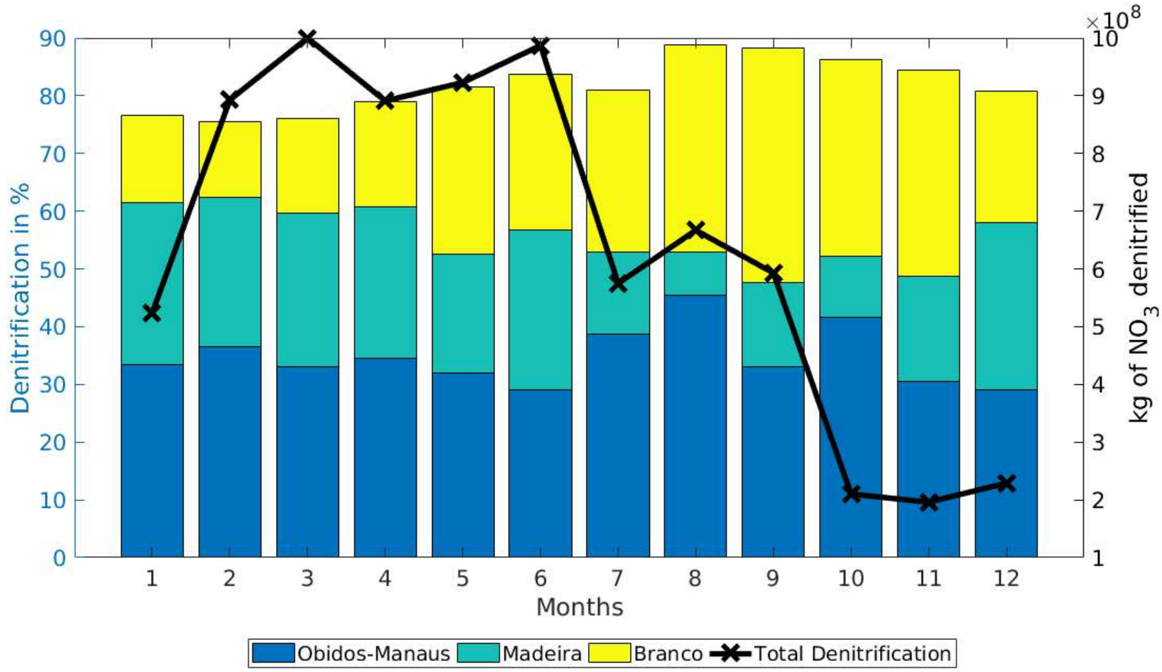

Figure 7. Average monthly contribution of each floodplain: the O-M FP (blue), the Madeira FP (green), Branco FP (yellow) to the Amazon total denitrification. The residual contribution from the 100% is associated to the other wetlands in the basin. The black line represents the average monthly denitrification for the period of the study and it shows the main trend observed over the Amazonian watershed.

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 x 10^8	2.20 x 10^9 ± 2.75 x 10^8	1.03 x 10^9 ± 2.57 x 10^7	9.26 x 10^9 ± 2.57 x 10^8
Obidos - Manaus FP	2.5 x 10^7	7.63 x 10^8 ± 9.94 x 10^7	3.56 x 10^8 ± 9.28 x 10^6	3.21 x 10^9 ± 9.28 x 10^7
Madeira FP	3.7 x 10^7	4.79 x 10^8 ± 2.65 x 10^8	2.24 x 10^8 ± 2.47 x 10^7	2.01 x 10^9 ± 2.47 x 10^8
Branco FP	6.78 x 10^7	5.57 x 10^8 ± 6.17 x 10^8	2.6 x 10^8 ± 5.75 x 10^7	2.34 x 10^9 ± 5.75 x 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

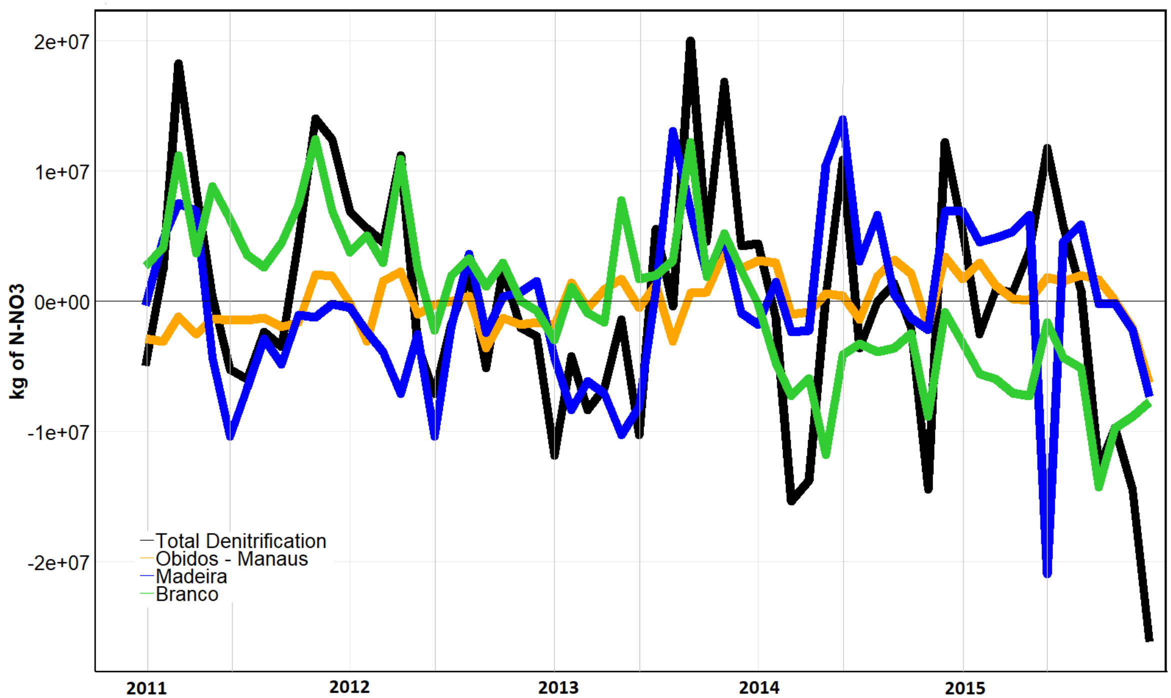

Figure 8. Monthly anomalies at the basin and main floodplains scale for denitrification throughout the period (2011-2015).

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 fact, DOC determines 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 were 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 for indirectly 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. We extracted the average simulated value of the period from the simulation node. When comparing the N_2O with in situ campaigns performed by Koschorreck (2005), Keller et al. (2005) and Liengaard et al. (2014) at the different locations, the wetlands emissions from our study are roughly lower from a factor 10^2 of the integrated ecosystem observed emissions. This difference comes from different spatial and temporal scales for both the in situ measurements and our model. To decrease the variability, we extracted the maximal pixel value simulated during the period of the study. On average, in situ measurements return emissions of about 4.9×10^7 gN/km²/yr while our highest simulation value estimated an emission of about $2.6 \pm 1.3 \times 10^7$ gN/km²/yr.

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 the 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. 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 anthropogenic changes of the land-cover the carbon budget of the once wetland areas and now non-inundated surfaces will greatly increase.

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

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	$8.6 \pm 0.7 \times 10^6$	$5.2 \pm 0.9 \times 10^4$
Liengaard et al. (2014)	N_2O	Rio Solimoes	4.4×10^7	$5.7 \pm 2.8 \times 10^5$
Liengaard et al. (2014)	N_2O	Rio Cupea	8.3×10^7	$5.7 \pm 2.8 \times 10^5$
Liengaard et al. (2014)	N_2O	Rio Amazonas	-	$9.3 \pm 4.6 \times 10^5$
Liengaard et al. (2014)	N_2O	Iagarapé de Paracuba	1.9×10^7	$1.1 \pm 0.6 \times 10^5$
Liengaard et al. (2014)	N_2O	Rio Tapajos	1.9×10^7	$1.5 \pm 0.7 \times 10^6$
Liengaard et al. (2014)	N_2O	Rio Mucajai	7.8×10^7	$2.1 \pm 1.1 \times 10^5$
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	$5.7 \pm 0.6 \times 10^7$	$1.6 \pm 0.9 \times 10^3$

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. Sixth, denitrification and dissimilatory nitrate reduction to ammonium (DNRA) are two natural processes for NO_3^- reduction. In their, review Rütting et al. (2011) states that DNRA competition for NO_3^- should be considered for some ecosystems which did not include aquatic ecosystems. They added that more studies are needed for terrestrial aquatic ecosystems based on Burgin and Hamilton (2007). Tiedje et al. (1982) showed that under NO_3^- limiting and strongly reducing conditions, DNRA has the advantage over denitrification. Sotta et al. (2008) estimated at 12-50% the reduction of NO_3^- from DNRA in low land Brazilian forest but in non-flooded periods. In our case, NO_3^- is non-limiting, thus we do not need to take into account the impact of NO_3^- loss from DNRA. Moreover, since estimates of the DNRA direct contribution to N_2O emissions is about 1% (Cole, 1988) and considering the uncertainty and errors linked to the modelling of denitrification in the wetlands of the whole Amazon basin the DNRA processes were not considered. Finally, in our study we focused on denitrification solemnly. In order to provide a complete nitrogen budget for the whole Amazon basin, future studies will need to complexify the proposed methodology by integrating additional biogeochemical processes (DNRA, nitrification,...) and physically relative datasets (soil temperature, soil moisture,...) in order to extend the approach to non-flooded periods and other ecosystems.

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 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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