

Interactive comment on “Modelling land atmosphere daily exchanges of NO, NH₃, and CO₂ in a semi-arid grazed ecosystem in Senegal” by Claire Delon et al.

Anonymous Referee #1

Received and published: 13 January 2019

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We thank both referees for their careful consideration and comments on the manuscript. We bring answers to every comment hereafter, and indicate corresponding changes that will be made in our manuscript.

10 The authors investigate daily exchanges of NO, NH₃, and CO₂ in a semi-arid grazed ecosystem in Senegal. Three different models (STEP-GENDEC-NOflux, Zhang2010 and Surfalm) are used to simulate daily fluxes during the years 2012 and 2013. Model results are evaluated against experimental results acquired during three field campaigns. Despite the vast extent and importance for global C and N cycling, studies from semi-arid regions are underrepresented in the literature mainly due to challenging conditions for acquiring robust field data.

15 Hence, this study tackles an important topic by testing the suitability of different models to study the land surface-atmosphere exchange of NO, NH₃, and CO₂.

The manuscript is within the scope of BG, it is mostly well-written, has a relatively clear structure, and it presents new and important data. In principle, it has the potential to be a good contribution; however, the authors have shown little care in the description of the methods, and I unfortunately fail to recognize any interest in ensuring reproducibility of the results. Attention to detail and scientific rigor is rather underwhelming and not up to the standards of the journal. Additionally, some conclusions about NH₃ exchange are drawn on a temporal scale that is not warranted by concentrations measured with passive samplers on a monthly basis. I recommend addressing these issues and expanding the discussion in a major revision.

25

General remarks and major issues:

1) Typesetting is very sloppy. Subscripts are missing, there are periods in units where spaces should be, variables are not slanted and therefore indistinguishable from descriptive subscripts, captions are missing periods, etc.

30 The typesetting will be corrected in the whole manuscript.

2) The manuscript unfortunately suffers from a lack of units, written variable descriptions, and necessary information in general, both in the main text and the appendix. E.g. Table A5, while generally important and potentially useful, is entirely useless in its current state. It is downright impossible to extract any kind of meaningful information from it unless the reader already knows the model anyway. Time scales are often missing from figures.

35 A careful read of the entire manuscript will allow the correction of these errors. Equations and variables used will be gathered in a single table (Table A4) to make the reading easier, this will clarify between input data (table A1), initialization parameters (table A2), numerical values of parameters used in the equations (Table A3) and equations (table A4) with explanation of variables, constants and parameters used in them.

40 Units and variable descriptions will be brought everywhere it is necessary throughout the manuscript. Time scales will be added in the figures.

3) The authors need to carefully address the consequences of using monthly concentration data as input data for a model that is being executed at a 3 hour time step. There needs to be an effort at convincing the reader that the conclusions they draw about the exchange of NH₃ are valid, given that the flux is directly driven by Ca-Xcp, and Ca is only available at a 1 month resolution, whereas Xcp is calculated every 3 hours and bound to be variable throughout the day and over the course of a month, due to its exponential dependence on temperature. Part of their first modelling goal is to investigate daily NH₃ fluxes, so this is crucial to their objectives.

To address this remark we investigated the relevance of passive samplers for concentration measurements to be used in modeling at a shorter time scale.

In the discussion section 4.1, a paragraph will be added:

“4.1.1 Relevance of monthly NH₃ concentration input vs daily NH₃ flux outputs

In the two models, C_{NH₃} used as input data arises from passive sampler measurements, integrated at the monthly scale (see section 2.2.2). Outputs fluxes are provided at a 3h timescale, averaged at the daily scale for the purpose of this study. The relevance of using monthly NH₃ concentrations instead of concentrations with finer resolution in time has been already approached in the literature. Riddick et al. (2014, 2016) have used ALPHA samplers to measure NH₃ concentrations at the scale of the week and/or the month. They have noticed that time averaged NH₃ fluxes from these samplers provided similar estimated fluxes to those calculated from on line sampling. In the case of passive sampling concentration measurements, meteorological and area sources of uncertainty can still be accounted for in the flux calculation. Riddick et al. (2014) conclude that active and passive sampling strategies give similar results, which support the use of low cost passive sampling measurements at remote locations where it is often logistically hard to deploy expensive active sampling methods for flux measurements. These statements have been confirmed in Loubet et al. (2018), and provide a valuable reason to use monthly concentrations as inputs in the present study.”

The following references will be added:

Loubet B. , M. Carozzi, P. Voylokov , J.-P. Cohan, R. Trochard, and S. Générumont, Evaluation of a new inference method for estimating ammonia volatilisation from multiple agronomic plots, *Biogeosciences*, 15, 3439–3460, 2018.

Riddick, S. N., Blackall, T. D., Dragosits, U., Daunt, F., Braban, C. F., Tang, Y. S., MacFarlane, W., Taylor, S., Wanless, S., and Sutton, M. A.: Measurement of ammonia emissions from tropical seabird colonies, *Atmos. Environ.*, 89, 35–42, 2014.

Riddick, S. N., Blackall, T. D., Dragosits, U., Daunt, F., Newell, M., Braban, C. F., Tang, Y. S., Schmale, J., Hill, P. W., Wanless, S., Trathan, P., and Sutton, M. A.: Measurement of ammonia emissions from temperate and sub-polar seabird colonies, *Atmos. Environ.*, 134, 40–50, 2016.

4) Another one of the three modelling goals is to compare the two NH₃ models; however, only for one of them the component fluxes (Fveg and Fsoil) are analysed separately. Even then, there is no further differentiation into stomatal and cuticular fluxes. Why? This is where you learn the most about when exactly the models behave differently.

Indeed, the difference between Fcut and Fstom is available from Surf atm and Zhang2010. Fig. 10 will be modified to show Fstom and Fcut behavior, for both models. Outputs will be compared, added in Table 2 (now table 4 because of inclusion of 2 new tables asked by reviewer 2) and in a new figure 10.

As asked by reviewer 2, Fig. 10 will be mentioned in the result section in paragraph 3.4, with the comparison of Fcut and Fstom from Zhang2010 and Surfatom. In the discussion section, the figures will be interpreted. The abstract will be modified accordingly.

5 New figure 10:

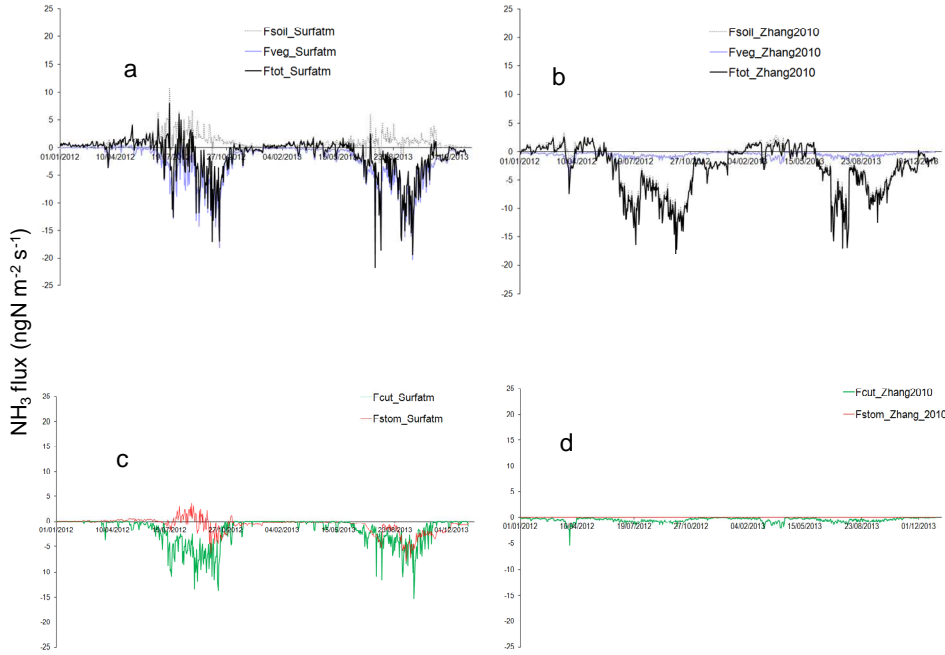


Figure 10: Figure 10: Daily NH_3 flux (in $\text{ngN m}^{-2} \text{s}^{-1}$) partitioned between soil and vegetation. Black line is for total net flux (Ftot), grey dashed line is for soil flux (Fsol) and blue line is for vegetation flux (Fveg) for Surfatom in (a), and for Zhang2010 in (b). Red line is for stomatal flux (Fstom) and green line is for cuticular flux (Fcut) for Surfatom in (c) and for Zhang2010 in (d).

10

New table 4 (ancient table 2)

Average flux and standard deviation	Ftotal (net flux) ($\text{ngN.m}^{-2}.\text{s}^{-1}$)	Fsoil ($\text{ngN.m}^{-2}.\text{s}^{-1}$)	Fvegetation (=Fstom + Fcut) ($\text{ngN.m}^{-2}.\text{s}^{-1}$)	Fstom ($\text{ngN.m}^{-2}.\text{s}^{-1}$)	Fcut ($\text{ngN.m}^{-2}.\text{s}^{-1}$)
Dry seasons Surfatom	-0.2 ± 1.6	0.7 ± 0.6	-0.9 ± 1.7	-0.4 ± 0.8	-0.5 ± 1.2
Wet seasons	-4.3 ± 4.8	2.0 ± 1.9	-6.3 ± 3.7	-1.5 ± 2.2	-4.8 ± 2.7

Surfatm					
2012-2013 Surfatm	-1.4±3.5	1.1±1.3	-2.5±3.5	-0.7±1.5	-1.8±2.7
Dry seasons Zhang	-0.9±2.3	-0.5±2.3	-0.4±0.5	-0.02±0.01	-0.4±0.5
Wet seasons Zhang	-8.1±3.2	-7.3±3.0	-0.8±0.3	-0.03±0.01	-0.7±0.3
2012-2013 Zhang	-3.1±4.2	-2.6±4.0	-0.5±0.4	-0.02±0.01	-0.5±0.4

Specific comments:

- P3L17: 2nd objective is unclear, more detail needed.
- 5 "Formalisms" will be replaced by "outputs". Actually the behavior of the two models is investigated.
- P3L31-32: Please check sentence. How can rainfall be on average 356 mm for 2013? Or does "average" relate to the period 1951-2013?
The sentence is replaced by: "At Dahra, the annual rainfall was 515mm in 2012 and 356mm in 2013 with an average of 416mm for the period 1951-2013"
- 10
- P4L11p., P8L14p., P8L28, and other parts of the manuscript: What is the reason for the use of 3 h averages instead of a higher resolution, if all the forcing variables except NH3 concentrations are available every 15 min? The meteorological data were available every 15 minutes but the forcing in Zhang2010 was designed to be every 3h. To keep consistency between the two models, we chose to force Surfatm every 3h as well.
- 15
- P4L15: Which Gill sonic model exactly?
Gill R3 Ultrasonic anemometer. The specification will be added in the text.
- 20
- P4-5: (How) were the different measurement heights (meteorology, sonic and IRGA, passive sampler concentrations) considered in the modelling studies?
Meteorology sensors were located 2m above ground level (AGL), and concentrations were measured 1.5m AGL. IRGA and sonic were located 9m AGL but not used in modeling forcing. Fluxes measured by IRGA and sonic give surface fluxes and hence independent on measurement height (as long as it is recorded within the inertial sublayer). All data were used as measured without any correction for height differences in the models.
- 25
- P4L16: Why was an outdated version of EddyPro used? There have been lots of bug fixes since 2013. These are published data, and the data treatment was originally done for the study of Tagesson et al. (2015b). The EddyPro version used was the best available at the time of the data analysis.
- 30
- P7L6: Add parentheses around Eq. reference.

Corrected.

- P7L7pp. / Eq. (1): Units are missing. Move number to right margin.
Units will be added and number moved to right margin.

5

- P7L29: Fix typesetting of Eq. Remove "equation" in "(equation 3)". Move number to right margin.
Corrected.

10 - P8L19: Typo in "Surface".
Corrected.

- P8L27: Typo in "Hansen"
Corrected.

15 - P8L30: (How) was LAI measured?

LAI was measured according to the methodology developed in Mougin et al., Estimation of LAI, fAPAR and fCover of Sahel rangelands (Gourma, Mali), Agricultural and Forest Meteorology 198–199 (2014) 155–167. Data from Dahra were measured monthly during the wet season and were not published (Mougin, personal communication). Linear interpolation was performed between these monthly estimations, and values for the dry season were found in Adon et al. (2013), for an equivalent semi arid ecosystem in Mali, derived from MODIS measurements. These explanations will be added in the text P8L30.

20 An error was found in the text in the sentence P8L30: "Forcing also includes constant values of roughness length Z_0 , Leaf Area Index (LAI), displacement height D , canopy height Z_h , measurement height Z_{ref} , stomatal emission potential, and ground emission potential."

25 This sentence will be modified: "Forcing also includes values of Leaf Area Index (LAI, measured), canopy height Z_h (estimated), roughness length Z_0 ($0.13Z_h$), displacement height D ($0.7Z_h$), stomatal emission potential (constant), ground emission potential (derived from measurements during field campaigns, constant the rest of the time), and measurement height Z_{ref} (2m)".

30 - P9L3pp.: Are surface values of T and RH used for the calculation of R_c and compensation points, and if yes, were the parameterisations adapted to it in any way?
According to Personne et al., (2009), R_c depends on RH , and the compensation points depend on T . These parameterizations were not adapted specifically for semi arid conditions.

35 I assume most of them were originally developed using ambient values at a certain reference height?
Always according to Personne et al. (2009), yes, these parameterizations were developed using ambient values at a certain height, RH at $Z_{ref}=2m$. T is the temperature of the leaves, calculated by the energy budget model using air temperature at $Z_{ref}=2m$.

40 - P9L6pp.: This section needs to be significantly expanded. It is completely unclear what was done. p -values need a null hypothesis.
This section is an indication of the tools used to calculate simple and multiple regressions between matrices. The text will be modified:

- “The R software (<http://www.R-project.org>) was used to provide results of simple and multiple linear regression analysis. The `cor.test()` function was used to test a single correlation coefficient R , i.e. a test for association between paired samples, using one of Pearson's product moment correlation coefficient. The p-value is used to determine the significance of the correlation. If p-value is less than 0.05, the correlation is considered as non significant. The `lm()` test was used for stepwise multiple regression analysis. The adjusted R-Squared (i.e. normalized multiple R-squared R^2), determines how well the model fits to the data. Again, the p-value is calculated, and has to be less than 0.05 to give confidence in the significance of the determination coefficient R^2 .”
- 5
- 10 - P9L11pp.: Correlations alone are not really helpful in determining the accuracy of the models, please report offsets and slopes of the regressions as well.
Thanks for this suggestion, offsets and slopes will be added on the figures or in the text when necessary.
- P9L26: Decimal point missing.
15 Decimal point added.
- P10L1pp.: Sign convention needs to be mentioned somewhere.
Positive fluxes correspond to emission. The sign convention will be specified.
- 20 - P10L28: Was the ANN trained on data from similar ecosystems?
The ANN was trained with data from both temperate and semi arid ecosystems (Gourma region, Sahel, Mali).
This will be specified line 28.
- P12L6-8: $p=0.2$ is not “weakly correlated”, it is simply not significantly correlated. There is no such thing as
25 “almost significant” in null-hypothesis significance testing.
This will be changed by “not significantly correlated.”
- P12L13-15: “Indeed, canopy compensation point and ambient concentration values are quite similar” How do
you know if you compare 3 h modelled compensation points with 1 month ambient concentrations? This needs
30 to be discussed.
The sentence will be modified as follows: “Monthly averaged compensation point and ambient concentration
values are quite similar during the dry seasons. Compensation point concentration averaged during the 2012
and 2013 dry seasons is 3.8 ± 1.5 ppb, and averaged ambient concentration is 4.3 ± 1.5 ppb for the same period. If
the 2012 and 2013 dry seasons are considered separately, the values of the means remain the same.”
- 35 - P12L25-26: Again, how do you know that the concentration decreases within a single month if you only have
one data point?!
Actually, the sentence is not correctly written. We meant that the concentration decreases in August compared
to the month of July. This specification will be added in the text.
- 40 - P13L6p. and P14L29pp.: Soil temperature at which depth?
Soil surface temperature was specified in the text.

- P13L9pp.: How exactly was the model selection done? Have you thought about using an information criterion, such as AIC? Also note that most of these variables are inherently correlated through overlapping diurnal cycles. The model selection was done by adding each variable step by step, i.e. the best combination was chosen with the best associated significant R^2 (p -value < 0.05). This technique was preferred to the AIC to avoid any statistical over interpretation instead of physical interpretation. In other words, the inclusion of indispensable variables (usually used in parameterizations) in the combination could have been dismissed by the AIC, whereas its physical impact on fluxes is incontestable.

The variables we consider are: NH_3 concentrations, air humidity, wind speed, soil surface temperature and moisture. Correlations were calculated between each variable (except NH_3 concentration). The results are shown in the table below. The only significant correlation was found between air humidity and soil surface moisture. Furthermore, the stepwise multiple linear regression analysis was performed with daily means for all variables, and the diurnal cycle is therefore hidden.

	Air humidity	Wind speed	Surface temp	Surface moisture
Air Humidity		0.0045	0.01	0.5
Wind speed			0.2	0.06
Surface temp				0.02
surface moisture				

Only the following sentence will be added P13L9: "The model selection was done by adding each variable step by step, i.e. the best combination was chosen with the best associated significant R^2 (p -value < 0.05)."

- P13L15p.: I can't really follow this, please elaborate.

The sentence beginning line 15 will be modified as follows:
 "As for Zhang2010 fluxes, a stepwise multiple linear regression analysis is run between Surf atm NH_3 fluxes and NH_3 concentrations, air humidity, wind speed, soil surface temperature and latent heat fluxes since. R^2 is 0.6 (with $p < 0.001$)."

- P13L21: This should also be possible with Zhang2010 since both Zhang2010 and Surf atm follow a similar structure after Nemitz (2001). I don't understand why this was only done for Surf atm .
 As mentioned in point 4 of the general remarks, the comparison of F stom and F cut in Zhang2010 and Surf atm will be added in the manuscript, along with a new figure 10 in the result section.
 The following will be added in paragraph 3.4:

"In Fig. 10a, the total net flux above the canopy in Surf atm results from an emission flux from the soil and a deposition flux onto the vegetation via stomata and cuticles, especially during the wet season. On the contrary, the total flux in Zhang2010 in Fig. 10b results from a strong deposition flux on the soil and a very low deposition flux onto the vegetation. This is explained by a strong contribution of deposition on cuticles in Surf atm (Fig. 10c) whereas it is close to zero in Zhang2010 (Fig. 10d).
 In Surf atm , emission from stomata also occurs but it is largely offset by the deposition on leaf surfaces which leads to a deposition flux onto vegetation (Sutton et al., 1995). In Surf atm , the deposition on cuticles is effective until the end of the wet season, whereas deposition through stomata lasts until the vegetation is completely dry, i.e. approximately 2 months after the end of the wet season. On the basis of the different averages for each

contributing flux in table 4, we estimate that the soil is a net source of NH₃ during the wet season, while the vegetation is a net sink in Surf atm, and the soil is a net sink in Zhang2010.”

Paragraph 4.1.4 will be modified as follows:

5 “4.1.4 Contribution of soil and vegetation to the net NH₃ flux:

In Surf atm, during the wet season, deposition on the vegetation through stomata and cuticles dominates the exchange. Indeed, during rain events, the cuticular resistance becomes small and cuticular deposition dominates despite an increase of soil emission. This increase is due to an increase of the deposition velocity of NH₃, consecutive to the humidity response of the surface, and a decrease of the canopy compensation point, sensitive to the surface wetness (Wichink-Kruit et al., 2007). In Zhang2010, despite the difference in magnitude, cuticular deposition increases as well during the wet season, but is dominated by deposition on the soil. During the dry season, aboveground herbaceous dry biomass stands for a few months after the end of the wet season when the soil becomes bare, and the vegetation effect negligible in both models. At the end of wet season 2013, the soil contribution to the total flux increases significantly in Surf atm due to the increase of the ground emission potential prescribed at 2000 (instead of 400 for the rest of the year, to be consistent with measurements noted in Delon et al., (2017)).”

The following sentence will be added in paragraph 4.1.5:

20 “Again, the flexibility of this parameter is more adapted than fixed values for 1D modeling, and this may lead to completely different repartitions of the fluxes between the soil and the vegetation, as shown in Fig. 10. This difference in flux repartition highlights the importance of the choice in the type of soil and/or vegetation for the simulations. However, the close correlation between both models (R²=0.5, p<0.01, slope=0.6, offset=0.4) indicates a similar representation of the net flux in each model and emphasizes clear changes at the transition between seasons.”

25

- P14L14p.: “Indeed, Zhang2010 model was specifically designed to address [. . .] average temporal scales [. . .]”
See above, I don’t think you can predict more than average temporal scales from your input data.

30 As discussed in point 3 of the general remarks, the objective of our study is to estimate NH₃ exchange fluxes on an annual timescale rather than exploring processes in detail. In that purpose, the use of passive methods for measuring NH₃ concentration is particularly suited, especially for field campaigns in remote places. We agree that for the reasons evoked here, even Surf atm results comport an uncertainty associated with monthly averaged concentrations forcing. This sentence will be canceled, and the rest of the paragraph will be more moderated about temporal rapid changes. We propose to modify the paragraph as follows:

35 “The lack of variability of the ground emission potential in Zhang2010 highlights the sensitivity of fluxes to this specific parameter for 1D modelling in semi arid soils. The abrupt transitions between seasons needs a certain flexibility of the ground emission potential to represent the changes in flux direction.”

40 - Appendix A: Typesetting of Tables is wildly inconsistent. A1-A4 look completely different from A5. A5 is absolutely impossible to follow, because not a single variable is explained. Table A5 will be merged with Table A4 to explain each variable in due place and avoid referring to another table for understanding the equations.

- Appendix C / P28L11: Typo "Penman"
Corrected.
- Table 1: Numbers come out of the blue. Please add sources. Add period at the end of caption.
- 5 Numbers will be explained. A column will be added in Table 1. Some parameters are measured and refer to Delon et al., 2017. They are noted "measured" in the Table. Some parameters are estimated from the ranges given in Hansen et al., 2017. They are noted "Estimated" in Table 1. Some parameters are given out of these ranges, and are clearly adapted to semi arid ecosystems. They are noted "estimated specifically for semi arid ecosystems". A sentence will be added P9L1 to specify that these parameters were adjusted.
- 10
- Table 2: See above, why only Ftotal for Zhang2010?
Fveg, Fstom and Fcut from Zhang2010 outputs were not generated at first because not directly available from the outputs. They will be generated, and comparisons with Surf atm outputs will be made and available in Table 4 and in the results and discussion parts.
- 15
- Figure 1: Questionable use of Comic Sans in a professional setting.
The font will be changed for a more adapted one (Calibri).
- Figure 3: Remove white space (put the subplots next to each other). What is the temporal scale (I assume 3
20 hour averages)? 1:1 line and regression are hard to distinguish, I advise plotting one as a dashed line. The systematic mismatch for LE in the 20- 60 W m⁻² region is a little suspicious, do you have an idea what is happening there?
As all the manuscript discussion is based on daily averages for all variables, the figures contain daily averages. Figure 3 will be corrected with dashed line for 1:1 line, white spaces will be removed. As mentioned in the caption, "Available measured EC data are more numerous for H than for LE due to the criteria applied by the postprocessing (see supplementary material of Tagesson et al. (2015b))". These criteria lead to numerous
25 missing data for intermediate periods between dry and wet seasons for medium flux values.
We found errors in equations of the linear regressions written on the figures. The equations will be replaced by correct ones.
- 30
- Figure 4: See above re: whitespace. 4a is also a good example why I asked for slopes and offsets in section 3.
Figure 4 will be corrected. Daily will be added in the caption. 1:1 line will be dashed.
- Figure 6: NH₄⁺ is not ammonia. Same error appears in the text when the figure is referenced.
35 Ammonia will be replaced by ammonium both in the text and in the caption.
- Figure 9: Caption mentions error bars, I don't see any.
Error bars are actually black for measured values. We will specify "error bars for measurements" in the caption and change
the colors as asked by reviewer 2.
- 40 Interactive comment on "Modelling land atmosphere daily exchanges of NO, NH₃, and CO₂ in a semi-arid grazed ecosystem in Senegal" by Claire Delon et al.

Anonymous Referee #2

Received and published: 28 January 2019

5 The study on nitrogen and carbon fluxes under grazing in a semi-arid region in Senegal aims to better understand their driver contributions in wet and dry seasons. The authors use field data from the years 2012 and 2013 and apply three models to derive daily time series which are evaluated against the field data. Thus, the work contributes a valuable piece of knowledge in a not-well studied system with measurements under difficult field conditions and the corresponding simulation results to evaluate the representation of processes
10 controlling NO, NH₃ and CO₂ fluxes under these conditions.
The manuscript represents a concise and well-designed piece of knowledge on N and C fluxes in a semi-arid region, is within the scope of BG and is surely worth being published. Before recommending this, a major effort is needed to clarify 1) the structure of the text, 2) the methodological description and 3) the modelling concept. Therefore, I recommend major revisions.

15 [We thank both referees for their careful consideration and comments on the manuscript. We bring answers to every comment hereafter, and indicate corresponding changes that will be made in our manuscript.](#)

20 My main concerns are:
1) So far, methods, results and discussion are partly mixed and contain a large number of back and forth references. Please keep the structure more clear. E.g. in section 3.2, the role of the spatial heterogeneity represented in sampling is discussed in relation to the simulations which would better fit in the methods. The results sections contain parts in which the simulations are already discussed which could be moved to the
25 existing discussion sections. Figure 10 is introduced in the discussion and belongs clearly to the results.

[The results and discussion sections will carefully be read to avoid mixing results and discussion, and corrected when necessary.](#)

30 [A new point will be added in section 2.2.3 "Measurements of NO, NH₃ and CO₂ \(respiration\) fluxes from soil and physical parameters " to precise that soil pH and texture measurements will be used in the rest of the manuscript.
The paragraph concerning the spatial heterogeneity in section 3.2 will be moved to section 4.2 in the discussion part, as follows:](#)

35 ["The over or underestimations of NO emissions in the model in Fig. 5 may be explained by the ammonium content shown in Fig. 6. Released N is overestimated during the J13 wet season, and underestimated at the end of the wet season \(as N13\), when the presence of standing straw may lead to N emissions in addition to soil emissions, not accounted for in the model because litter is not yet buried. The slight underestimation of modelled soil moisture \(Fig. 2\) at the end of the wet season may also explain why modelled fluxes are lower than measured fluxes. The large spatial heterogeneity in measurements may be explained by variations in soil
40 pH and texture, and by the presence of livestock and the short term history of the Dahra site, i.e. how livestock have trampled, grazed and deposited manure during the different seasons and at different places. This spatial variation is evidently not represented in the 1D model, where unique soil pH and soil texture are given, as well as a unique input of organic fertilization by livestock excreta."](#)

The following paragraphs of section 3.2 will be moved to section 4.2

“With wet season NO fluxes being more than twice higher than dry season fluxes, results emphasize the influence of pulse emissions in that season This increase at the onset of the wet season over the Sahel, due to the drastic change in soil moisture, has been previously highlighted by satellite measurements of the NO₂ column, by Vinken et al. (2014), Hudman et al. (2012), Jaegle et al. (2004) and Zörner et al. (2016).”

And

“After the pulses of NO at the beginning of the wet season (Fig. 5), emissions decrease most likely because the available soil mineral N is used by plants during the growing phase of roots and green biomass, especially in 2013, and is less available for the production of NO to be released to the atmosphere (Homayk et al., 2014, Meixner & Fenn 2004, Krul et al., 1982). During the wet season, NO emissions to the atmosphere in the model are reduced by 18% due to plant uptake (compared to NO emissions when plant uptake is not taken into account). Indeed, N uptake by plants is enhanced when transpiration increases during the wet season (Appendix C).”

The following paragraph will be moved from section 3.3 to section 4.2

“ the model over-predicts the death rate of microbes and subsequently underestimates the CO₂ respired, whereas microbes and residues of roots respiration persist in the field despite low soil moisture. A second explanation of this underestimation might be the lower soil moisture in the model than in measurements at the end of the wet season (Fig. 2).”

Figure 10 will also be mentioned in the result section (paragraph 3.4), and discussed in the discussion section.

The following text will be added in paragraph 3.4:

“In Fig. 10a, the total net flux above the canopy in Surf_{atm} results from an emission flux from the soil and a deposition flux onto the vegetation via stomata and cuticles, especially during the wet season. On the contrary, the total flux in Zhang2010 in Fig. 10b results from a strong deposition flux on the soil and a very low deposition flux onto the vegetation. This is explained by a strong contribution of deposition on cuticles in Surf_{atm} (Fig. 10c) whereas it is close to zero in Zhang2010 (Fig. 10d). In Surf_{atm}, emission from stomata also occurs but it is largely offset by the deposition on leaf surfaces which leads to a deposition flux onto vegetation (Sutton et al., 1995). In Surf_{atm}, the deposition on cuticles is effective until the end of the wet season, whereas deposition through stomata lasts until the vegetation is completely dry, i.e. approximately 2 months after the end of the wet season. On the basis of the different averages for each contributing flux in table 4, we estimate that the soil is a net source of NH₃ during the wet season, while the vegetation is a net sink in Surf_{atm}, and the soil is a net sink in Zhang2010.”

The last paragraph of section 4.3 concerning the lagged correlation between NO and CO₂ fluxes has not been separated between results and discussion to avoid inconsistency in the ideas.

2) The methods section would benefit from an overview of measurements including the temporal resolution of the variables and a correspondence table to the simulations. Here, you could specify which simulations are compared to which measurements and why.

Model (resolution)	Simulated and measured	Methods used for measured variables
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	variables (units)	(resolution and reference)
Surfatm (3h)	NH ₃ bidirectional fluxes (ngN m ⁻² s ⁻¹)	Closed dynamic chamber (15 – 20 fluxes a day, Delon et al., 2017)
	Soil surface temperature (°C)	Campbell 107 probe (15min, Tagesson et al., 2015a)
	Sensible and latent heat fluxes (W m ⁻²)	Eddy Covariance (15min, Tagesson et al., 2015a)
Zhang2010 (3h)	NH ₃ bidirectional fluxes (ngN m ⁻² s ⁻¹)	Closed dynamic chamber (15 – 20 fluxes a day, Delon et al., 2017)
STEP (day)	NO biogenic fluxes (ngN m ⁻² s ⁻¹)	Closed dynamic chamber (15 – 20 fluxes a day, Delon et al., 2017)
	CO ₂ respiration fluxes (ngN m ⁻² s ⁻¹)	Closed dynamic chamber (15 – 20 fluxes a day, Delon et al., 2017)
	Ammonium content (%)	Laboratory analysis (6 samples/campaign, Delon et al., 2017)
	Soil temperature at two depths: 0-2cm and 2-30cm (°C)	Campbell 107 probe at 2 depths: 5 and 10 cm (15min, Tagesson et al., 2015a)
	Soil moisture at two depths: 0- 2cm and 2-30cm (%)	HH2 Delta probe at 2 depths: 5 and 10 cm (15min, Tagesson et al., 2015a)

Table 1: Summary of different models used in the study, with the variables simulated and compared to measurements. All simulated and measured variables were daily averaged for the purpose of the study.

The reference for this table will be added at the end of section 2.3.2 for STEP model, and at the end of section 2.4.2 for the two models simulating NH₃ fluxes, to specify which models are used, and compared to which measured data.

3) Firstly, it is clear that a model which is already published does not have to be given in detail in a new manuscript. Here, the outcome strongly depends on the details of the models applied and you give a lot of information in the appendix. Please give this information at the beginning of section 2.3 before the details of single processes are described. Here, also try to separate the basic principles from input data and variables calculated within the models. Clarify why there is the double description of resistencies (Ra, Rb, Rc) in 2.4.1 and 2.4.2. Do not mix 'parameters' with 'variables'.

Parameters are fixed values in equations whereas variables stand for state variables in the models and measured values. Also here, a better overview of input data (with temporal resolution) and simulated variables is needed.

At the beginning of section 2.3.1, we will add the following sentence:

"STEP model is presented in Appendix A, with forcing variables detailed in Tab. A1, site parameters used in the initialization in Tab. A2, numerical values of parameters used in the equations in Tab. A3, and equations, variables, parameters and constants used in the equations in Tab. A4." Indeed, we prefer to keep this information in Appendix section to avoid too much tables in the main text. The basic principles are described for each model already.

Equations and variables used will be gathered in a single table (Table A4) to make the reading easier, this will clarify between input data (table A1), initialization parameters (table A2), numerical values of parameters used in the equations (Table A3) and equations (table A4) with explanation of variables, constants and parameters used in them.

- 5 As Zhang2010 and Surf atm are based on the same resistance analogy, it is indeed not necessary to recall the resistances in section 2.4.2.
Parameters and variables have been differentiated by writing variables in *italics* in table A4.
Input data are already précised in sections 2.4.1 and 2.4.2 for Zhang and Surf atm, and the resolution is 3h (already mentioned). We have also specified that STEP simulations are performed at the daily scale in table A1
10 where input data are specified for STEP.

General remarks:

- 1) There are a lot of missing or misleading information on units, scales, subscripts. Unfortunately, typesetting needs more effort.
15 **Typesetting will be carefully proofread. Units will be added in the equations and the tables.**
- 2) The analysis of drivers needs more substance. Relating simulated respiration to simulated soil moisture, this shows that there is a linkage in the model, but not more. In the study region, the variation of soil moisture dominates over the variation in temperature so that this variable is more important for the processes studied.
20 The interesting part would be to see this linkage in measured values as well.
At the end of section 3.3, it is mentioned that “soil field measured respiration show a lower correlation ($R^2=0.4$ and $p=0.09$, $R^2=0.3$ and $p=0.1$ in J13 and N13 respectively) with surface soil moisture”. The analysis of measured fluxes with drivers is comprehensively described in Delon et al., (2017), where weak or non correlations were found between fluxes and environmental variables. In the present paper, we analyze the modeling results, and the role of soil moisture overriding the role of soil temperature is highlighted in the discussion part in sections
25 4.1 and 4.2, as well as the linkages between environmental drivers and soil fluxes.
- 3) The text is mostly well-written but please consider to get rid of most of the brackets. These insets can better be integrated into the sentences.
30 **Brackets will be removed every time it is considered as necessary.**

Specific remarks:

- In section 3.4, please give all the values in a table.
The values will be moved in a table as follows and the paragraph will be shortened accordingly.
35

Period / NH ₃ fluxes	Measurements (ngN m ⁻¹ s ⁻¹)	Surf atm (ngN m ⁻¹ s ⁻¹)	Zhang2010 (ngN m ⁻¹ s ⁻¹)
J12	1.3±1.1	2.6±2.6	-9.0±0.9
J13	-0.1±1.1	-1.7±2.4	-7.8±2.2
N13	0.7±0.5	-0.2±1.1	-2.8±0.9
2012		-0.9±3.3 (-0.3±1.0 kgN ha ⁻¹ yr ⁻¹)	-3.5±4.6 (-0.3±1.0 kgN ha ⁻¹ yr ⁻¹)
2013		-2.0±3.7 (-0.6±0.3 kgN ha ⁻¹ yr ⁻¹)	-2.7±3.8 (-0.8±1.2 kgN ha ⁻¹ yr ⁻¹)

Dry season		-0.2±1.6	-0.9±2.3
Wet season		-4.3±4.8	-8.1±3.2

Table 3: Averaged NH₃ fluxes for measurements, Surf atm and Zhang2010 models during specific periods.

- Section 4.1.1 begins with a reasoning that involves something not shown. Please avoid this or give a different reasoning.

5 The paragraph will be written as follows:

“Dahra is a grazed savanna where the main source of NH₃ emission to the atmosphere is the volatilization of livestock excreta (Delon et al., 2012); the excreta quantity and quality is at a maximum at the end of the wet season, (Hiernaux et al., 1998, Hiernaux and Turner 2002, Schlecht and Hiernaux 2004), because animals are better fed. In August, a strong leaching of the atmosphere occurs which decreases the NH₃ atmospheric concentration (not shown here), compared to July concentration, and the deposition flux decreases as well. Indeed, if the concentration decreases from July to August whereas the canopy compensation point remains stable, the flux will decrease as shown by equation 3.”

The title of this paragraph will be modified to “NH₃ deposition flux variation”.

15 - P8L19: Typo in ‘Surface-Atmosphere’
Corrected.

- P9L19: sentence, verb missing

The sentence will be modified as follows:

20 “However, the drying of the layers is sharper in the model than in measurements at the end of the wet season, leading to an underestimation of the model compared to measurements until December each year”

- all figures: please use better colors. Blue and black lines and symbols cannot be distinguished well and having two grey lines as in figure 10 also does not help. Use red color or dashed lines.

25 In figures 3 and 4, dashed lines will be added for the 1:1 line. In figures 5, 6, 7 and 8, measurements will be colored in red. In figures 9 and 10, grey dashed lines will replace grey lines.

- Fig. 1: This scheme would be a very valuable orientation. Please be more informative here. Include the input data and the variables which are exchanged. It would be good to have such an overview of the other 2 models as well.

30 Very good schemes are made in the two reference papers for Zhang2010 (Zhang et al., 2010, Fig. 1) and Surf atm (Personne et al., 2009, Fig. 1), and we did not think it was necessary to copy these schemes or try to propose different ones.

35 In Fig. 1 of the present study, some of the exchanged variables are already included, in reference to the fluxes that are evaluated. The input data for forcing will be added, instead of “meteo forcing”.

- Fig. 3: this shows a consistent underestimation of the latent heat fluxes. This does not fit to the text stating that this is ‘giving confidence’.

To moderate the statement, the sentence will be completed as follows:

“The significant correlation between Surf_{atm} and EC latent heat fluxes indicates that the stomatal, aerodynamic and soil resistances are correctly characterized in the model, giving confidence in the further realistic parameterization of NH₃ fluxes, despite missing values in intermediate fluxes, due to the criteria applied by the postprocessing (see supplementary material of Tagesson et al. (2015b)).”

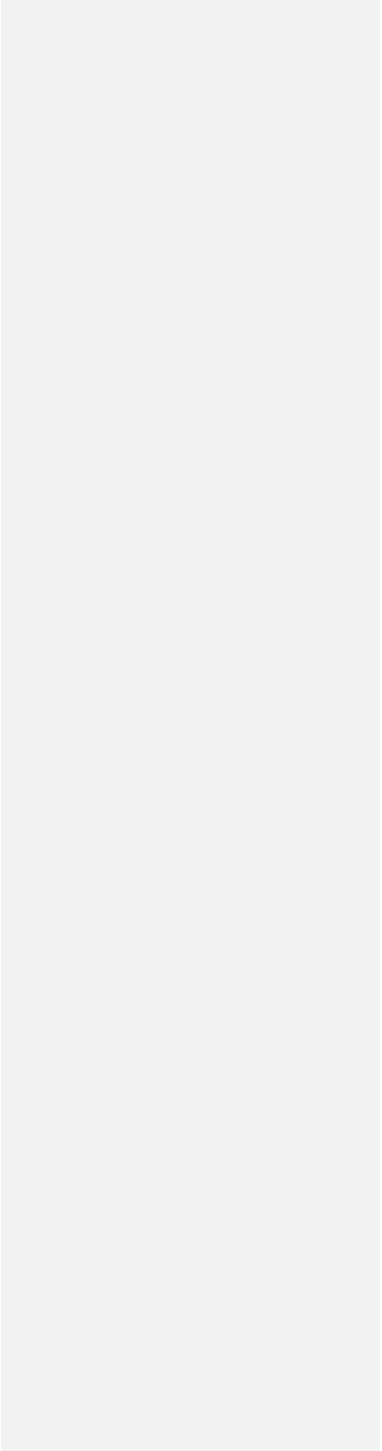
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Modelling land atmosphere daily exchanges of NO, NH₃, and CO₂ in a semi-arid grazed ecosystem in Senegal

Claire Delon¹, Corinne Galy-Lacaux¹, Dominique Serça¹, Erwan Personne², Eric Mougin³, Marcellin Adon^{1,6}, Valérie Le Dantec⁴, Benjamin Loubet², Rasmus Fensholt⁵, Torbern Tagesson⁵

¹ Laboratoire d'Aérodologie, Université de Toulouse, CNRS, UPS, France.

² ~~UMR ECOSYS, INRA, AgroParisTech, Université Paris-Saclay, 78850, Thiverval-Grignon, France, INRA, EeoSys INRA, AgroParisTech, Université Paris-Saclay, Thiverval-Grignon, France.~~

³ Géosciences Environnement Toulouse, Université de Toulouse, CNES, CNRS, IRD, UPS, France.

⁴ Centre d'Etudes Spatiales de le BIOSphère, Université de Toulouse, CNES, CNRS, IRD, UPS, France.

⁵ Department of Geosciences and Natural Resource Management, University of Copenhagen, Denmark.

⁶ ~~Laboratoire de Physique de l'Atmosphère, et de Mécanique des Fluides, Université Félix Houphouët-Boigny, Abidjan, Cote d'Ivoire.~~

Correspondence to: Claire Delon (claire.delon@aero.obs-mip.fr)

Abstract. Three different models (STEP-GENDEC-NOflux, Zhang2010 and Surfalm) are used to simulate NO, CO₂, and NH₃ fluxes at the daily scale during two years (2012-2013) in a semi-arid grazed ecosystem at Dahra (15°24'10"N, 15°25'56"W, Senegal, Sahel). Model results are evaluated against experimental results acquired during three field campaigns. At the end of the dry season, when the first rains rewet the dry soils, the model STEP-GENDEC-NOflux simulate the sudden mineralization of buried litter, leading to pulses in soil respiration and NO fluxes. The contribution of wet season fluxes of NO and CO₂ to the annual mean is respectively 51% and 57%. NH₃ fluxes are simulated by two models: Surfalm and Zhang2010. During the wet season, air humidity and soil moisture increase, leading to a transition between low soil NH₃ emissions (which dominate during the dry months) to large NH₃ deposition on vegetation during wet months, ~~Results show a great impact of the soil emission potential, a difference in the deposition processes on the soil and the vegetation between the two models with however a close agreement of the total fluxes~~ ~~Results show a great impact of the soil emission potential and a close agreement between the two models.~~ The order of magnitude of NO, NH₃ and CO₂ fluxes are correctly represented by the models, as well as the sharp transitions between seasons, specific to the Sahel region. The role of soil moisture on flux magnitude is highlighted, whereas the role of soil temperature is less obvious. The simultaneous increase of NO and CO₂ emissions and NH₃ deposition at the beginning of the wet season is attributed to the availability of mineral nitrogen in the soil and also to microbial processes which distribute the roles between respiration (CO₂ emissions), nitrification (NO emissions), volatilization and deposition (NH₃ emission/deposition). This objective of this study is to understand the origin of carbon and nitrogen compounds exchanges between the soil and the atmosphere, and to quantify these exchanges on a longer time scale when only few measurements have been performed.

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Exposant

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1 Introduction

The Sahel is one of the largest semi-arid regions in the world and it is a transition zone between the Sahara desert in the north and the more humid Sudanese savanna in the south. In semi-arid zones, the exchanges of trace gases are strongly influenced by hydrologic pulses defined as temporary increases in water inputs (Harms et al., 2012). In the West African Sahel (between 12°N:18°N, 15°W:10°E), soil water availability strongly affects microbial and biogeochemical processes in all ecosystem compartments (Wang et al., 2015), which in turn determines the exchange fluxes of C and N (Austin et al., 2004, Tagesson et al., 2015a, Shen et al., 2016). After a long dry period (8 to 10 months in the Sahel), the first rainfall events of the wet season cause strong pulse of CO₂, N₂O, NO and NH₃ to the atmosphere (Jaeglé et al., 2004; Mc Calley & Sparks, 2008; Delon et al., 2015; Shen et al., 2016, Tagesson et al., 2016b). Anthropogenic activities have a strong impact on N and C cycling, and in large parts of the world, deposition of N compounds have several damaging impacts on ecosystem functions, such as changes in species biodiversity (Bobbink et al., 2010). The Sahel is still a protected region from this N pollution (Bobbink et al., 2010), but climate change could create an imbalance in biogeochemical cycles of nutrients (Delgado-Baquerizo et al., 2013).

The emission of NO from soils leads to the formation of NO₂ and O₃ in the troposphere. Soil NO biogenic emissions from the African continent expressed in TgN.yr⁻¹ are considered as the largest in the world (Fowler et al., 2015) because of extended natural areas. The pulses of NO from the Sahel region at the beginning of the wet season have been shown to strongly influence the overlying NO₂ tropospheric column (Jaegle et al., 2004, Hudman et al., 2012, Zörner et al., 2016), indicating the urgent need of improved understanding of the dynamics of NO pulses from this region. NH₃ emissions lead to the formation of particles in the atmosphere, such as ammonium-nitrates (NH₄NO₃), which vapour phase dissociation further produces NH₃ and HNO₃ (Fowler et al., 2015). The land-atmosphere exchange of ammonia varies in time and space depending on environmental factors such as climatic variables, soil energy balance, soil characteristics and plant phenology (Flechard et al., 2013). Emissions of these compounds involve changes in atmospheric composition (ozone and aerosol production) and effects on climate (through greenhouse gas impacts).

The N exchange fluxes are also influenced by the soil N content, and the main inputs of N compounds into the soil in semi-arid uncultivated regions are biological nitrogen fixation (BNF), decomposition of organic matter (OM), and atmospheric wet and dry deposition (Perroni-Ventura et al., 2010). Soil N losses to the atmosphere involve N₂O, NH₃ and NO gaseous emissions, whereas within the soil, N can be lost via erosion, leaching and denitrification. NO emissions to the atmosphere are mainly the result of nitrification processes, which is the oxidation of NH₄⁺ to nitrates (NO₃⁻) via nitrites NO₂⁻ through microbial processes (Pilegaard et al., 2013; Conrad, 1996). In remote areas, where anthropogenic emissions (such as industrial or traffic pollution) do not happen, NH₃ bidirectional exchanges are regulated through diverse processes: NH₃ is emitted by livestock excreta, by soil and litter, regulated by the availability of NH₄⁺ and NH₃ in the aqueous phase (NH_x), by the rate of mineralization of NH₄⁺, and by the availability of water which allows NH_x to be dissolved, to be taken up by organisms and to be released through decomposition (Schlesinger et al., 1991, Sutton et al., 2013). Additionally NH₃ can be

dry and wet deposited on soil and litter (Laouali et al., 2012; Vet et al., 2014), on leaf cuticles and stomata, and regulated by chemical interactions within the canopy air space (Loubet et al., 2012). The N cycle is closely linked to the C cycle, and it has been suggested that C-N interactions may regulate N availability in the soil (Perroni-Ventura et al., 2010). The link between N and C cycles in the soil, and their effect on OM decomposition, affect the emissions of C and N compounds to the atmosphere. These cycles are interlinked by respiration and decomposition processes in the soil, and the balance between C and N is controlled by biological activity, mainly driven by water availability in drylands (Delgado-Baquerizo et al., 2013). Indeed, the decomposition of soil OM_t (and its efficiency) regulates the amount of CO₂ that is released to the atmosphere (Elberling et al., 2003).

Biogeochemical regional models have been applied for N compound emissions mostly in temperate regions (Butterbach-Bahl et al., 2001, Butterbach-Bahl et al., 2009), where the spatial and temporal resolution of data is well characterized. Global approaches have also been developed, with simplified description of processes and with coarse spatial resolution (Yienger & Levy, 1995; Potter et al., 1996; Yan et al., 2005; Hudman et al., 2012). Considering the weak amount of experimental data in semi-arid regions about trace gas exchanges and their driving parameters, one dimensional modelling is a complementary, essential and alternative way of studying the annual cycle dynamics and the underlying processes of emission and deposition. The specificity of the semi-arid climate needs to be precisely addressed in the models used to be able to correctly represent the pulses of emissions and the strong changes in C and N dynamics at the transition between seasons. Improving the description of processes in 1D models in tropical regions is therefore a necessary step before implementing regional modelling.

In this study, three main modelling objectives are focused on: 1) investigating the links between N and C cycles in the soil and consecutive daily exchanges of NO, NH₃ and CO₂ between the soil and the atmosphere, at the annual scale and specifically at the transition between seasons, 2) comparing two different formalisms for NH₃ bidirectional exchange 3) highlighting the influences of environmental parameters on these exchanges. Different one dimensional models, specifically developed or adapted for semi-arid regions, were used in the study. As a study site, representative of the semi-arid region of the Western Sahel, we selected the Dahra field site located in the Ferlo region of Senegal (Tagesson et al., 2015b). The one dimensional models were applied for the years 2012 and 2013 to simulate the land-atmosphere exchange fluxes of CO₂, NO and NH₃. Model results were compared to flux measurements collected during three field campaigns in Dahra in July 2012 (7 days), July 2013 (8 days) and November 2013 (10 days), and presented in Delon et al. (2017).

2 Materials and Methods

2.1 Field site

Measurements were performed at the Dahra field station, (part of the Centre de recherche Zootechnique, (CRZ), in the Sahelian region of Ferlo, Senegal (15°24'10"N, 15°25'56"W). The Dahra field site is located within the Centre de Recherche Zootechnique (CRZ) managed by the Institut Sénégalais de Recherche Agronomique (ISRA). This site is a semi-arid

savanna used as a grazed rangeland. The Sahel is under the influence of the West African Monsoon (cool wet southwesterly wind) and the Harmattan (hot dry northeasterly wind) depending on the season. Rainfall is concentrated in the core of the monsoon season which extends from mid-July to mid-October. At Dahra, the annual rainfall was 515mm in 2012 ~~and with an average of~~ 356mm in 2013 ~~and with an average of~~ 416mm for the period 1951-2013. The annual mean air temperature at 2m height was 28.4°C in 2012 and 28.7°C in 2013, with an average of 29°C for the period 1951-2003. The most abundant tree species are *Balanites aegyptiaca* and *Acacia tortilis*, and the herbaceous vegetation is dominated by annual C4 grasses (e.g. *Dactyloctenium aegyptium*, *Aristida adscensionis*, *Cenchrus biflorus* and *Eragrostis tremula*) (Tagesson et al., 2015a). Livestock is dominated by cows, sheep, and goats, and grazing occurs permanently all year-round (Assouma et al., 2017). This site was previously described in Tagesson et al., (2015b) and Delon et al., (2017).

2.1 Field data

2.2.1 Hydro-meteorological data and sensible and latent heat fluxes

A range of hydro-meteorological variables are measured by a meteorological station at the Dahra field site (Tagesson et al., 2015b). The hydro-meteorological variables used in this study were rainfall (mm), air temperature (°C), relative air humidity (%), wind speed ($m \cdot s^{-1}$), air pressure (hPa) at 2m height, soil temperature (°C), soil moisture (%) at 0.05 m, 0.10 m and 0.30 m depth, and net radiation ($W \cdot m^{-2}$). Data were sampled every 30 s and stored as 15 min averages (sum for rainfall). Data have then been 3h and daily averaged for the purpose of this study.

Land-atmosphere exchange of sensible and latent heat were measured for the years 2012 and 2013 with an eddy covariance system consisting of an open-path infrared gas analyzer (LI-7500, LI-COR Inc., Lincoln, USA) and a three-axis sonic anemometer (Gill R3 Ultrasonic anemometer Gill instruments, Hampshire, UK) (Tagesson et al., 2015a). The sensors were mounted 9 m above the ground and data were collected at a 20 Hz rate. The post processing was done with the EddyPro 4.2.1 software (LI-COR Biosciences, 2012) and statistics were calculated for 30 minute periods. For a thorough description of the post processing of sensible and latent heat fluxes, see supplementary material of Tagesson et al. (2015b).

2.2.2 Atmospheric NH₃ concentrations using passive samplers

Atmospheric concentrations of NH₃ (and other compounds such as NO₂, HNO₃, O₃ and SO₂) were measured using passive samplers on a monthly basis, in accordance with the methodology used within the INDAAF (International Network to study Deposition and Atmospheric chemistry in Africa) program (<https://indaaf.obs-mip.fr>) driven by the Laboratoire d'Aerologie (LA) in Toulouse. While not being actually part of the INDAAF network, the Dahra site was equipped with the same passive sampler devices and analysis of these samplers were performed following the INDAAF protocol at LA.

Passive samplers were mounted under a stainless-steel holder to avoid direct impact from wind transport and splashing from precipitation. The holder was attached at a height of about 1.5m above ground. All the samplers were exposed in pairs in order to ensure the reproducibility of results. The samplers were prepared at LA in Toulouse, installed and collected after

one month exposure by a local investigator, and sent back to the LA. Samplers before and after exposition were stored in a fridge (4 °C) to minimize possible bacterial decomposition or other chemical reactions. Samplers were then analyzed by Ion Chromatography (IC) to determine ammonium and nitrate concentrations. Validation and quality control of passive samplers according to international standards (World Meteorological Organization report), as well as the sampling procedure and chemical analysis of samples, have been widely detailed in Adon et al. (2010). Monthly mean NH₃ concentrations in ppbv are calculated for the period 2012 and 2013. The measurement accuracy of NH₃ passive samplers, evaluated through covariance with duplicates and the detection limit evaluated from field blanks were estimated respectively at 14 % and 0.7±0.2 ppb (Adon et al., 2010).

2.2.3 Measurements of NO, NH₃ and CO₂ (respiration) fluxes from soil and soil physical parameters

NO, NH₃ and CO₂ fluxes were measured during 7 days in July 2012, 8 days in July 2013 and 10 days in November 2013; these periods will hereafter be called J12, J13 and N13 respectively. The samples were taken at three different locations along a 500m transect following a weak dune slope (top, middle and bottom) with one location per day. Each location was then sampled every 3 days, approximately from 8 AM to 7 PM for soil fluxes, and 24 hours a day for NO and NH₃ concentrations. Between 15 and 20 fluxes were measured each day during the three campaigns.

NO and NH₃ fluxes were measured with a manual closed dynamic Teflon chamber (non-steady-state through-flow chamber, Pumpanen et al. 2004) with dimensions of 200 mm width x 400 mm length x 200 mm height. During the J12 campaign, the chamber was connected to a ThermoScientific 17C analyzer, whereas in J13 and N13, it was connected to a ThermoScientific 17I analyzer (ThermoFischer Scientific, MA, USA). The calculation of fluxes is based on an equation detailed in Delon et al. (2017), adapted from Davidson et al. (1991). The increase rate of NO and NH₃ mixing ratios used in the flux calculation equation was estimated by a linear regression fitted to data measured during 180 to 300s for NO (120s for NH₃) following the installation of the chamber on the soil, as detailed in Delon et al. (2017). Close to the Teflon chamber, soil CO₂ respiration was measured with a manual closed dynamic chamber (SRC-1 from PP-systems, 150 mm height x 100 mm diameter) coupled to a non-dispersive infrared CO₂/H₂O analyzer EGM-4 (PP-Systems, Hitchin, Hertfordshire, UK). Soil CO₂ respiration was measured within 30 cm to the location of the NO and NH₃ fluxes. Measurements were performed on bare soil to ensure only roots and microbe respiration. Results of NO, NH₃ and CO₂ fluxes are presented as daily means with daily standard deviations. Along with flux measurements, soil physical parameters were measured during the campaigns: soil pH ranges from 5.77 to 7.43, sand content ranges between 86 and 94%, and clay content between 4.7 and 7.9%. All the methods, calculations and results from the field campaigns are fully detailed in Delon et al. (2017).

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2.3 Modeling biogenic NO fluxes, and CO₂ respiration and ammonium content in STEP-GENDEC-NOFlux

2.3.1 The STEP-GENDEC model

STEP model is presented in Appendix A, with forcing variables detailed in Tab. A1, site parameters used in the initialization in Tab. A2, numerical values of parameters used in the equations in Tab. A3, and equations, variables, parameters and constants used in the equations in Tab. A4.

STEP is an ecosystem process model for Sahelian herbaceous savannas (Mougin et al., 1995; Tracol et al., 2006; Delon et al., 2015). It is coupled to GENDEC which aims at representing the interactions between litter, decomposer microorganisms, microbial dynamics, and C and N pools (Moorhead and Reynolds, 1991). It simulates the decomposition of the organic matter and microbial processes in the soil in arid ecosystems. Information such as the quantity of organic matter ~~from~~ (faecal matter from livestock and herbal masses) are transferred from STEP as inputs to GENDEC (Fig. 1).

Soil temperatures are simulated from air temperature according to Parton (1984). This model requires daily max and min air temperature, global radiation (provided by forcing data), herbaceous aboveground biomass (provided by the model), initial soil temperature, and soil thermal diffusivity. Details of equations are given in Delon et al. (2015) and appendix A (Parameters in table Tables A3, variables in table and A4, equations in table A5).

Soil moistures are calculated following the tipping bucket approach (Manabe 1969): when the field capacity is reached, the excess water in the first layer (0-2 cm) is transferred to the second layer, between 2 and 30 cm. Two other layers are defined, between 30-100 cm and 100-300 cm. Equations related to soil moisture calculation are detailed in Appendix A (table A5) and in Jarlan et al. (2008). This approach, while being simple in its formulation, is especially useful in regions where detailed description of the environment is not available or unknown, and where the natural heterogeneity of the soil profile is high due to the presence of diverse matter fragments ~~such as~~ (buried litter, dead roots from herbaceous mass and trees, stones, branches, tunnels dug by insects and little mammals).

The STEP model is forced daily by rain, global radiation, air temperature, wind speed and relative air humidity at 2m height. Initial parameters specific to the Dahra site are listed in table A1 and site parameters in table A2 (Appendix A).

2.3.2 Respiration and biogenic NO fluxes

The quantity of carbon in the soil was calculated from the total litter input (from faecal and herbal mass, where faecal matter is obtained from the number of livestock heads grazing at the site; (Diawara 2015, Diawara et al., 2018). The quantity of carbon is 50 % the buried litter mass. The carbon and nitrogen exchanges between pools and all equations are detailed in Moorhead & Reynolds (1991) and will not be developed here. Carbon dynamics depends on soil temperature, soil moisture and soil nitrogen (linked to microbial dynamics). The concentration of nitrogen in the soil is derived from the quantity of carbon using C/N ratios.

Biogenic NO fluxes were calculated using the coupled model STEP/GENDEC/NOFlux, as detailed in Delon et al. (2015). The NOFlux model uses an Artificial Neural Network approach to estimate the biogenic NO emission from soil to the

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atmosphere (Delon et al., 2007, 2015). The NO flux is calculated from and depends on parameters such as soil surface temperature and moisture, soil temperature at 30cm depth, sand percentage, N input (here given as a percentage of the ammonium content in the soil), wind speed, soil pH. The input of N to the soil from the buried litter is provided by STEP, and the calculation of the ammonium content in the soil coming out from this N input is provided by GENDEC. The equations used for NO flux calculation are reported in Appendix B, taken from Delon et al. (2015).

The main structure of the model is kept identical as in the Delon et al., (2015) version, except for N uptake by plants, for which the present paper proposes a formulation, detailed in Appendix C. In brief, in the previous version of the model 2% of the NH_4^+ pool of the soil was used for NO emission calculation. In the current version, the NO emitted to the atmosphere results from 1% of the NH_4^+ pool in the soil minus the N absorbed by plants. The percentage of soil NH_4^+ pool used to calculate the NO emission has been changed from 2 to 1% based on Potter et al (1996) who proposed a range between 0.5 and 2%. In the present study, the 1% value was more adapted to fit experimental values.

Soil respiration is the sum of autotrophic (root only) and heterotrophic respiration. The autotrophic respiration in STEP is calculated from growth and maintenance respirations of roots and shoots (Mougin et al., 1995), following equations reported in table A45 (Appendix A). Autotrophic respiration depends on root depth soil moisture and soil temperature (2-30cm) and root biomass, which dynamics is simulated by STEP. The heterotrophic respiration is calculated in GENDEC from the growth and death of soil microbes in the soil depending on the available litter C (given by STEP). Microbial respiration ρ in gC d^{-1} is calculated as in (Eq. equation 1).

$$\rho = (1 - \varepsilon) Ca \quad (1)$$

Microbial growth in gC d^{-1} is $\gamma = \varepsilon \cdot Ca$, where ε is the assimilation efficiency (unitless) and Ca is total C available in gC d^{-1} , i.e., total C losses from four different litter inputs, i.e., buried litter, litter from trees, faecal matter and dry roots. Microbial death is driven by the death of the living microbe mass, and the change in water potential during drying-wetting cycles (change between -1.5 and -0.01 MPa in the layer 2-30cm). These calculations are described in Moorhead & Reynolds (1991) and Delon et al., (2015) and are not reported in detail in this study. A schematic view of STEP-GENDEC-NOFlux is presented in Fig. 1. Simulated variables and corresponding measurements used for validation are summarized in table 1.

2.4 Modeling NH_3 fluxes

The net NH_3 flux between the surface and the atmosphere depends on the concentration difference $\chi_{cp} - C_{\text{NH}_3}$, where C_{NH_3} is the ambient NH_3 concentration in $\mu\text{g m}^{-3}$, and χ_{cp} is the concentration of the canopy compensation point in $\mu\text{g m}^{-3}$. The canopy compensation point concentration is the atmospheric NH_3 concentration in the canopy for which the fluxes between the soil, the stomatal cavities and the air inside the canopy switch from emission to deposition, or vice versa (Farquhar et al., 1980, Wichink Kruit et al., 2007). The canopy compensation point concentration takes into account the stomatal and soil layers. The soil compensation point concentration, χ_g in ppb has been calculated from the emission potential Γ_g (unitless), as a function of soil surface temperature (T_g in K) according to Wentworth et al., (2014):

$$\chi_g (\text{ppb}) = 13\,587 \cdot \Gamma_g \cdot e^{-(10\,396\text{K}/T_g)} \times 10^9, \quad (2)$$

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A large Γ_g indicates that the soil has a high propensity to emit NH_3 , considering that the potential emission of NH_3 depends on the availability of ammonium in the soil and on the pH. ($\Gamma_g = [\text{NH}_4^+]/[\text{H}^+]$; concentrations were values measured in the field and available in Delon et al., (2017)).

Two different models designed to simulate land atmosphere NH_3 bidirectional exchange are used in this study, and described below.

2.4.1 Inferential method (Zhang et al., 2010)

An inferential method was used to calculate the bi-directional exchange of NH_3 . The overall flux F_{NH_3} (in $\mu\text{g m}^{-2} \text{s}^{-1}$) is calculated as:

$$F_{\text{NH}_3} = (\chi_{cp} - C_{\text{NH}_3}) \times Vd \quad (3)$$

$$F_{\text{NH}_3} = (\chi_{cp} - C_{\text{NH}_3}) \times Vd$$

with $Vd = 1/(R_a + R_b + R_c)$

where Vd (m s^{-1}) is the deposition velocity, determined by using the big-leaf dry deposition model of Zhang et al. (2003). R_a (s m^{-1}) and R_b (s m^{-1}) are the aerodynamic and quasi-laminar resistances respectively, R_c (s m^{-1}) is the total resistance to deposition resulting from component terms such as stomatal, mesophyll, non-stomatal/external/cuticular and soil resistances (Flechard et al., 2013 and references therein). C_{NH_3} ($\mu\text{g m}^{-3}$) is determined at the monthly scale from passive sampler measurements. The χ_{cp} term ($\mu\text{g m}^{-3}$) is calculated following the two-layer Zhang et al. (2010) model (hereafter referred to as Zhang2010). This model gives access to an extensive literature review on compensation point concentrations and emission potential values classified for 26 different Land Use Classes (LUC). Compensation point concentrations are calculated in the model and vary with canopy type, nitrogen content, and meteorological conditions. This model was adapted by Adon et al. (2013) for the specificity of semi-arid ecosystems such as Leaf Area Index (LAI) or type of vegetation, assuming a ground emission potential of 400 (unitless), considered as a low end value for non fertilized ecosystems according to Massad et al., (2010) and based on Delon et al. (2017) experimental results, and a stomatal emission potential of 100 (unitless) based on Massad et al. (2010) for grass, and on the study of Adon et al. (2013) for similar ecosystems as the one found in Dahra. Considering the bidirectional nature of NH_3 exchange, emission occurs if the canopy compensation point concentration is superior to the ambient concentration (Nemitz et al., 2001). Emission fluxes are noted as positive. Meteorological forcing required for the simulation are 3h-averaged wind speed, net radiation, pressure, relative humidity, air temperature at 2m height, surface temperature at 5cm depth, and rainfall. The equations used in this model are extensively described in Zhang et al. (2003, 2010), and will not be detailed here.

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2.4.2 The Surf atm model

The Surface-Atmosphere (Surfatm) model combines an energy budget model (following Choudhury and Monteith, (1988)) and a pollutant exchange model (following Nemitz et al., (2001)), which allows distinction between the soil and the plant exchange processes. As in Zhang2010, the scheme is based on the traditional resistance analogy describing the bi-directional transport of NH_3 governed by a set of resistances controlled by the atmosphere, R_a (s m^{-1}), the quasi-laminar boundary layer, R_b (s m^{-1}), and the canopy, R_c (s m^{-1}) respectively (Hansen et al., 2017 and references therein) already described in the preceding paragraph. Surf atm includes a diffusive resistance term from the topsoil layer to the soil surface. Surf atm represents a comprehensive approach to study pollutant exchanges and their link with plant and soil functioning. The NH_3 exchange is directly coupled to the energy budget, which determines the leaf and surface temperatures, the humidity of the canopy, and the resistances in the layers above the soil and in the soil itself. This model has been comprehensively described in Personne et al. (2009) and more recently in Hansson et al (2017).

The model is forced every 3h by net radiation, deep soil temperature (30 cm), air temperature, relative humidity, wind speed, rainfall, atmospheric NH_3 concentration (with monthly values from passive samplers measurements repeated every 3 hours). Forcing also includes constant values of roughness length Z_0 , Leaf Area Index (LAI), displacement height D, canopy height Z_h , measurement height Z_{ref} , stomatal emission potential, and ground emission potential. Forcing also includes values of Leaf Area Index (LAI, measured), canopy height Z_h (estimated), roughness length Z_0 ($0.13Z_h$), displacement height D ($0.7Z_h$), stomatal emission potential (constant), ground emission potential (derived from measurements during field campaigns, constant the rest of the time), and measurement height Z_{ref} (2m). LAI was measured according to the methodology developed in Mougin et al., (2014). Data from Dahra were measured monthly during the wet season and were not published (Mougin, personal communication). Linear interpolation was performed between these monthly estimates, and values for the dry season were found in Adon et al. (2013), for an equivalent semi arid ecosystem in Mali, derived from MODIS measurements. The ground emission potential has been set to 400 (unitless), and the stomatal emission potential has been set to 100 (unitless) as in the simulation based on Zhang2010, except during field campaign periods, where the ground emission potential has been derived from experimental values (700 in J12 and J13 and 2000 in N13). In table 2, constant input parameters are listed. Some of them were adapted to semi-arid conditions to get the best fit between measured and simulated fluxes, specified in Table 2, and their values are listed in Table 1.

The main difference between Surf atm and Zhang2010 is the presence of a SVAT (Surface Vegetation Atmosphere Transfer) model in Surf atm (Personne et al., 2009), allowing for energy budget consideration and accurate restitution of surface temperature and moisture. Simulated variables and corresponding measurements used for validation are summarized in table 1.

2.5 Statistic analysis

Modeling and experimental results (trace gas fluxes and environmental parameters) have been analyzed on the basis of their correlation (R^2) with an indication of the p-value, and with stepwise multiple regression analysis. The R software (<http://www.R-project.org>) was used to provide results of this linear regression analysis.

The R software (<http://www.R-project.org>) was used to provide results of simple and multiple linear regression analysis. The `cor.test()` function was used to test a single correlation coefficient R, i.e. a test for association between paired samples, using one of Pearson's product moment correlation coefficient. The p-value is used to determine the significance of the correlation. If p-value is less than 0.05, the correlation is considered as non significant. The `lm()` test was used for stepwise multiple regression analysis. The adjusted R-Squared (i.e. normalized multiple R-squared R^2), determines how well the model fits to the data. Again, the p-value is calculated, and has to be less than 0.05 to give confidence in the significance of the determination coefficient R^2 .

3 Results

3.1 Soil moisture, soil temperature and land atmosphere heat fluxes

Soil moisture simulated by STEP in the surface layer (Fig. 2a) is limited at 11% during the wet season. This value corresponds to the field capacity calculated by STEP. The soil moisture modelling follows the tipping bucket approach, i.e. when the field capacity is reached, the excess water is transferred to the second layer, between 2 and 30 cm. Experimental values measured at 5 and 10 cm are better represented by the model in this second layer (Fig. 2b). Linear regression gives a R^2 of 0.74 (resp. 0.81), a slope of 0.98 (resp. 1.05) and an offset of 0.34 (resp. 0.32) between STEP soil moisture in the 0-2cm (resp. 2-30cm) layer and experimental soil moisture at 5 cm. R^2 is 0.77, slope is 0.93 and offset is 0.84 between STEP soil moisture in the 2-30cm layer and experimental soil moisture at 10 cm. The temporal dynamics given by STEP, the filling of the surface layer, the maximum and minimum values are comparable to the data. However, the drying of the layers is sharper in the model than in measurements at the end of the wet season, leading to an underestimation of the model compared to measurements until December each year. However, the drying of the layers is sharper in the model than in measurements at the end of the wet season, hence the underestimation of the model compared to measurements until December each year.

As a comparison, linear correlation between STEP H (resp. STEP LE) and EC H (resp. EC LE) gives R^2 of 0.4 (resp. 0.7), for both years of simulation (Fig. 3a and 3b). The significant correlation between Surf_{atm} and EC latent heat fluxes indicates that the stomatal, aerodynamic and soil resistances are correctly characterized in the model, giving confidence in the further realistic parameterization of NH_3 fluxes, despite missing values in intermediate fluxes, due to the criteria applied by the postprocessing (see supplementary material of Tagesson et al. (2015b)).

Surfatm soil surface temperature is very close to measured soil surface temperature (Fig. 4a, $R^2=0.70$, $p<0.001$ in 2012-2013). Mean annual values were 35.8°C and 34.2°C respectively for surface Surfatm and measured soil surface temperatures in 2012, and 32.4°C and 33.8°C in 2013. STEP surface temperatures (0-2cm layer) presents mean values of 32.0°C in 2012, and 32.6°C in 2013. Linear regression between STEP 0-2cm layer and measured surface temperatures (Fig. 4b) gives a R^2 of 0.7 ($p<0.001$) for 2012-2013. Slopes and offsets are indicated on the figures.

3.2 Biogenic NO fluxes from soil and ammonium content

In J12, average NO fluxes are $5.1\pm 2.8 \text{ ngN}_2\text{-m}^{-2}\text{-s}^{-1}$ and $5.7\pm 3.1 \text{ ngN}_2\text{-m}^{-2}\text{-s}^{-1}$ for modelled and measured fluxes respectively. In J13, average NO fluxes are $10.3\pm 3.3 \text{ ngN}_2\text{-m}^{-2}\text{-s}^{-1}$ and $5.1\pm 2.1 \text{ ngN}_2\text{-m}^{-2}\text{-s}^{-1}$ for modelled and measured fluxes respectively. In N13, average NO fluxes are $2.2\pm 0.3 \text{ ngN}_2\text{-m}^{-2}\text{-s}^{-1}$ and $4.0\pm 2.2 \text{ ngN}_2\text{-m}^{-2}\text{-s}^{-1}$ for modelled and measured fluxes respectively. Emission fluxes are noted as positive.

In Fig. 5, the model represents the daily fluxes for 2012 and 2013 and is compared to measurements. The model is comprised within the standard deviation of the measurements in J12 and N13 but overestimates fluxes in J13. ~~This overestimation may be explained by the ammonia content overestimated by the model at this period, shown in Fig. 6 which reports 9 points of measured ammonia from Delon et al., (2017), showing an overestimation of released N during the J13 wet season, and an underestimation at the end of the wet season (as N13), when the presence of standing straw may lead to N emissions in addition to soil emissions, not accounted for in the model because litter is not yet buried. The slight underestimation of modelled soil moisture (Fig. 2) at the end of the wet season may also explain why modelled fluxes are lower than measured fluxes. The large spatial heterogeneity in measurements may be explained by variations in soil pH (ranging from 5.77 to 7.43, see Delon et al., (2017)) and texture (sand between 86 and 94%, clay between 4.7 and 7.9%), and by the presence of livestock and the short term history of the Dahra site, i.e. how livestock have trampled, grazed and deposited manure during the different seasons and at different places. This spatial variation is evidently not represented in the 1D model, where unique soil pH and soil texture are given, as well as a unique input of organic fertilization by livestock excreta.~~

Modelled dry and wet season NO fluxes are respectively $2.5\pm 2.5 \text{ ngN}_2\text{-m}^{-2}\text{-s}^{-1}$ and $6.2\pm 4.1 \text{ ngN}_2\text{-m}^{-2}\text{-s}^{-1}$ for both 2012 and 2013, and the simulation gives a mean flux of $3.6\pm 2.9 \text{ ngN}_2\text{-m}^{-2}\text{-s}^{-1}$ for the entire study period. Wet season fluxes represent 51% of the annual mean, even though lasting only 3 to 4 months. ~~With wet season NO fluxes being more than twice higher than dry season fluxes, results emphasize the influence of pulse emissions in that season. This increase at the onset of the wet season over the Sahel, due to the drastic change in soil moisture, has been previously highlighted by satellite measurements of the NO_2 column, by Vinken et al. (2014), Hudman et al. (2012), Jaegle et al. (2004) and Zörner et al. (2016).~~

Simulated NO fluxes are significantly correlated with measured soil moisture at 5 cm depth ($R^2=0.42$, $p<0.001$, $\text{slope}=0.65$, $\text{offset}=0.69$) and 10 cm depth ($R^2=0.43$, $p<0.001$, $\text{slope}=0.72$, $\text{offset}=0.33$) for both years, but not directly with soil temperature. A multiple linear regression model involving soil moisture at 5 cm depth, soil temperature at 5 and 30 cm depth and wind speed to explain simulated NO fluxes leads to a R^2 of 0.43 ($p<0.001$). These parameters have been shown as

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important drivers of NO emissions in several previous studies, such as Homyak et al. (2016), Medinets et al. (2015), or Delon et al. (2007). Indeed, as detailed in Appendix B, NO fluxes in STEP-GENDEC-NOflux are calculated by an equation derived from an Artificial Neural Network (ANN) algorithm ~~trained with data from temperate and tropical ecosystems~~, taking into account these 4 parameters, together with sand percentage, soil pH and N input.

~~After the pulses of NO at the beginning of the wet season (Fig. 5), emissions decrease most likely because the available soil mineral N is used by plants during the growing phase of roots and green biomass (especially in 2013), and is less available for the production of NO to be released to the atmosphere (Homyak et al., 2014, Meixner & Fenn 2004, Krul et al., 1982). During the wet season, NO emissions to the atmosphere in the model are reduced by 18% due to plant uptake (compared to NO emissions when plant uptake is not taken into account). Indeed, N uptake by plants is enhanced when transpiration increases during the wet season (Appendix C).~~

3.3 Soil CO₂ respiration

Soil respiration includes soil heterotrophic respiration_h (which refers to the decomposition of dead soil organic matter (SOM)_h by soil microbes) and root respiration_r (including all respiratory processes occurring in the rhizosphere; (Xu et al., (2016)). The simulated respiration of aboveground biomass is not included as in measured data.

In J13, the average measured flux is $2.6 \pm 0.6 \text{ gC}_r\text{-m}^{-2}\text{-d}^{-1}$, and the average modelled flux is $1.9 \pm 0.4 \text{ gC}_r\text{-m}^{-2}\text{-d}^{-1}$. The correlation between the two data sets is not significant. In N13, the average measured flux is $0.78 \pm 0.11 \text{ gC}_r\text{-m}^{-2}\text{-d}^{-1}$, and the average modelled flux is $0.18 \pm 0.02 \text{ gC}_r\text{-m}^{-2}\text{-d}^{-1}$. The two data sets are not correlated. November fluxes are less important than July fluxes, as illustrated by both the model and the measurements (Fig. 7), and as previously shown with eddy covariance data (Tagesson et al., 2015a). Simulated respiration fluxes are in the range of measured fluxes in J13, but appear to underestimate measured fluxes in N13 (Fig. 7), ~~likely because the model over-predicts the death rate of microbes and subsequently underestimates the CO₂ respired, whereas microbes and residues of roots respiration persist in the field despite low soil moisture. A second explanation of this underestimation might be the lower soil moisture in the model than in measurements at the end of the wet season (Fig. 2).~~

The simulated autotrophic respiration (roots + aboveground biomass) is shown, together with the heterotrophic (microbes) respiration, to check for a possible role of aboveground biomass in comparison with measurements (Fig. 8). As expected, the heterotrophic respiration is higher than the autotrophic respiration before and after the growth of the vegetation, i.e. at the beginning and end of the wet season in 2012, or during precipitation dry spells (e.g. in J13). At the end of the wet season, the late peaks of simulated heterotrophic respiration are linked to late rain events ~~because~~ (autotrophic respiration is no more effective ~~because when~~ vegetation is not growing anymore). Adding the autotrophic respiration to the heterotrophic respiration does not help to better fit to measured respiration in N13.

Average dry and wet season simulated soil respiration are respectively $0.3 \pm 0.7 \text{ gC}_r\text{-m}^{-2}\text{-d}^{-1}$ and $1.0 \pm 0.4 \text{ gC}_r\text{-m}^{-2}\text{-d}^{-1}$, while annual mean is $0.5 \pm 0.7 \text{ gC}_r\text{-m}^{-2}\text{-d}^{-1}$. This annual mean is below global estimates for grassland ($2.2 \text{ gC}_r\text{-m}^{-2}\text{-d}^{-1}$) and deserts

partially vegetated ($1.0 \text{ gC}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, Xu et al., 2016). The wet season has the largest contribution (57%) on the annual respiration budget (with wet seasons of 114 and 81 days in 2012 and 2013 respectively).

Simulated daily respiration from microbes and roots is significantly correlated with measured soil moisture at 5 cm depth with $R^2=0.50$, $p<0.001$, $\text{slope}=0.17$, $\text{offset}=0.26$, and 10 cm depth (~~both~~ with $R^2=0.5$, $p<0.001$, $\text{slope}=0.19$, $\text{offset}=-0.37$) for both years, whereas soil field measured respiration show a lower correlation with surface soil moisture, with ($R^2=0.4$, and $p=0.09$, $\text{slope}=0.03$, $\text{offset}=-0.07$ in J13, and $R^2=0.3$ ~~and~~, $p=0.1$, $\text{slope}=0.02$, $\text{offset}=-0.02$ in J13 ~~and~~ in N13 ~~respectively~~), with surface soil moisture.

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3.4 NH_3 bidirectional exchange

NH_3 fluxes were simulated by two different models: Surfalm (Personne et al., 2009), and Zhang2010 (Fig.9). The same ambient concentrations deduced from in situ measurements are prescribed in both models. Average fluxes are reported in Tab. 2. In J12, average fluxes are $1.3\pm 1.1 \text{ ngN}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $2.6\pm 2.6 \text{ ngN}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and $9.0\pm 0.9 \text{ ngN}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, for measured, Surfalm and Zhang2010 respectively. Simulated fluxes are not significantly correlated with measured data. In J13, average fluxes are $0.1\pm 1.1 \text{ ngN}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $1.7\pm 2.4 \text{ ngN}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $7.8\pm 2.2 \text{ ngN}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, for measured, Surfalm and Zhang2010 respectively. Surfalm and measurements fluxes are weakly-not significantly correlated ($R^2=0.2$ $p=0.2$). In N13, average fluxes are $0.7\pm 0.5 \text{ ngN}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $0.2\pm 1.1 \text{ ngN}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $2.8\pm 0.9 \text{ ngN}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, for measured, Surfalm and Zhang2010 respectively. Surfalm and measurements fluxes are weakly-not significantly correlated ($R^2=0.2$, $p=0.2$), and Zhang2010 and measurements fluxes are significantly correlated ($R^2=0.5$; $p=0.01$, $\text{slope}=1.5$, $\text{offset}=-3.8$).

At the annual scale, modelled NH_3 dry deposition flux is $-0.9\pm 3.3 \text{ ngN}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ($-0.3\pm 1.0 \text{ kgN}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) and $-3.5\pm 4.6 \text{ ngN}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ($-1.1\pm 1.4 \text{ kgN}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) in 2012, and $-2.0\pm 3.7 \text{ ngN}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ($-0.6\pm 0.3 \text{ kgN}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) and $-2.7\pm 3.8 \text{ ngN}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ($-0.8\pm 1.2 \text{ kgN}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) in 2013, in Surfalm and Zhang2010 respectively. Fig. 9 shows alternative changes between low NH_3 emission and low deposition. This switch occurs during the dry seasons (from mid October to end of June). Indeed, canopy compensation point and ambient concentration values are quite similar monthly averaged compensation point and ambient concentration values are quite similar during the dry seasons. Compensation point concentration averaged during the 2012 and 2013 dry seasons is $3.8\pm 1.5 \text{ ppb}$, and averaged ambient concentration is $4.3\pm 1.5 \text{ ppb}$ for the same period. If the 2012 and 2013 dry seasons are considered separately, the values of the means remain the same. Low deposition dominates when air humidity is sufficiently high, roughly above 25% (before and after the wet season), whereas low emission dominates when air humidity is low (<25%).

Dry season fluxes are on average $0.9\pm 2.3 \text{ ngN}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and $0.2\pm 1.6 \text{ ngN}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and wet season fluxes are $8.1\pm 3.2 \text{ ngN}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and $4.3\pm 4.8 \text{ ngN}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for Zhang2010 and Surfalm respectively. The net dry and wet season fluxes reported in table 3 are in a similar range as NH_3 fluxes calculated by Adon et al. (2013) using Zhang2010 at comparable Sahelian sites in Mali and Niger. NH_3 fluxes ranged between -3.2 and $0.9 \text{ ngN}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ during the dry season and between -14.6 and $-6.0 \text{ ngN}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ during the wet season.

Fig. 10 shows the partition between the different contributions of soil and vegetation to the NH_3 fluxes in Surfalm and Zhang2010. During the wet season, the contributions of vegetation and soil in Surfalm (Zhang2010) are $-6.3 \pm 3.7 \text{ ngN m}^{-2} \text{ s}^{-1}$ ($-0.8 \pm 0.36 \text{ ngN m}^{-2} \text{ s}^{-1}$) and $2.0 \pm 1.9 \text{ ngN m}^{-2} \text{ s}^{-1}$ ($-7.3 \pm 3.0 \text{ ngN m}^{-2} \text{ s}^{-1}$) respectively for both years. During the dry season, vegetation (i.e. stomata + cuticles) and soil contributions are low: -0.9 ± 1.7 and $0.7 \pm 0.6 \text{ ngN m}^{-2} \text{ s}^{-1}$ respectively in Surfalm, 0.4 ± 0.5 and $-0.5 \pm 2.3 \text{ ngN m}^{-2} \text{ s}^{-1}$ in Zhang2010, as reported in table 4. In N13, at the end of the wet season, the soil contribution is $2.9 \pm 0.7 \text{ ngN m}^{-2} \text{ s}^{-1}$ in Surfalm, whereas it is $-2.6 \pm 0.8 \text{ ngN m}^{-2} \text{ s}^{-1}$ in Zhang2010.

In Fig. 10a, the total net flux above the canopy in Surfalm results from an emission flux from the soil and a deposition flux onto the vegetation via stomata and cuticles, especially during the wet season. On the contrary, the total flux in Zhang2010 in Fig. 10b results from a strong deposition flux on the soil and a very low deposition flux onto the vegetation. This is explained by a strong contribution of deposition on cuticles in Surfalm (Fig. 10c) whereas it is close to zero in Zhang2010 (Fig. 10d). In Surfalm, emission from stomata also occurs but it is largely offset by the deposition on leaf surfaces which leads to a deposition flux onto vegetation (Sutton et al., 1995). In Surfalm, the deposition on cuticles is effective until the end of the wet season, whereas deposition through stomata lasts until the vegetation is completely dry, i.e. approximately 2 months after the end of the wet season. On the basis of the different averages for each contributing flux in table 4, we estimate that the soil is a net source of NH_3 during the wet season, while the vegetation is a net sink in Surfalm, and the soil is a net sink in Zhang2010.

4. Discussion

4.1 NH_3 exchanges

4.1.1 Relevance of monthly NH_3 concentration input vs daily NH_3 flux outputs

In the two models, C_{NH_3} used as input data arises from passive sampler measurements, integrated at the monthly scale (see section 2.2.2). Outputs fluxes are provided at a 3h timescale, averaged at the daily scale for the purpose of this study. The relevance of using monthly NH_3 concentrations instead of concentrations with finer resolution in time has been already approached in the literature. Riddick et al. (2014, 2016) have used ALPHA samplers to measure NH_3 concentrations at the scale of the week and/or the month. They have noticed that time averaged NH_3 fluxes from these samplers provided similar estimated fluxes to those calculated from on line sampling. In the case of passive sampling concentration measurements, meteorological and area sources of uncertainty can still be accounted for in the flux calculation. Riddick et al. (2014) conclude that active and passive sampling strategies give similar results, which support the use of low cost passive sampling measurements at remote locations where it is often logistically hard to deploy expensive active sampling methods for flux measurements. These statements have been confirmed in Loubet et al. (2018), and provide a valuable reason to use monthly concentrations as inputs in the present study.

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4.1.21 NH₃ deposition flux increase/variation

Dahra is a grazed savanna where the main source of NH₃ emission to the atmosphere is the volatilization of livestock excreta (Delon et al., 2012); the excreta quantity and quality is at a maximum at the end of the wet season, (Hiernaux et al., 1998, Hiernaux and Turner 2002, Schlecht and Hiernaux 2004), because animals are better fed. In August, a strong leaching of the atmosphere occurs which decreases the NH₃ atmospheric concentration (not shown here), compared to July concentration, and the deposition flux decreases as well. Indeed, if the concentration decreases from July to August whereas the canopy compensation point remains stable, the flux will decrease as shown by equation 3.

In the months of August 2012 and 2013, there is a decrease of NH₃ deposition fluxes, explained by a decrease in NH₃ concentration (not shown here: if the concentration decreases, whereas the canopy compensation point remains stable, the flux will decrease as shown by equation 3). This decrease in NH₃ atmospheric concentration is explained by a strong leaching of the atmosphere in August: Dahra is a grazed savanna, and the main source of NH₃ emission to the atmosphere is the volatilization of livestock excreta (Delon et al., 2012); the excreta quantity and quality is at a maximum at the end of the wet season, (Hiernaux et al., 1998, Hiernaux and Turner 2002, Schlecht and Hiernaux 2004), because animals are better fed. August is the month with the maximum ammonium wet deposition, which leads to a strong leaching of the atmosphere, and explains the decrease of the NH₃ concentration (Laouali et al., 2012).

4.1.32 Role of soil moisture and soil temperature on NH₃ fluxes:

A significant correlation ($p < 0.01$) is found between Zhang2010 and measured soil moisture at 5 cm depth ($R^2 = 0.6$, $p < 0.01$, slope = -1.2, offset = 2.1) for 2012-2013. Surf atm fluxes and measured soil moisture at 5 cm depth, (0.6 and are also significantly correlated with $R^2 = -0.3$, $p < 0.01$, slope = -0.7, offset = 1.7 for 2012-2013 respectively), and this correlation is higher if only the dry season is considered (0.7 and 0.5 respectively). A weak but significant correlation is found between Surf atm fluxes and soil surface temperature ($R^2 = 0.2$, $p < 0.001$, slope = 0.14, offset = 33.9) for both wet seasons, whereas it is not found with Zhang2010 fluxes. An explanation may be that the NH₃ exchange in Surf atm is directly coupled with the energy balance via the surface temperature (Personne et al., 2009). A stepwise multiple linear regression analysis was performed between Zhang2010 fluxes and NH₃ ambient concentrations, air humidity, wind speed, soil surface temperature and moisture, for both years of simulation. The model selection was done by adding each variable step by step, i.e. the best combination was chosen with the best associated significant R^2 (p -value < 0.05). The resulting model gives a R^2 of 0.9 ($p < 0.001$), showing a large interdependence of the above cited parameters on NH₃ fluxes (whereas the correlation between NH₃ fluxes and each individual parameter is not significant). While the isolated soil temperature effect is not demonstrated, these complex interactions between influencing parameters suggest that the contribution of soil temperature to NH₃ fluxes, together with other environmental parameters, becomes relevant.

The same multiple linear regression model is run between Surf atm NH₃ fluxes and the above cited parameters, but with soil moisture replaced by latent heat fluxes since soil moisture in Surf atm is not available at a constant depth. R^2 is 0.6 (with

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~~p<0.001). As for Zhang2010 fluxes, a stepwise multiple linear regression analysis is run between Surf atm NH₃ fluxes and NH₃ concentrations, air humidity, wind speed, soil surface temperature and latent heat fluxes. R² is 0.6 with p<0.001. As for Zhang2010, the nested influences of environmental parameters in Surf atm are highlighted. These interactions become more complex with the energy balance effect, but may be more accurate in representing the partition between surface and plant contributions.~~

4.1.43 Contribution of soil and vegetation to the net NH₃ flux in Surf atm:

~~Surf atm allows differentiating between the different contributions of soil and vegetation to the NH₃ fluxes (Fig. 10). The net flux above the canopy results from an emission flux from the soil and a deposition flux onto the vegetation via stomata and cuticles, especially during the wet season. Emission from stomata may also occur (Sutton et al., 1995) but is largely offset by the deposition on leaf surfaces which leads to a deposition flux onto vegetation. The deposition on cuticles is effective until the end of the wet season, whereas deposition through stomata lasts until the vegetation is completely dry, i.e. approximately 2 months after the end of the wet season (the details between stomata and cuticle deposition is not shown here). On the basis of the different averages for each contributing flux, we estimate that the soil is a net source of NH₃ during the wet season, while the vegetation is a net sink.~~

~~During the wet season, the contributions of vegetation and soil in Surf atm are $-6.3 \pm 3.7 \text{ ngN} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ and $2.0 \pm 1.9 \text{ ngN} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ respectively for both years. Deposition on the vegetation through stomata and cuticles dominate the exchange at that time of the year, (during rain events, the cuticular resistance becomes small and cuticular deposition dominates) despite an increase of soil emission. This increase is due to an increase of the deposition velocity of NH₃ (consecutive to the humidity response of the surface) and a decrease of the canopy compensation point, sensitive to the surface wetness (Wichink-Kruit et al., 2007).~~

~~During the dry season, vegetation (i.e. stomata + cuticles) and soil contributions are low (-0.9 ± 1.7 , and $0.7 \pm 0.6 \text{ ngN} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ respectively, as reported in Table 2). Aboveground herbaceous dry biomass stands for a few months after the end of the wet season when the soil becomes bare, and the vegetation effect negligible. At the end of wet season 2013 (Fig. 11), the soil contribution to the total flux increases significantly ($2.9 \pm 0.7 \text{ ngN} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in N13) due to the increase of the ground emission potential prescribed at 2000 in Surf atm (instead of 400 for the rest of the year, to be consistent with measurements noted in Delon et al., (2017)).~~

~~In Surf atm, during the wet season, deposition on the vegetation through stomata and cuticles dominate the exchange. Indeed, during rain events, the cuticular resistance becomes small and cuticular deposition dominates despite an increase of soil emission. This increase is due to an increase of the deposition velocity of NH₃, consecutive to the humidity response of the surface, and a decrease of the canopy compensation point, sensitive to the surface wetness (Wichink-Kruit et al., 2007). In Zhang2010, despite the difference in magnitude, cuticular deposition increases as well during the wet season, but is dominated by deposition on the soil.~~

During the dry season, aboveground herbaceous dry biomass stands for a few months after the end of the wet season when the soil becomes bare, and the vegetation effect negligible in both models. At the end of wet season 2013, the soil contribution to the total flux increases significantly in Surf atm due to the increase of the ground emission potential prescribed at 2000 (instead of 400 for the rest of the year, to be consistent with measurements noted in Delon et al., (2017)).”

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4.1.54 Surf atm versus Zhang2010 NH₃ bidirectional models

The two models are based on the same two layer model approach developed in Nemitz et al. (2001). In the two models, the ground emission potential and the NH₃ ambient concentrations are prescribed. The comparison of modelled and measured flux values in Fig. 9 shows differences especially for results predicted by Zhang2010. This is partly because in Surf atm ground emission potential varies with time and was specifically modified for the field campaign periods, whereas this parameter does not vary in Zhang2010. ~~Indeed, Zhang2010 model was specifically designed to address the regional scale and average temporal scales rather than hot spots or hot moments of NH₃ exchange. The lack of variability of the ground emission potential in Zhang2010 highlights the sensitivity of fluxes to this specific parameter for 1D modelling in semi arid soils, where the rapid turnover of N cycle and the abrupt transitions between seasons needs a high flexibility of the ground emission potential to represent the processes more closely. The lack of variability of the ground emission potential in Zhang2010 highlights the sensitivity of fluxes to this specific parameter for 1D modelling in semi arid soils. The abrupt transitions between seasons need a certain flexibility of the ground emission potential to represent the changes in flux direction.~~

In Surf atm, the temperatures (above and in the soil) are calculated through the sensible heat flux, the humidity and evaporation at the soil surface are calculated through the latent heat flux. The resistances needed for the compensation point concentration and for the flux calculation are deduced from the energy budget. This allows taking simultaneously into account the role of temperature and humidity of the soil. In Zhang2010, the R_a, R_b, R_c resistances are calculated directly from the meteorological forcing, and the soil resistance is prescribed. ~~Again, the flexibility of this parameter is more adapted than fixed values for 1D modelling. Again, the flexibility of this parameter is more adapted than fixed values for 1D modeling, and this may lead to completely different repartitions of the fluxes between the soil and the vegetation, as shown in Fig. 10. This difference in flux repartition highlights the importance of the choice in the type of soil and/or vegetation for the simulations.~~

However, the close correlation between both models ($R^2=0.5$, $p<0.01$, slope=0.6, offset=0.4) indicates a similar representation of ~~processes the net flux~~ in each model and emphasizes clear changes at the transition between seasons.

4.2 Effect of soil moisture, ~~and soil temperature~~ **and soil characteristics** on exchange processes

For most of the biomes the temperature strongly governs soil respiration through metabolism of plants and microbes (Lloyd and Taylor, 1994; Reichstein et al., 2005; Tagesson and Lindroth, 2007). However, in our results we found no significant

correlation between soil surface temperature and trace gas fluxes. This confirms that in the semi-arid tropical savannas, physiological activity is not limited by temperature (Archibald et al., 2009; Hanan et al., 2011; Hanan et al., 1998; Tagesson et al., 2016a; Tagesson et al., 2015a). Instead, soil moisture variability overrides temperature effects as also underlined by Jia et al. (2006). Indeed, for low soil moisture conditions, slight changes in soil moisture may have a primordial effect, while temperature effect on microbial activities is not observable (Liu et al., 2009). This may explain why soil temperature and NO, CO₂ and NH₃ fluxes are not correlated at the annual scale (dominated by dry months) as mentioned in the preceding paragraphs. Due to higher soil moisture in wet seasons (8.1±2.7% vs 3.2±1.5% in dry seasons), soil temperature effect becomes visible, elevated temperatures may increase microbial activity, and changes in soil temperature may have an influence on N turnover and N exchanges with the atmosphere (Bai et al., 2013).

The over or underestimations of NO emissions in the model in Fig. 5 may be explained by the ammonium content shown in Fig. 6. Released N is overestimated during the J13 wet season, and underestimated at the end of the wet season (as N13), when the presence of standing straw may lead to N emissions in addition to soil emissions, not accounted for in the model because litter is not yet buried. The slight underestimation of modelled soil moisture (Fig. 2) at the end of the wet season may also explain why modelled fluxes of NO (Fig. 5) and CO₂ (Fig. 7) are lower than measured fluxes. Furthermore, the model over-predicts the death rate of microbes and subsequently underestimates the CO₂ respired, whereas microbes and residues of roots respiration persist in the field despite low soil moisture. The large spatial heterogeneity in measurements may be explained by variations in soil pH and texture, and by the presence of livestock and the short term history of the Dahra site, i.e. how livestock have trampled, grazed and deposited manure during the different seasons and at different places. This spatial variation is evidently not represented in the 1D model, where unique soil pH and soil texture are given, as well as a unique input of organic fertilization by livestock excreta.

During the dry season, substrates become less available for microorganisms, and their diffusion is affected by low soil moisture conditions (Xu et al., 2016). The microbial activity slows down gradually and stays low during the dry season (Wang et al., 2015, Borken and Matzner, 2009). De Bruin et al. (1989) have experimentally shown that drying did not kill the microbial biomass during alternating wet/dry conditions at a Sahelian site. It is therefore likely that the transition from activity to dormancy or death at the end of the wet season is too abrupt in the STEP-GENDEC-NOFlux model, leading to smaller NO and CO₂ fluxes than the still rather large measured fluxes. Furthermore, the two first layers of the soil in the model dry up more sharply than what measurements indicate, and the lower modelled soil moisture has an effect on modelled fluxes.

During the wet season, (and just before and after), the link between soil or leaf wetness (related to air humidity) and NH₃ dry deposition is straightforward, as NH₃ is highly soluble in water. Water droplets, and thin water films formed by deliquescent particles on leaf surfaces increase NH₃ dry deposition (Flechard and Fowler, 1998). This process is easily reproduced by the two models used in this study, as shown in Fig. 9 where a net NH₃ dry deposition flux is observed during the wet season.

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5 | With wet season NO fluxes being more than twice higher than dry season fluxes, results emphasize the influence of pulse
emissions in that season. This increase at the onset of the wet season over the Sahel, due to the drastic change in soil
moisture, has been previously highlighted by satellite measurements of the NO₂ column, by Vinken et al. (2014), Hudman et
al. (2012), Jaegle et al. (2004) and Zörner et al. (2016). After the pulses of NO at the beginning of the wet season (Fig. 5),
emissions decrease most likely because the available soil mineral N is used by plants during the growing phase of roots and
green biomass, especially in 2013, and is less available for the production of NO to be released to the atmosphere (Homyak
et al., 2014, Meixner & Fenn 2004, Krul et al., 1982). During the wet season, NO emissions to the atmosphere in the model
are reduced by 18% due to plant uptake (compared to NO emissions when plant uptake is not taken into account). Indeed, N
uptake by plants is enhanced when transpiration increases during the wet season (Appendix C).

4.3 Coupled processes of NO, CO₂ and NH₃ emissions

15 | Larger CO₂ and NO fluxes were seen at the beginning of the wet season (Fig. 5 and 7), compared to the core of the wet
season and to the dry season. This can be explained by the rapid response of the soil decomposers to the increase in soil
moisture leading to a rapid decomposition of the litter buried during the preceding dry season (and a rapid increase in
ammonium as shown in Fig. 6). A pool of enzymes remains in the soil during the dry season and ensures decomposition
with the first rains even when microorganism population is not yet fully developed. Austin et al. (2004) have stated that as
microbial substrates decompose rapidly, microbes will be sufficiently supplied for growth and respiration, involving CO₂
emissions, and the excess N will therefore be mineralized. Indeed, the NH₄⁺ dynamics controls nitrification and volatilization
processes (Schlesinger and Peterjohn, 1991; McCalley et al., 2011). The NH₄⁺ pool may be depleted via nitrification,
20 | involving NO emissions, and in parallel volatilized, involving concomitant NH₃ emissions. On the other hand, a major
depletion of NH₄⁺ pool via nitrification may favour deposition of NH₃ if NH₄⁺ is no more available in the soil to be
volatilized.

25 | During the dry season, as the microbial activity is reduced to its lower limit, the N retention mechanism in microbial biomass
does not work anymore. (N retention is linked to the mineralization of organic C caused by heterotrophic microbial activity
and allows N to be available for plants), and mineral N may accumulate in the soil during this time (Perroni-Ventura et al.,
2010, Austin et al., 2004). Therefore, N loss should neither occur via NH₃ volatilization during that period, nor via NO
emission. Furthermore, the very low soil moisture and air humidity do not stimulate NH₃ deposition on bare soil or
vegetation (if present) during the dry season, knowing that NH₃ is very sensitive to ambient humidity. NH₃, NO and CO₂
fluxes are affected by the same biotic and abiotic factors, including amount of soil organic C, N quantity and availability,
30 | soil oxygen content, soil texture, soil pH, soil microbial communities, hydro-meteorological conditions, amount of above and
below ground biomass, species composition and land use (Xu et al., 2016, Pilegaard et al., 2013, Chen et al., 2013).

At the end of the wet season, the increase of the senescent aboveground biomass increases the quantity of litter which leads
to an input of new organic matter to the soil and therefore a new pool of mineral N available for the production of NO and

NH₃ to be released to the atmosphere, at a time where herbaceous species no longer would benefit from it. This process has been highlighted in Delon et al. (2015) in a similar dry savanna in Mali. Furthermore, NO and NH₃ emissions are suspected to come from the litter itself, as shown in temperate forests by Gritsch et al. (2016), where NO litter emissions increase with increasing moisture.

5 | In the STEP-GENDEC-NOFlux model respiration and soil NO fluxes were significantly correlated ($R^2=0.6$, $p<0.001$,
| slope=0.2, offset=-0.2), but not directly in the measurements, due to the spatial variability of the site. The microbial activity
| is not efficient enough in the model when the soil moisture is low, whereas in measurements, as for NO fluxes, this
| microbial activity seems to remain at a residual level leading to a release of both NO and CO₂ to the atmosphere (Delon et
| al., 2017). A lagged relationship may somehow be displayed in measurements if measured NO fluxes are shifted by 1 day
10 | (i.e. CO₂ is in advance) in J13, then $R^2=0.6$, ($p=0.03$, slope=62.4, offset=-2.5 ($R^2=0.2$ if not shifted), highlighting a lag
| between CO₂ and NO emission processes. If the same lag is applied in model predictions, then $R^2=0.6$, ($p<0.001$), slope=3.3,
| offset=2.0, showing that soil respiration and nitrification processes (causing NO release) are closely linked by microbial
| processes through soil microorganisms that trigger soil respiration and decomposition of soil organic matter (Xu et al., 2008,
| Ford et al., 2007). This one day lag however has to be considered as an open question. The exact lag duration should be
15 | studied more thoroughly, but highlights anyway the close relationship between processes of nitrification and respiration.

5 Conclusions

This study has shown that NH₃, NO and CO₂ exchanges between the soil and the atmosphere are driven by the same microbial processes in the soil, presupposing that moisture is sufficient to engage them, and taking into account the very specific climatic conditions of the Sahel region. Indeed, low soil and air water content are a limiting factor in semi-arid regions in N cycling between the surface and the atmosphere, whereas processes of N exchanges rates are enhanced when water content of the exchange zone (where microbial processes occur) becomes more important. The role of soil moisture involved in N and C cycles is remarkable and obvious in initiating microbial and physiological processes. On the contrary, the role of soil temperature is not as obvious because its amplitude of variation is weak compared to soil moisture. Temperature effects are strongly alleviated when soil moisture is low in the dry season, and become again an influencing parameter in the wet season for N exchange. CO₂ respiration fluxes in this study are not influenced by soil temperature variations, overridden by soil moisture variation at the seasonal and annual scale. NH₃ bidirectional fluxes, simulated by two different models, have shown a high sensitivity to the ground emission potential. The possibility of adjusting this parameter to field measurements has greatly improved the capacity of the Surf atm model to fit the observation results.

30 | The understanding of underlying mechanisms, coupling biogeochemical, ecological and physico-chemical process approaches, are very important for an improved knowledge of C and N cycling in semi-arid regions. The contrasted ecosystem conditions due to drastic changes in water availability have important non linear impacts on the biogeochemical N

cycle and ecosystem respiration. This affects atmospheric chemistry and climate, indicating a strong role of coupled surface processes within the earth system. If changes in precipitation regimes occur due to climate change, the reduction of precipitation regimes may affect regions not considered as semi arid until now, and drive them to semi-arid climates involving exchange processes such as those described in this study. Additionally, an increase in demographic pressure leading to increases in livestock density and changes in land uses will cause changes in soil physical and chemical properties, vegetation type and management, important factors affecting N and C exchanges between natural terrestrial ecosystems and the atmosphere.

Author contribution: CD, CGL and DS planned and designed the research. EP and BL developed the Surfadm model, EM, CD and VLD developed the STEP-GENDEC-NOflux model, MA provided model results with Zhang2010 model, RF and TT provided data from the Dahra meteorological station. All authors participated to the writing of the manuscript.

Data availability: data used in this study are not publicly available. They are available upon request from Claire Delon (Claire.delon@aero.obs-mip.fr) for modelling outputs and measurements, and in Delon et al., (2017) for measurements. Data from the meteorological station in Dahar are available upon request from Torbern Tagesson (torbern.tagesson@ign.ku.dk) and Rasmus Fensholt (rf@geo.ku.dk).

Code availability: Surfadm model is available on request from Erwan Personne (erwan.personne@agroparistech.fr). STEP-GENDEC-NOflux is available on request from Eric Mougín (eric.mougin@get.omp.eu). Zhang2010 is available on request from Leiming Zhang (leiming.zhang@ec.gc.ca).

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

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5 **Appendix A: Details on STEP formulations**

<u>Variable</u>	<u>Symbol</u>	<u>Unit</u>	<u>Source</u>
<u>Rainfall</u>	<u>P</u>	<u>mm</u>	<u>Dahra meteorological station</u>
<u>Maximum air temperature</u> <u>Minimum air temperature</u>	<u>$T_{a_{max}}, T_{a_{min}}$</u>	<u>°C</u>	<u>Dahra meteorological station</u>
<u>Incident Global Radiation</u>	<u>R_{glo}</u>	<u>MJ m⁻²</u>	<u>Dahra meteorological station</u>
<u>Mean relative air humidity</u>	<u>Hr</u>	<u>%</u>	<u>Dahra meteorological station</u>
<u>Wind Speed</u>	<u>w_s</u>	<u>m s⁻¹</u>	<u>Dahra meteorological station</u>

▲ Table A1: Daily climatic data of the Dahra station used for the forcing of STEP-GENDEC-NOFlux model.

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<u>Parameter</u>	<u>Symbol</u>	<u>Unit</u>	<u>Value</u>	<u>Source</u>
<u>Latitude</u>	<u>lat</u>	<u>°</u>	<u>15°24'10"N</u>	<u>GPS measurement</u>
<u>Longitude</u>	<u>long</u>	<u>°</u>	<u>15°25'56"W</u>	<u>GPS measurement</u>
<u>Soil depth</u>	<u>Sd</u>	<u>m</u>	<u>3</u>	<u>measurement</u>
<u>Number of soil layers</u>	<u>Ni</u>	<u>z</u>	<u>4</u>	
<u>Thickness of layer i</u>	<u>e_i</u>	<u>cm</u>	<u>2 / 28 / 70 / 200</u>	
<u>Sand content of layer i</u>	<u>Sand_i</u>	<u>%</u>	<u>89 / 89 / 91 / 91</u>	<u>Delon et al. 2017</u>
<u>Clay content of layer i</u>	<u>Clay_i</u>	<u>%</u>	<u>7.9 / 7.9 / 7.4 / 5; 5</u>	<u>Delon et al. 2017</u>
<u>pH value of layer i</u>	<u>pH_i</u>	<u>z</u>	<u>6.4 / 6.4 / 6.4 / 6.4</u>	<u>Delon et al. 2017</u>
<u>Initial water content of layer i</u>	<u>Shum_i</u>	<u>mm</u>	<u>0.4 / 8 / 10 / 38</u>	<u>Field measurement</u>
<u>Initial soil temperature of layer i</u>	<u>Ts_i</u>	<u>°C</u>	<u>23.5 / 23.9 / 28 / 30</u>	<u>Field measurement</u>
<u>Run-off(on) coefficient</u>	<u>C_Ruiss</u>	<u>z</u>	<u>0</u>	<u>Endorehic site</u>
<u>Soil albedo</u>	<u>ω_s</u>	<u>z</u>	<u>0.45</u>	<u>Station scale, satellite</u>
<u>Initial dry mass</u>	<u>BMs0</u>	<u>g m⁻²</u>	<u>10</u>	<u>Delon et al., 2015</u>
<u>Initial litter mass</u>	<u>BMI0</u>	<u>g m⁻²</u>	<u>30</u>	<u>Delon et al., 2015</u>
<u>C3/C4 herb proportion</u>	<u>C3C4</u>	<u>%</u>	<u>43/67</u>	<u>Field measurement</u>
<u>Dicotyledon. contribution</u>	<u>Dicot</u>	<u>%</u>	<u>43</u>	<u>Field measurement</u>
<u>Root mass proportion of layer i</u> (layers 2 to 4)	<u>Root</u>	<u>%</u>	<u>75 / 20 / 5</u>	<u>Mougin et al. (1995)</u>
<u>Initial soil Carbon content</u>	<u>Cs</u>	<u>gC m⁻²</u>	<u>50</u>	<u>Unpublished data</u>
<u>Initial soil N content</u>	<u>Ns</u>	<u>gN m⁻²</u>	<u>3</u>	<u>Unpublished data</u>

▲ Table A2: site parameters necessary for initialization of STEP-GENDEC-NOFlux model.

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Parameter	Symbol	Unit	Value [range]	Source
<u>Vegetation albedo</u>	ω_v	-	<u>0.2</u>	<u>Station measurement, satellite</u>
<u>Canopy Extinction coefficient for green vegetation</u>	k_c	-	<u>0.475</u>	<u>Mougin et al., 2014</u>
<u>PAR extinction coefficient</u>	k_{fAPAR}	-	<u>0.581</u>	<u>Mougin et al., 2014</u>
<u>Maximum conversion efficiency</u>	ϵ_{max}	gDM MJ^{-1}	<u>4 [4 - 8]</u>	<u>Scaling parameter</u>
<u>Initial aboveground green mass</u>	BMg0	g m^{-2}	<u>0.8 [0.1, 3]</u>	<u>Scaling parameter</u>
<u>Specific Plant Area at emergence</u>	SLAg0	$\text{m}^2 \text{g}^{-1}$	<u>0.018 [0.01 - 0.03]</u>	<u>Scaling parameter</u>
<u>Slope of the relation SLA(t)</u>	k_{SLA}	-	<u>0.028</u>	<u>Unpublished data (Mougin)</u>
<u>Specific Plant Area for dry mass</u>	SLAd	$\text{m}^2 \text{g}^{-1}$	<u>0.0144</u>	<u>Unpublished data (Mougin)</u>
<hr/>				
<u>Shoot maintenance respiration cost</u>	m_{ss}	<u>(-)</u>	<u>0.015</u>	<u>Breman & de Ridder, 1991</u>
<u>Root maintenance respiration cost</u>	m_{gr}	<u>(-)</u>	<u>0.01</u>	<u>Breman & de Ridder, 1991</u>
<u>Shoot growth conversion efficiency</u>	Y_G	<u>(-)</u>	<u>0.75</u>	<u>McCree, 1970</u>
<u>Root growth conversion efficiency</u>	Y_{Gr}	<u>(-)</u>	<u>0.8</u>	<u>Bachelet et al., 1989</u>
<u>Green mass senescence rate</u>	s	d^{-1}	<u>0.00191</u>	<u>Mougin et al., 1995</u>
<u>Live root senescence rate</u>	s_r	d^{-1}	<u>0.00072</u>	<u>Nouvellon, 2000</u>
<u>Optimal temperature for photosynthesis</u>	T_{max}	$^{\circ}\text{C}$	<u>38</u>	<u>Penning de Vries & Djitèye, 1982</u>

<u>Leaf water potential for 50% stomatal closure</u>	$\Psi_{1/2}$	MPa	0.6	<u>Rambal & Cornet, 1982</u>
<u>Shape parameter</u>	n	(-)	5	<u>Rambal & Cornet, 1982</u>
<u>Minimum stomatal resistance</u>	r_{s_min}	$d\ m^{-1}$	100	<u>Körner et al. 1979</u>
<u>Parameters of the canopy height curve</u>	a, b, c	(-)	-0.0000024, 0.0055, 0.047	<u>Mougin et al., 1995</u>
<u>Infiltration time constant</u>	K_i	$cm\ d^{-1}$	1200/ 120/ 120/ 80	<u>Casnavé & Valentin, 1989</u>
<u>Parameters of the soil water resistance equation</u>	a_s, b_s	(-)	4140, 805	<u>Camillo & Gurney, 1986</u>
<u>Parameters of the soil characteristic retention curve</u>	a_i b_i	(-)	3.95/5.42/6.97/9.80 2.93/2.71/2.59/2.43	<u>Modified from Cornet, 1981</u>
<u>Field capacity</u>	FC_i	$m^3\ m^{-3}$	0.093/0.093/0.086/ 0.081	<u>Prescribed</u>
<u>Psychrometric constant</u>	γ	Bar C^{-1}	0.00066	<u>Monteith, 1995</u>
<u>Allocation factor</u>	a_factor	(-)	0.5 [0.1]	<u>Mougin et al., 1995</u>

Table A3: model parameters used to run STEP-GENDEC-NOFlux model.

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<u>Equations</u>	<u>Parameters, Variables, constants</u>	<u>Unit</u>	<u>Source</u>
<u>Soil Temperature</u>			
$T_{s_{max}} = T_{a_{max}} + (Er + 0.35T_{a_{max}}) \times Eb$ $T_{s_{min}} = T_{a_{min}} + 0.006BMg - 1.82$ $Er = 24.07(1 - \exp(-0.000038Rglo))$ $Eb = \exp(-0.0048BMg) - 0.13$	$T_{s_{max(min)}}$ =max(min) soil temperature $T_{a_{max(min)}}$ =max(min) air temperature $Rglo$ =global radiation BMg =Above ground green mass	°C °C kJ m ⁻² gDM m ⁻²	Parton et al., 1984
<u>Carbon budget</u>			
$Vcft = 1 - \exp(-k_c LAI)$	$Vcft$ =Total vegetation cover fraction LAI =Leaf Area Index k_c = Canopy Extinction coefficient for green vegetation (Tab. A3)	m ² m ⁻² m ² m ⁻² (-)	Mougin et al., 2014
$Vcfg = Vcft(LAIg/LAI)$ $Vcfd = Vcft(LAId/LAI)$ $LAIg = SLAg * BMg$ $LAId = SLAd * BMd$ $LAI = LAIg + LAId$	$Vcfg$ =green vegetation cover fraction $Vcfd$ =dry vegetation cover fraction $LAIg$ =green LAI $LAId$ =dry LAI LAI =total LAI BMd =above ground dry mass	m ² m ⁻² m ² m ⁻² m ² m ⁻² m ² m ⁻² m ² m ⁻² m ² m ⁻²	Mougin et al., 2014 Mougin et al., 1995
$SLAg = SLAg0 \exp(-k_{SLA} t)$	$SLAg$ =specific green leaf area $SLAd$ =specific plant area for dry mass (TabA3) k_{SLA} =Constant slope (Tab A3) $SLAg0$ =scaling parameter (TabA3) t =time	m ⁻² kg ⁻¹ m ⁻² kg ⁻¹ (-) m ² kg ⁻¹ s	Mougin et al., 1995
<u>Water budget</u>			

Tableau mis en forme

<p>if $P < 5$ $I = P$; if $P > 5$ $I = P + C \cdot \text{Ruiss}(2P-10)$</p>	<p>P=Precipitation I=Infiltration C Ruiss=runoff coefficient</p>	<p>mm d^{-1} mm d^{-1} (-)</p>	<p>Hiernaux, 1984</p>
<p>$dW_i/dt = I - E_i - D_i$ $dW_i/dt = D_{i-1} - E_i - Tr_i - D_i$</p>	<p>i=first soil layer, $i=2$ to 4 W_i=Water content in layer i E_i=Evaporation in layer i D_i=Drainage in layer i Tr_i=Transpiration in layer i</p>	<p>mm d^{-1} mm d^{-1} mm d^{-1} mm d^{-1} mm d^{-1}</p>	<p>Manabe, 1969</p>
<p>if $W_i > FC$ $D_i = (D_{i-1} - FC_i)/Ak_i$ with $Ak_i = e_i / K_i$</p>	<p>FC_i=Field capacity in layer i (Tab. 3) Ak_i=time constant e_i=layer depth (Tab. A3) K_i=Infiltration time constant (Tab. A3)</p>	<p>mm d^{-1} d^{-1} cm cm d^{-1}</p>	
<p>$\Psi_{s,i} = a_i W_i^{b_i}$</p>	<p>$\Psi_{s,i}$=Soil water potential in layer i W_i=Water content in layer i a_i=retention curve parameter b_i=retention curve parameter</p>	<p>MPa</p>	
<p>$W_{s,i} = 0.332 - 7.251 \times 10^{-4} (\text{Sand}_i) +$ $0.1276 \log_{10}(\text{Clay}_i)$</p>	<p>$W_{s,i}$=Soil water content at saturation in layer i Sand_i=Sand content of layer i (Tab. A2) Clay_i=Clay content of layer i (Tab. A2)</p>	<p>$\text{m}^3 \text{m}^{-3}$ % %</p>	<p>Saxton et al., 1986</p>

$\dot{B}M_d = s \dot{B}M_g$	$s =$ Green mass senescence rate (Tab. A3)	d^{-1}
$\dot{B}M_{rd} = s_r \dot{B}M_r$	$s_r =$ dry mass senescence rate (Tab. A3)	d^{-1}
	$\dot{B}M_{rd} =$ dry root mass	$g \text{ DM } m^{-2}$

Table A4: ~~model variables used to run STEP GENDEC NOFlux. DM=Dry Matter. Equations, variables, parameters and constants used in STEP. Variables are in italics. DM=Dry Matter.~~

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Appendix B – Equations used in NOflux for NO flux calculation from ANN parameterization.

$$\text{NOFlux} = c_{15} + c_{16} \times \text{NOfluxnorm} \text{ in } kgN \text{ ha}^{-1} d^{-1}$$

$$\text{NOfluxnorm} = w_{24} + w_{25} \tanh(S1) + w_{26} \tanh(S2) + w_{27} \tanh(S3)$$

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where NOfluxnorm is the normalized NO flux

$$S1 = w_0 + \sum_{i=1}^7 w_i x_{j, norm}$$

$$S2 = w_8 + \sum_{i=9}^{15} w_i x_{j, norm}$$

$$S3 = w_{16} + \sum_{i=17}^{23} w_i x_{j, norm}$$

5 where j is 1 to 7, and $x_{1, norm}$ to $x_{7, norm}$ correspond to the seven normalized inputs, as follows:

j = 1: $x_{1, norm} = c_1 + c_2 \times$ (surface soil temperature),

j = 2: $x_{2, norm} = c_3 + c_4 \times$ (surface WFPS),

j = 3: $x_{3, norm} = c_5 + c_6 \times$ (deep soil temperature),

j = 4: $x_{4, norm} = c_7 + c_8 \times$ (fertilization rate),

10 j = 5: $x_{5, norm} = c_9 + c_{10} \times$ (sand percentage),

j = 6: $x_{6, norm} = c_{11} + c_{12} \times$ pH,

j = 7: $x_{7, norm} = c_{13} + c_{14} \times$ (wind speed).

Soil surface temperature is in °C, surface WFPS in %, deep soil temperature in °C, fertilization rate in $\text{kgN ha}^{-1} \text{d}^{-1}$, sand percentage in %, pH unitless and wind speed in m s^{-1} .

15 Weights w and normalization coefficients c are given in Table B1.

w0	0.561	w14	1.611	C1	-2.454
w1	-0.439	w15	0.134	C2	0.143
w2	-0.435	w16	-0.213	C3	-4.609
w3	0.501	w17	0.901	C4	0.116
w4	-0.785	w18	-5.188	C5	-2.717
w5	-0.283	w19	1.231	C6	0.163
w6	0.132	w20	-2.624	C7	-0.364
w7	-0.008	w21	-0.278	C8	5.577
w8	-1.621	w22	0.413	C9	-1.535
w9	0.638	w23	-0.560	C10	0.055
w10	3.885	w24	0.599	C11	-25.55
w11	-0.943	w25	-1.239	C12	3.158
w12	-0.862	w26	-1.413	C13	-1.183
w13	-2.680	w27	-1.206	C14	0.614

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				C15	3.403
				C16	9.205

▲ Table B1: weights and coefficients for ANN calculation of NO flux.

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Appendix C

In STEP the seasonal dynamics of the herbaceous layer is a major component of the Sahelian vegetation, and is represented through the simulation of the following processes: water fluxes in the soil, evaporation from bare soil, transpiration of the vegetation, photosynthesis, respiration, senescence, litter production, and litter decomposition at the soil surface. Faecal matter deposition and decomposition is also included from the livestock total load given as input parameter.

The N uptake by plants (absorption of mineral N by plant roots) is calculated by the product of the soil water absorption by roots, with the mineral N concentration in the soil water. In the STEP model, daily root absorption is equal to the daily transpiration which depends on climatic conditions (global radiation, air temperature, wind velocity and air relative humidity), soil water potential (water content in soil layers) and hydric potential of the plant which controls its stomatal aperture (and then the transpiration). Transpiration is calculated with the Penman-Monteith equation (Monteith, 1965), in which the stomatal resistance depends on the plant hydric potential, itself depending on the soil moisture and climatic conditions. For equivalent climatic conditions, a dry soil involves a high potential, a closure of stomatas and a reduction of the transpiration. On the contrary, a humid soil involves a low potential, open stomatas and a large transpiration. The plant hydric potential is calculated daily with transpiration equivalent to root absorption, which itself is calculated from the difference between soil and plant potentials (Mougin et al., 1995).

References

Adon M., C. Galy-Lacaux, V. Yoboué, C. Delon, J.P. Lacaux, P. Castera, E. Gardrat, J. Pienaar, H. Al Ourabi, D. Laouali, B. Diop, L. Sigha-Nkamdjou, A. Akpo, J.P. Tathy, F. Lavenu, and E. Mougin: Long term measurements of sulfur dioxide, nitrogen dioxide, ammonia, nitric acid and ozone in Africa using passive samplers, Atmos. Chem. Phys., 10, 7467–7487, doi:10.5194/acp-10-7467-2010, 2010

Adon M., C. Galy-Lacaux, C. Delon, V. Yoboue, F. Solmon, and A.T. Kaptue Tchunte: Dry deposition of nitrogen compounds (NO₂, HNO₃, NH₃), sulfur dioxide and ozone in west and central African ecosystems using the inferential method, Atmos. Chem. Phys., 13, 11351–11374, doi:10.5194/acp-13-11351-2013, 2013

Archibald, SA; A. Kirton, M.R. van der Merwe, R.J. Scholes, C.A. Williams, N. Hanan, Drivers of inter-annual variability in Net Ecosystem Exchange in a semi-arid savanna ecosystem, South Africa. Biogosciences, 6: 251-266, 2009.

- .Assouma M. H, D. Serça, F. Guerin, V. Blanfort, P. Lecomte, I. Traoré, A. Ickowicz, R.J. Manlay, M. Bernoux, and J. Vayssières Livestock induces strong spatial heterogeneity of soil CO₂, N₂O, CH₄ emissions within a semi-arid sylvo-pastoral landscape in West Africa, *Journal of Arid Land*, 10 doi: 10.1007/s40333-017-0001-y, 2017.
- Austin, A. T., Yahdjian, L., Stark, J. M., Belnap, J., Porporato, A., Norton, U., Ravetta, D. A., and Schaeffer, S. M.: Water pulses and biogeochemical cycles in arid and semi-arid ecosystems, *Oecologia*, 141, 221–235, 2004.
- Bachelet D., Hunt HW, Detling JK A, simulation model of intraseasonal carbon and nitrogen dynamics of blue grama swards as influenced by above-ground and belowground grazing, *Ecological Modeling* Volume: 44 Issue: 3-4 Pages: 231-252, 1989.
- Bai E., S. Li, W. Xu, W. Li, W. Dai and P. Jiang, A meta-analysis of experimental warming effects on terrestrial nitrogen pools and dynamics, *New Phytologist*, 199: 441–451, 2013.
- 10 Bobbink, R., Hicks, K., Galloway, J., Spranger, T., Alkemade, R., Ashmore, M., Cinderby, S., Davidson, E., Dentener, F., Emmett, B., Erisman, J., Fenn, M., Nordin, A., Pardo, L., Vries, W. De, Hicks, K., Galloway, J., Bobbink, R., Davidson, E., Dentener, F., Cinderby, S., Spranger, T., Bustamante, M., Global assessment of nitrogen deposition effects on terrestrial plant diversity. *Ecol. Appl.* 20, 30–59. doi:10.1890/08-1140.1, 2010.
- Breman, H., and de Ridder, N., Manuel sur les pâturages des pays sahéliens, DLO, Centre de Recherches Agrobiologiques, 15 Wageningen, 1991.
- Borken, W., and E. Matzner, Reappraisal of drying and wetting effects on C and N mineralization and fluxes in soils. *Global Change Biology*, 15:808–824, 2009.
- Butterbach-Bahl, K., Stange, F., Papen, H., and Li, C (2001), Regional inventory of nitric oxide and nitrous oxide emissions for forest soils of southeast Germany using the biogeochemical model PnET-N-DNDC, *J. Geophys. Res.* 106, 34155–34166.
- 20 Butterbach-Bahl K, M. Kahl, L. Mykhayliv, C. Werner, R. Kiese, C. Li, A European-wide inventory of soil NO emissions using the biogeochemical models DNDC/Forest-DNDC, *Atmospheric Environment* 43, 1392–1402, 2009.
- Camillo, P. J., & Gurney, R. J., A resistance parameter for bare soil evaporation models. *Soil Sciences*, 141, 95 – 105, 1986.
- Casenave, A. and Valentin, C., Les états de surface de la zone sahélienne: influence sur l'infiltration. Ed. de l'ORSTOM, 229 pp, 1990.
- 25 Chen W., X Zheng, Q. Chen, B. Wolf, K. Butterbach-Bahl, N. Brüggemann, S. Lin, Effects of increasing precipitation and nitrogen deposition on CH₄ and N₂O fluxes and ecosystem respiration in a degraded steppe in Inner Mongolia, China, *Geoderma* 192, 335–340, 2013.
- B.J. Choudhury, J.L. Monteith, A four-layer model for the heat budget of homogeneous land surfaces *Q.J.R. Meteorol. Soc.*, 11, pp. 373–398, 1988.
- 30 Conrad, R, Soil microorganisms as controllers of atmospheric trace gases (H₂, CO, CH₄, OCS, N₂O, and NO), *Microbiol. Rev.*, 60, 609–640, 1996.
- De Bruin B., F. W. T. Penning de Vries, L. W. Van Broekhoven, N. Vertregt, and S. C. Van de Geijn, Net mineralization, nitrification and CO₂ production in alternating moisture conditions in an unfertilized low humus sandy soil from the Sahel, *Plant Soil*, 113, 69–78, 1989.

- Delgado-Baquerizo M., F.T. Maestre, A. Gallardo, M.A. Bowker, M.D. Wallenstein, J.L. Quero, V. Ochoa, B. Gozalo, M. García-Gomez, S. Soliveres, P. García-Palacios, M. Berdugo, E. Valencia, C. Escolar, T. Arredondo, C. Barraza-Zepeda, D. Bran, J.A. Carreira, M. Chaieb, A.A. Conceição, M. Derak, D.J. Eldridge, A. Escudero, C.I. Espinosa, J. Gaitán, M. Gabriel Gatica, S. Gómez-González, E. Guzman, J.R. Gutiérrez, A. Florentino, E. Hepper, R.M. Hernández, E. Huber-Sannwald, M. Jankju, J. Liu, R.L. Mau, M. Miriti, J. Moneris, K. Naseri, Z. Noumi, V. Polo, A. Prina, E. Pucheta, E. Ramírez, D.A. Ramírez-Collantes, R. Romão, M. Tighe, D. Torres, C. Torres-Díaz, E.D. Ungar, J. Val, W. Wamiti, D. Wang & E. Zaady, Decoupling of soil nutrient cycles as a function of aridity in global drylands, doi:10.1038/nature12670, *Nature*, Vol. 502, 2013.
- 5 Delon, C., Serça, D., Boissard, C., Dupont, R., Dutot, A., Laville, de Rosnay, P., and Delmas, R., Soil NO emissions modelling using artificial neural network, *Tellus*, 59B, 502–513, 2007.
- 10 Delon, C., Galy-Lacaux, C., Boone, A., Liousse, C., Serça, D., Adon, M., Diop, B., Akpo, A., Lavenu, F., Mougín, E., and Timouk, F, Atmospheric nitrogen budget in Sahelian dry savannas, *Atmos. Chem. Phys.*, 10, 2691–2708, doi:10.5194/acp-10-2691-2010, 2010.
- Delon, C., Galy-Lacaux, C., Adon, M., Liousse, C., Serça, D., Diop, B., and Akpo, A., Nitrogen compounds emission and deposition in West African ecosystems: comparison between wet and dry savanna, *Biogeosciences*, 9, 385–402, doi:10.5194/bg-9-385-2012, 2012.
- 15 Delon C., E. Mougín, D. Serça, M. Grippa, P. Hiernaux, M. Diawara, C. Galy-Lacaux¹, and L. Kergoat, Modelling the effect of soil moisture and organic matter degradation on biogenic NO emissions from soils in Sahel rangeland (Mali), *Biogeosciences*, 12, 3253–3272, 2015.
- 20 Delon C., C. Galy-Lacaux, D. Serça, B. Loubet, N. Camara, E. Gardrat, , I. Saneh, R. Fensholt, T. Tagesson, V. Le Dantec, B. Sambou, C. Diop, E. Mougín, Soil and vegetation-atmosphere exchange of NO, NH₃, and N₂O from field measurements in a semi-arid grazed ecosystem in Senegal, *Atmospheric Environment* 156, 36-51, 2017.
- Diawara, M.. Impact de la variabilité climatique au nord Sahel (Gourma) sur la dynamique des ressources pastorales et leurs conséquences sur les productions animales (Ph.D. thesis), Toulouse Univ., 150 p., 2015.
- 25 Diawara M., 2 2 2 P. Hiernaux , E. Mougín , M. Grippa , C. Delon et H.S. Diakité, Effets de la pâture sur la dynamique de la végétation herbacée au Sahel (Gourma, Mali) : une approche par modélisation, *Cahiers de l’Agriculture*, 27, 15010, 2018.
- Elberling B., R. Fensholt, L. Larsen, A-I. S. Petersen & I. Sandholt, Water content and land use history controlling soil CO₂ respiration and carbon stock in savanna soil and groundnut fields in semi-arid Senegal, *Geografisk Tidsskrift-Danish Journal of Geography*, 103:2, 47-56, DOI: 10.1080/00167223.2003.10649491,2003.
- 30 Farquhar, G. D., Firth, P. M., Wetselaar, R., and Weir, B, On the gaseous exchange of ammonia between leaves and the environment: determination of the ammonia compensation point, *Plant Physiol.*, 66, 710–714,1980.
- Flechard C.R. and D. Fowler, Atmospheric ammonia at a moorland site. II: Long-term surface-atmosphere micrometeorological flux measurements, *Q. J. R. M. S.*, Volume 124, Issue 547, Part A, Pages 759–791,1998.

- Flechard C.R., R.-S. Massad, B. Loubet, E. Personne, D. Simpson, J. O. Bash, E. J. Cooter, E. Nemitz, and M. A. Sutton, Advances in understanding, models and parameterizations of biosphere-atmosphere ammonia exchange, *Biogeosciences*, 10, 5183–5225, 2013.
- Ford D.J., W.R. Cookson, M.A. Adams, P.F. Grierson, Role of soil drying in nitrogen mineralization and microbial
5 community function in semi-arid grasslands of north-west Australia, *Soil Biology & Biochemistry* 39, 1557–1569, 2007.
- Fowler D., C. E. Steadman, D. Stevenson, M. Coyle, R. M. Rees, U. M. Skiba, M. A. Sutton, J. N. Cape, A. J. Dore, M. Vieno, D. Simpson, S. Zaehle, B. D. Stocker, M. Rinaldi, M. C. Facchini, C. R. Flechard, E. Nemitz, M. Twigg, J. W. Erisman, K. Butterbach-Bahl, and J. N. Galloway, Effects of global change during the 21st century on the nitrogen cycle, *Atmos. Chem. Phys.*, 15, 13849–13893, 2015.
- 10 Gritsch C., F. Egger, F. Zehetner, and S. Zechmeister-Boltenstern, The effect of temperature and moisture on trace gas emissions from deciduous and coniferous leaf litter, *J. Geophys. Res. Biogeosci.*, 121, 1339–1351, doi:10.1002/2015JG003223, 2016.
- Hanan, N., N. Boulain, C. Williams, R. Scholes, and S. Archibald, Functional convergence in ecosystem carbon exchange in adjacent savanna vegetation types of the Kruger National Park, South Africa. In: M.J. Hill and N. Hanan (Editors),
15 *Ecosystem Function in Savannas*. CRC Press, Boca Raton, pp. 57-76, 2011.
- Hanan, N., P. Kabat, J. Dolman, and J.A.N. Elbers, Photosynthesis and carbon balance of a Sahelian fallow savanna. *Global Change Biol.*, 4(5): 523-538, 1998.
- Harms, T. K., and N. B. Grimm, Responses of trace gases to hydrologic pulses in desert floodplains, *J. Geophys. Res.*, 117, G01035, doi:10.1029/2011JG001775, 2012.
- 20 Hiernaux P., Fernandez-Rivera, S., Schlecht, E., Turner, M. D., and Williams, T. O., Livestock-mediated nutrient transfers in Sahelian agro-ecosystems, edited by: Renard, G., Neef, A., Becker, K., and von Oppen, M., *Soil fertility management in West African land use systems*, Niamey, Niger, 4-8.03.97, Margraf Verlag, Weikersheim, Germany, 339–347, 1998.
- Hiernaux, P. and Turner, M. D, The influence of farmer and pastoralism management practices on desertification processes in the Sahel, in: *Global desertification: do humans cause deserts?*, edited by: Reynolds, J. F. and Stafford Smith, D. M.,
25 Dahlem University Press, Berlin, 135–148, 2002.
- Homyak PM, Sickman J.O., Influence of soil moisture on the seasonality of nitric oxide emissions from chaparral soils, Sierra Nevada, California, USA. *Journal of Arid Environments*, 103, 46-52, 2014.
- Homyak P.M., M. Kamiyama, J.O. Sickman, and J. P. Schimel, Acidity and organic matter promote abiotic nitric oxide production in drying soils, *Global Change Biology*, doi: 10.1111/gcb.13507, 2016.
- 30 Hudman, R. C., Moore, N. E., Mebust, A. K., Martin, R. V., Russell, A. R., Valin, L. C., and Cohen, R. C., Steps towards a mechanistic model of global soil nitric oxide emissions: implementation and space based-constraints, *Atmos. Chem. Phys.*, 12, 7779–7795, doi:10.5194/acp-12-7779-2012, 2012.

- Jaeglé, L., Martin, R. V., Chance, K., Steinberger, L., Kurosu, T. P., Jacob, D. J., Modi, A. I., Yoboué, V., Sigha-Nkamdjou, L., and Galy-Lacaux, C., Satellite mapping of rain-induced nitric oxide emissions from soils, *J. Geophys. Res.*, 109, D21310, doi:10.1029/2003JD004406, 2004.
- Jia B., G. Zhou, Y. Wang, F. Wang, X. Wang, Effects of temperature and soil water-content on soil respiration of grazed and ungrazed *Leymus chinensis* steppes, Inner Mongolia, *Journal of Arid Environments* 67, 60–76, 2006.
- Jones, H. G., *Plants and Microclimate. A Quantitative Approach to Environmental Plant Physiology*, 2nd ed., Cambridge University Press, Cambridge, 428 pp, 1992.
- Körner, C. H., Scheel, J. A., and Bauer, H., Maximum leaf diffusive conductance in vascular plants, *Photosynthetica* 13(1):45-82, 1979.
- 10 Krul J.M., FWT Penning de Vries, K Traore, Les processus du bilan d'azote, in "La productivité des pâturages sahéliens", Eds Penning De Vries FWT and Traoré F, pp 226-246, Wageningen, 1982.
- Laouali D., Galy-Lacaux, C., Diop, B., Delon, C., Orange, D., Lacaux, J. P., Akpo, A., Lavenue, F., Gardrat, E., and Castera, P., Long term monitoring of the chemical composition of precipitation and wet deposition fluxes over three Sahelian savannas, *Atmos. Environ.*, 50, 314–327, 2012.
- 15 LI-COR Biosciences, EDDYPRO Eddy Covariance Software Version 4.0 User's Guide & Reference. LI-COR Inc., Lincoln, 200 pp, 2012.
- Liu, K., Crowley, D., Nitrogen deposition effects on carbon storage and fungal: bacterial ratios in coastal sage scrub soils of southern California. *J. Env. Qual.* 38, 2267-2272, 2009.
- Lloyd, J. and Taylor, J.A., On the temperature dependence of soil respiration. *Funct. Ecol.*, 8(3): 315-323, 1994.
- 20 Loubet B., C. Decuq, E. Personne, R. S. Massad , C. Flechard, O. Fanucci, N. Mascher, J.-C. Gueudet , S. Masson, B. Durand, S. Genermont, Y. Fauvel, and P. Cellier, Investigating the stomatal, cuticular and soil ammonia fluxes over a growing tritical crop under high acidic loads *Biogeosciences*, 9, 1537–1552, 2012.
- Loubet B., M. Carozzi, P. Voylokov, J.-P. Cohan, R. Trochard, and S. Générmont, Evaluation of a new inference method for estimating ammonia volatilisation from multiple agronomic plots, *Biogeosciences*, 15, 3439–3460, 2018.
- 25 ▲ Manabe, S., Climate and the Ocean circulation: 1. The atmospheric circulation and the hydrology of the earth's surface. *Monthly Weather Review*, 97, 739 – 774, 1969.
- Massad, R.-S., Nemitz, E., and Sutton, M. A., Review and parameterisation of bi-directional ammonia exchange between vegetation and the atmosphere, *Atmos. Chem. Phys.*, 10, 10359–10386, doi:10.5194/acp-10-10359-2010, 2010.
- 30 McCalley, C. K. and Sparks, J. P., Controls over nitric oxide and ammonia emissions from Mojave Desert soils, *Oecologia*, 156, 871–881, 2008.
- McCree, K. J., An equation for the rate of respiration of white clover plants grown under controlled conditions, in *Prediction and Measurements of Photosynthetic Productivity* (I. Setlik, Ed.), Pudoc, Wageningen, pp. 221-229, 1970.

Mis en forme : Sans interligne

Mis en forme : Anglais (États-Unis)

- Medinets S., Skiba, U., Rennenberg, H., and Butterbach-Bahl, K., A review of soil NO transformation: Associated processes and possible physiological significance on organisms, *Soil Biol. Biochem.*, 80, 92–117, 2015.
- Meixner T. and M. Fenn, Biogeochemical budgets in a Mediterranean catchment with high rates of atmospheric N deposition – importance of scale and temporal asynchrony, *Biogeochemistry* 70: 331–356, 2004.
- 5 Monteith, J. L., *Evaporation and environment in state and movement of water in living organisms* (19th symposium of the society for Experimental Biology) (pp. 205–234). UK: Cambridge University Press, 1965.
- Monteith J.L., M.H. Unsworth, *Principles of Environmental Physics*, Edward Arnold, London, p. 291, 1990.
- Moorhead, D. L. and Reynolds, J. F., A general model of litter decomposition in the northern Chihuahuan desert, *Ecol. Modell.*, 56, 197–219, 1991.
- 10 Mougin E., Lo Seen D., Rambal S., Gaston A., and Hiernaux P., A Regional Sahelian Grassland Model To Be Coupled with Multispectral Satellite Data. I: Model Description and Validation, *Remote Sens. Environ.*, 52, 181–193, 1995.
- Nemitz, E., Milford, C., and Sutton, M. A., A two-layer canopy compensation point model for describing bi-directional biosphere/atmosphere exchange of ammonia, *Q. J. Roy. Meteor. Soc.*, 127, 815–833, 2001.
- Nouvellon Y., Rambal S., Lo Seen D., Moran M.S., Lhomme J.P., Bégué A., Chehbouni A.G., Kerr, Y., Modelling of daily fluxes of water and carbon from shortgrass steppes. *Agricultural and Forest Meteorology*, 100, 137–153, 2000.
- 15 Parton, W. J.: Predicting soil temperatures in a shortgrass steppe, *Soil Sci.*, 138, 93–101, 1984.
- Penning de Vries, F. W. T., and Djitéye, M. A., *La productivité des pâturages sahéliens. Une étude des sols, des végétations et de l'exploitation de cette ressource naturelle*, Agric. Res. Rep. 918, Pudoc, Wageningen, 525 pp, 1982.
- Perroni-Ventura Y., C. Montaña and F. García-Oliva., Carbon-nitrogen interactions in fertility island soil from a tropical semi-arid ecosystem, *Functional Ecology*, 24, 233–242, doi: 10.1111/j.1365-2435.2009.01610.x, 2010.
- 20 Personne, E., Loubet, B., Herrmann, B., Mattsson, M., Schjoerring, J. K., Nemitz, E., Sutton, M. A., and Cellier, P., Surfatm-NH₃: a model combining the surface energy balance and bi-directional exchanges of ammonia applied at the field scale, *Biogeosciences*, 6, 1371–1388, doi:10.5194/bg-6-1371-2009, 2009.
- Pilegaard K., Processes regulating nitric oxide emissions from soils, *Phil. Trans. R. Soc. B* 2013 368, 20130126, 2013.
- 25 Potter, C. S., Matson, P. A., Vitousek, P. M., and Davidson, E. A., Process modelin of controls on nitrogen trace gas emissions from soils worldwide, *J. Geophys. Res.*, 101, 1361–1377, 1996
- Pumpanen J., P. Kolari, H. Ilvesniemi, K. Minkkinen, T. Vesala, S. Niinistö, A. Lohila, T. Larmola, M. Morero, M. Pihlatie, I. Janssens, J. Curiel Yuste, J.M. Grünzweig, S. Reth, J.-A. Subke, K. Savage, W. Kutsch G. Østreng, W. Ziegler, P. Anthoni, A. Lindroth, P. Hari., Comparison of different chamber techniques for measuring soil CO₂ efflux, *Agricultural and Forest Meteorology* 123, 159–176, 2004
- 30 Rambal, S., and Cornet, A., Simulation de l'utilisation de l'eau et de la production végétale d'une phytocénose sahélienne du Sénégal, *Acta Oecologica Oecol. Plant* 3(17),4: 381-397, 1982.
- Reichstein M., E. Falge, D. Baldocchi, D. Papale, M. Aubinet, P. Berbigier, C. Bernhofer, N. Buchmann, T. Gilmanov, A. Granier, T. Grunwald, K. Havrankova, H. Ilvesniemi, D. Janous, A. Knohl, T. Laurila, A. Lohila, D. Loustau, G. Matteucci,

T. Meyers, F. Miglietta, J.M. Ourcival, J. Pumpanen, S. Rambal, E. Rotenberg, M. Sanz, J. Tenhunen, G. Seufert, F. Vaccari, T. Vesala, D. Yakir and R. Valentini, On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. *Global Change Biol.*, 11(9): 1424-1439, 2005.

5 [Riddick, S. N., Blackall, T. D., Dragosits, U., Daunt, F., Braban, C. F., Tang, Y. S., MacFarlane, W., Taylor, S., Wanless, S., and Sutton, M. A.: Measurement of ammonia emissions from tropical seabird colonies. *Atmos. Environ.*, 89, 35–42, 2014.](#)

[Riddick, S. N., Blackall, T. D., Dragosits, U., Daunt, F., Newell, M., Braban, C. F., Tang, Y. S., Schmale, J., Hill, P. W., Wanless, S., Trathan, P., and Sutton, M. A.: Measurement of ammonia emissions from temperate and sub-polar seabird colonies. *Atmos. Environ.*, 134, 40–50, 2016.](#)

10 Saugier, B., Transport de CO₂ et de vapeur d'eau à l'interface végétation-atmosphère. Thèse Docteur d'Etat, Université des Sciences et Techniques du Languedoc, Montpellier, 156 pp, 1974.

Saxton KE, Rawls WJ, Romberger JS, Papendick RI, Estimating generalized soil-water characteristics from texture, Soil Science Society Of America Journal, Volume 50, Issue 4, pp 1031-1036, 1986.

Schlecht, E. and Hiernaux, P., Beyond adding up inputs andputs: process assessment and upscaling in modelling nutrient flows, *Nutr. Cy. Agroecosys.*, 70, 303–319, 2004.

15 Schlesinger W.H., and W.T. Peterjoh, Processes controlling ammonia volatilization from Chihuahuan desert soils, *Soil Biol. Biochem.* Vol. 23, No. 1, 1991.

Shen W., G. D. Jenerette, D. Hui, and R.L. Scott, Precipitation legacy effects on dryland ecosystem carbon fluxes: direction, magnitude and biogeochemical carryovers, *Biogeosciences*, 13, 425–439, 2016.

Sutton, M.A., Schjørring, J.K., Wyers, G.P., Plant atmosphere exchange of ammonia. *Phil. Trans. R. Soc. London A351* (1656), 261-276, 1995.

20 Sutton M.A., S. Reis, S.N. Riddick, U. Dragosits, E. Nemitz, M.R. Theobald, Y. Sim Tang, C.F. Braban, M. Vieno, A.J. Dore, R.F. Mitchell, S. Wanless, F. Daunt, D. Fowler, T.D. Blackall, C. Milford, C.R. Flechard, B. Loubet, R. Massad, P. Cellier, E. Personne, P.F. Coheur, L. Clarisse, M. Van Damme, Y. Ngadi, C. Clerbaux, C. Ambelas Skjøth, C. Geels, O. Hertel, R.J. Wichink Kruit, R.W. Pinder, J.O. Bash, J.T. Walker, D. Simpson, L. Horváth, T.H. Misselbrook, A. Bleeker, F.

25 Dentener and W. de Vries, Towards a climate-dependent paradigm of ammonia emission and deposition, *Phil Trans R Soc B* 368: 20130166. <http://dx.doi.org/10.1098/rstb.2013.0166>, 2013.

Tagesson, T. and Lindroth, A., High soil carbon efflux rates in several ecosystems in southern Sweden, *Boreal Environ. Res.*, 12: 65–80, 2007

Tagesson, T., R. Fensholt, F. Copley, I. Guiro, S. Horion, A. Ehammer, J. Ardö, Dynamics in carbon exchange fluxes for a
30 grazed semi-arid savanna ecosystem in West Africa. *Agr. Ecosyst. Environ.*, 205: 15-24, 2015a.

Tagesson, T. R. Fensholt, I. Guiro, M.O. Rasmussen, S. Huber, C. Mbow, M. Garcia, S. Horion, I. Sandholt, B. Holm-Rasmussen, F.M. Götsche, M.-E. Ridler, N. Olèn, J.L. Olsen, A. Ehammer, M. Madsen, F.S. Olesen, J. Ardö, Ecosystem properties of semi-arid savanna grassland in West Africa and its relationship to environmental variability. *Global Change Biol.*, 21(1): 250-264, 2015b

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- Tagesson, T., R. Fensholt, B. Cappelaere, E. Mougin, S. Horion, L. Kergoat, H. Nieto, C. Mbow, A. Ehammer, J. Demarty, J. Ardö, Spatiotemporal variability in carbon exchange fluxes across the Sahel Agric. For. Meteorol., 226–227: 108–118, 2016a
- Tagesson T., J. Ardö, I. Guiro, F. Cropley, C. Mbow, S. Horion, A. Ehammer, E. Mougin, C. Delon, C. Galy-Lacaux & R. Fensholt, Very high CO₂ exchange fluxes at the peak of the rainy season in a West African grazed semi-arid savanna ecosystem, Geografisk Tidsskrift-Danish Journal of Geography, <http://dx.doi.org/10.1080/00167223.2016.1178072>, 2016b
- 5 Thornley, JHM; Cannell, MGR, Modelling the components of plant respiration: Representation and realism, Annals of Botany, vol. 85, Issue 6, 937–937, 2000.
- Van Keulen, H., Simulation of water use and herbage growth in arid regions, Simulation Monographs, Pudoc, Wageningen, 10 176 pp, 1975.
- Vinken G. C. M, K. F. Boersma, J. D. Maasackers, M. Adon, and R. V. Martin, Worldwide biogenic soil NO_x emissions inferred from OMI NO₂ observations, Atmos. Chem. Phys., 14, 10363–10381, 2014
- Wang L., S. Manzoni, S. Ravi, D. Riveros-Iregui, and K. Caylor, Dynamic interactions of ecohydrological and biogeochemical processes in water-limited systems, Ecosphere 6(8):133. <http://dx.doi.org/10.1890/ES15-00122.1>, 2015.
- 15 Wichink Kruit, R. J., van Pul, W. A. J., Otjes, R. P., Hofschreuder, P., Jacobs, A. F. G., and Holtslag, A. A. M, Ammonia fluxes and derived canopy compensation points over non-fertilized agricultural grassland in the Netherlands using the new gradient ammonia – high accuracy – monitor (GRAHAM), Atmos. Environ., 41, 1275–1287, 2007
- Xu X., H. Tian, and D. Hui., Convergence in the relationship of CO₂ and N₂O exchanges between soil and atmosphere within terrestrial ecosystems, Global Change Biology 14, 1651–1660, doi: 10.1111/j.1365-2486.2008.01595.x., 2008.
- 20 Xu M. and H. Shang, Contribution of soil respiration to the global carbon equation, Journal of Plant Physiology 203, 16–28, 2016
- Yan, X., Ohara, T., and Akimoto, H., Statistical modelling of global soil NO_x emissions, Global Biogeochem. Cy., 19, GB3019, doi:10.1029/2004GB002276, 2005
- Yienger, J. J. and Levy II, H., Empirical model of global soil biogenic NO_x emissions, J. Geophys. Res., 100, 11447–11464, 25 1995
- Zhang, L., Brook, J. R., and Vet, R., A revised parameterization for gaseous dry deposition in air-quality models, Atmos. Chem. Phys., 3, 2067–2082, doi:10.5194/acp-3-2067-2003, 2003.
- Zhang, L., Wright, P. L., and Asman, W. A. H., Bi-directional air surface exchange of atmospheric ammonia – A review of measurements and a development of a big-leaf model for applications in regional-scale air-quality models, J. Geophys. Res., 30 115, D20310, doi:10.1029/2009JD013589, 2010.
- Zörner J., M. Penning de Vries, S. Beirle, H. Sihler, P.R. Veres, J. Williams, T. Wagner, Multi-satellite sensor study on precipitation-induced emission pulses of NO_x from soils in semi-arid ecosystems, Atmos. Chem. Phys., 16, 9457–9487, doi:10.5194/acp-16-9457-2016, 2016.

Tables

<u>Model (resolution)</u>	<u>Simulated and measured variables (units)</u>	<u>Methods used for measured variables (resolution and reference)</u>
<u>Surfatm (3h)</u>	<u>NH₃ bidirectional fluxes (ngN m⁻² s⁻¹)</u>	<u>Closed dynamic chamber (15 – 20 fluxes a day, Delon et al., 2017)</u>
▲	<u>Soil surface temperature (°C)</u>	<u>Campbell 107 probe (15min, Tagesson et al., 2015a)</u>
▲	<u>Sensible and latent heat fluxes (W m⁻²)</u>	<u>Eddy Covariance (15min, Tagesson et al., 2015a)</u>
<u>Zhang2010 (3h)</u>	<u>NH₃ bidirectional fluxes (ngN m⁻² s⁻¹)</u>	<u>Closed dynamic chamber (15 – 20 fluxes a day, Delon et al., 2017)</u>
<u>STEP (day)</u>	<u>NO biogenic fluxes (ngN m⁻² s⁻¹)</u>	<u>Closed dynamic chamber (15 – 20 fluxes a day, Delon et al., 2017)</u>
▲	<u>CO₂ respiration fluxes (ngN m⁻² s⁻¹)</u>	<u>Closed dynamic chamber (15 – 20 fluxes a day, Delon et al., 2017)</u>
▲	<u>Ammonium content (%)</u>	<u>Laboratory analysis (6 samples/campaign, Delon et al., 2017)</u>
▲	<u>Soil temperature at two depths: 0-2cm and 2-30cm (°C)</u>	<u>Campbell 107 probe at 2 depths: 5 and 10 cm (15min, Tagesson et al., 2015a)</u>
▲	<u>Soil moisture at two depths: 0-2cm and 2-30cm (%)</u>	<u>HH2 Delta probe at 2 depths: 5 and 10 cm (15min, Tagesson et al., 2015a)</u>

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5 Table 1: Summary of different models used in the study, with the variables simulated and compared to measurements. All simulated and measured variables were daily averaged for the purpose of the study.

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5 **Tables**

Description of parameters in Surfalm	Value in this study <u>(range)</u>	Sources
Time step	3 h	
Characteristic length of leaves	0.03 m <u>(0.03-0.5)</u>	<u>Minimum value</u>
Total soil depth	0.92 m	
Soil density	1500 kg.m ⁻³	
Radiation attenuation coefficient in the canopy	0.7 <u>(0.5-0.8)</u>	<u>Estimated</u>
Wind attenuation coefficient in the canopy	2.3 <u>(1.5-5)</u>	<u>Estimated</u>
Initial soil moisture	0.09 kg(H ₂ O)/kg(soil)	<u>Measured</u>
Dry soil moisture	0.02 kg(H ₂ O)/kg(soil)	<u>Measured</u>
Field capacity	0.14 kg(H ₂ O)/kg(soil)	<u>Measured</u>
Wilting point	0.02 kg(H ₂ O)/kg(soil)	<u>Measured</u>
Thermal conductivity of wet soil layers	2.5 W.m ⁻¹ .K ⁻¹ <u>(1.6-2.2)</u>	<u>Estimated</u>
Thermal conductivity of dry soil layers	1.5 W.m ⁻¹ .K ⁻¹ <u>(0.2-0.3)</u>	<u>Estimated</u>
Depth of temperature measurements	0.3 m	<u>Measured</u>
Soil porosity	0.45 <u>(0.25-0.4)</u>	<u>Estimated specifically for semi arid ecosystems</u>
Soil tortuosity	2.5 <u>(2-4)</u>	<u>Estimated specifically for semi arid ecosystems</u>

Table 12: Input parameters for the Surfalm model. Ranges refer to Hansen et al., 2017. All measured parameters refer to Delon et al., 2017.

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Period / NH ₃ fluxes	Measurements (ngN m ⁻¹ s ⁻¹)	Surfatm (ngN m ⁻¹ s ⁻¹)	Zhang2010 (ngN m ⁻¹ s ⁻¹)
J12	1.3±1.1	2.6±2.6	-9.0±0.9
J13	-0.1±1.1	-1.7±2.4	-7.8±2.2
N13	0.7±0.5	-0.2±1.1	-2.8±0.9
2012		-0.9±3.3 (-0.3±1.0 kgN ha ⁻¹ yr ⁻¹)	-3.5±4.6 (-0.3±1.0 kgN ha ⁻¹ yr ⁻¹)
2013		-2.0±3.7 (-0.6±0.3 kgN ha ⁻¹ yr ⁻¹)	-2.7±3.8 (-0.8±1.2 kgN ha ⁻¹ yr ⁻¹)
Dry season		-0.2±1.6	-0.9±2.3
Wet season		-4.3±4.8	-8.1±3.2

Table 3: Averaged NH₃ fluxes for measurements, Surfatm and Zhang2010 models during specific periods. Measurements are available during the 3 field campaigns and not at the annual or seasonal scale.

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Average flux and standard deviation (ngN.m ⁻² .s ⁻¹)	Ftotal (net flux)	Fsoil	Fvegetation (=Fstom + Feut)	Fstom	Feut
Dry seasons Surfatm	-0.2±1.6	0.7±0.6	-0.9±1.7	-0.4±0.8	-0.5±1.2
Wet seasons Surfatm	-4.3±4.8	2.0±1.9	-6.3±3.7	-1.5±2.2	-4.8±2.7
2012-2013 Surfatm	-1.4±3.5	1.1±1.3	-2.5±3.5	-0.7±1.5	-1.8±2.7
Dry seasons Zhang	-0.9±2.3				
Wet seasons Zhang	-8.1±3.2				

2012-2013 Zhang	-3.1±4.2				
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Average flux and standard deviation	Ftotal (net flux) (ngN.m ⁻² .s ⁻¹)	Fsoil (ngN.m ⁻² .s ⁻¹)	Fvegetation (=Fstom + Fcut) (ngN.m ⁻² .s ⁻¹)	Fstom (ngN.m ⁻² .s ⁻¹)	Fcut (ngN.m ⁻² .s ⁻¹)
Dry seasons Surf atm	-0.2±1.6	0.7±0.6	-0.9±1.7	-0.4±0.8	-0.5±1.2
Wet seasons Surf atm	-4.3±4.8	2.0±1.9	-6.3±3.7	-1.5±2.2	-4.8±2.7
2012-2013 Surf atm	-1.4±3.5	1.1±1.3	-2.5±3.5	-0.7±1.5	-1.8±2.7
Dry seasons Zhang	-0.9±2.3	-0.5±2.3	-0.4±0.5	-0.02±0.01	-0.4±0.5
Wet seasons Zhang	-8.1±3.2	-7.3±3.0	-0.8±0.3	-0.03±0.01	-0.7±0.3
2012-2013 Zhang	-3.1±4.2	-2.6±4.0	-0.5±0.4	-0.02±0.01	-0.5±0.4

Table 42: Contributions of vegetation and soil to the total NH₃ flux in SurfAtm, net NH₃ flux in and Zhang2010, wet season mean, dry season mean and annual mean, for both years of simulation.

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Figures

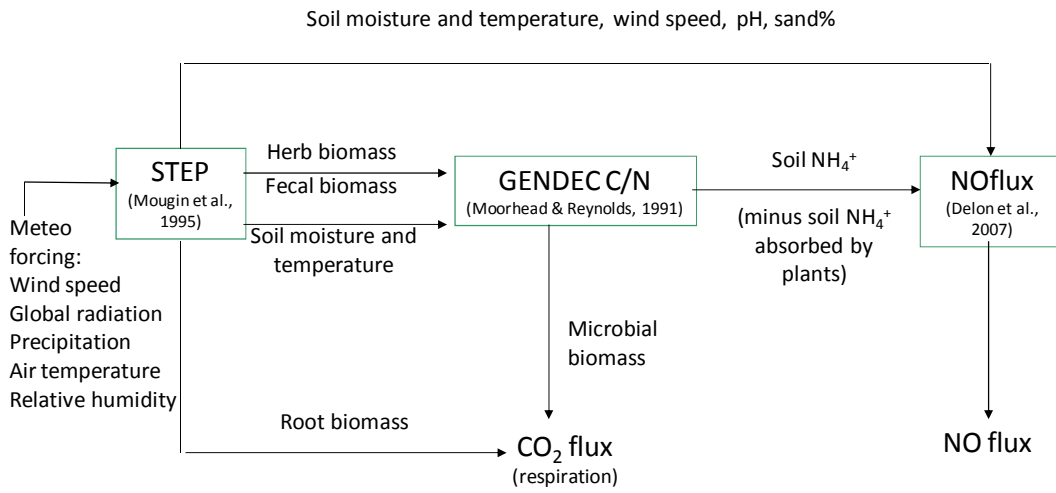


Figure 1: Schematic representation of NO and CO₂ flux modeling in STEP-GENDEC-NOFlux (adapted from Delon et al., 2015).

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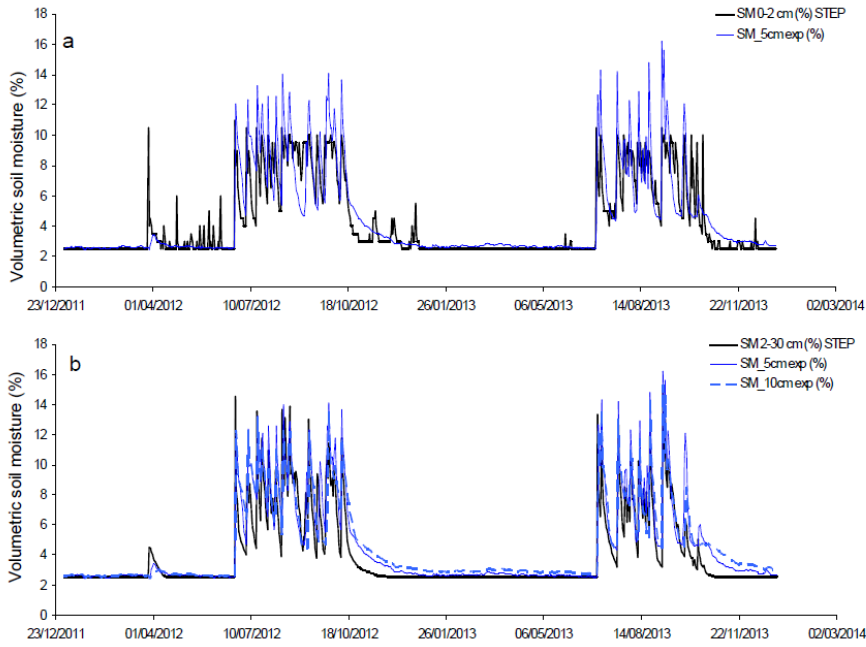
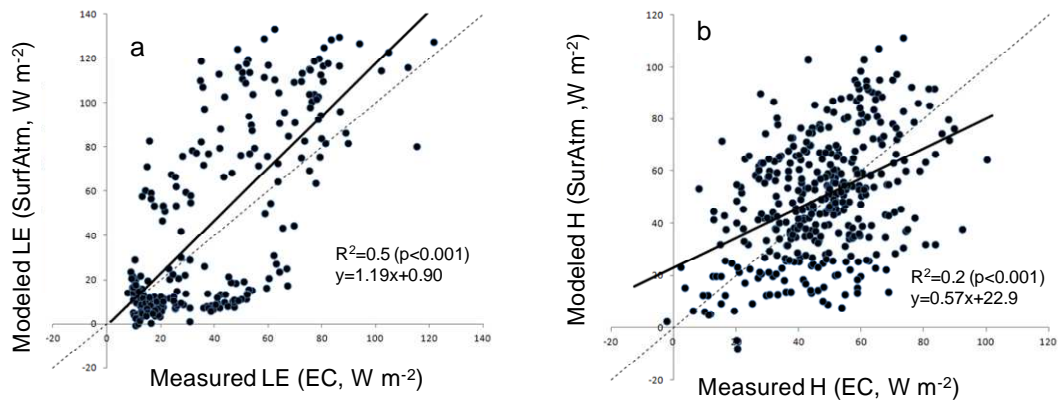


Figure 2 : a) Volumetric soil moisture simulated by STEP in the first layer (0-2cm) in black and soil moisture measured at 5cm in blue, in %, at daily scale. b) Volumetric soil moisture simulated by STEP in the second layer (2-30cm) in black, soil moisture measured at 5cm in blue solid line, measured at 10cm in blue dotted line, in %, at daily scale.

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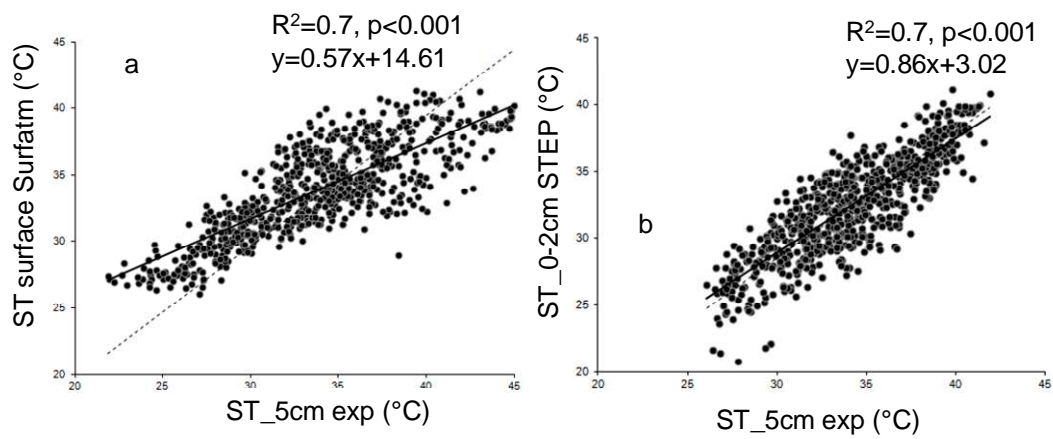


5 | Figure 3: a) Daily Modelled-modelled latent heat flux in SurfAtm vs daily measured latent heat flux, in W/m^2 ; b) Daily Modelled sensible heat flux in SurfAtm vs daily measured sensible heat flux, in W/m^2 . Thick black line is for the linear regression, thin dashed black line is the 1:1 line. Available measured EC data are more numerous for H than for LE due to the criteria applied by the postprocessing (see supplementary material of Tagesson et al. (2015b)).

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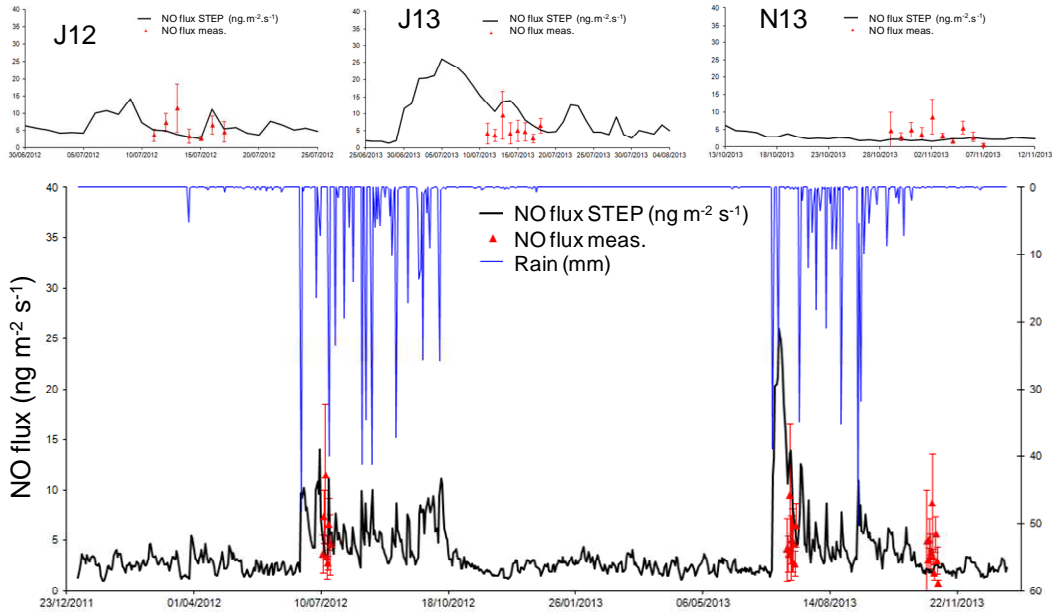
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5 | Figure 4: a) Modelled daily surface temperature in SurfAtm vs measured daily temperature at 5cm depth; b) Modelled daily surface temperature in STEP (0-2cm layer) vs measured daily temperature at 5cm depth. Thick black line is for the linear regression, thin-dashed black line is the 1:1 line.

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5 | Figure 5: Daily NO flux simulated by STEP-GENDEC-NOflux (ngN_x·m⁻²·s⁻¹, black line) and daily averaged NO flux measurements during the 3 field campaigns (blue-red triangles). Error bars in blue in red, give the standard deviation for measurements at the daily scale. Rain is represented by the blue line in mm in the bottom panel. Upper panels give a focus on each field campaign.

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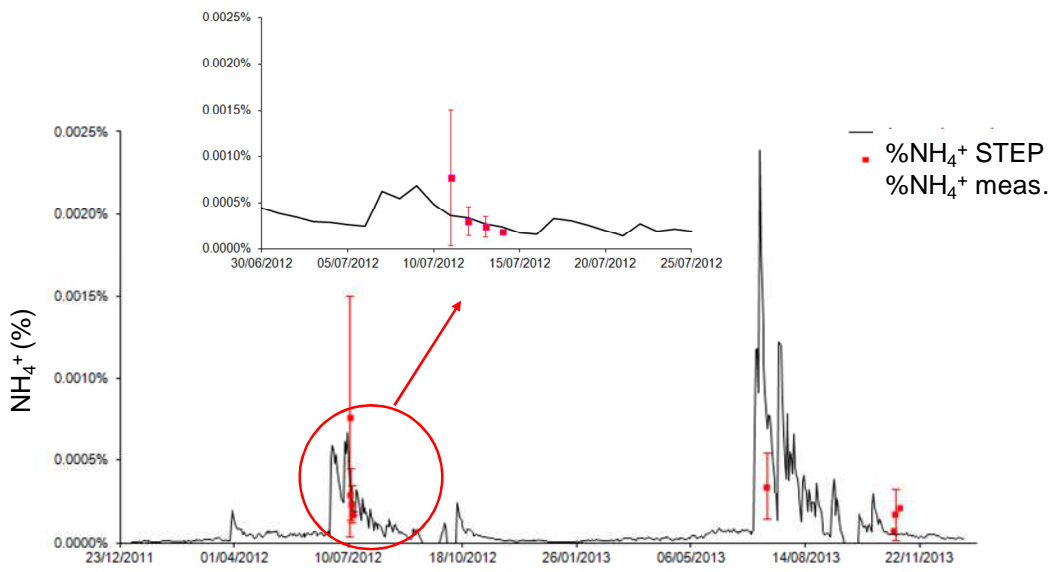
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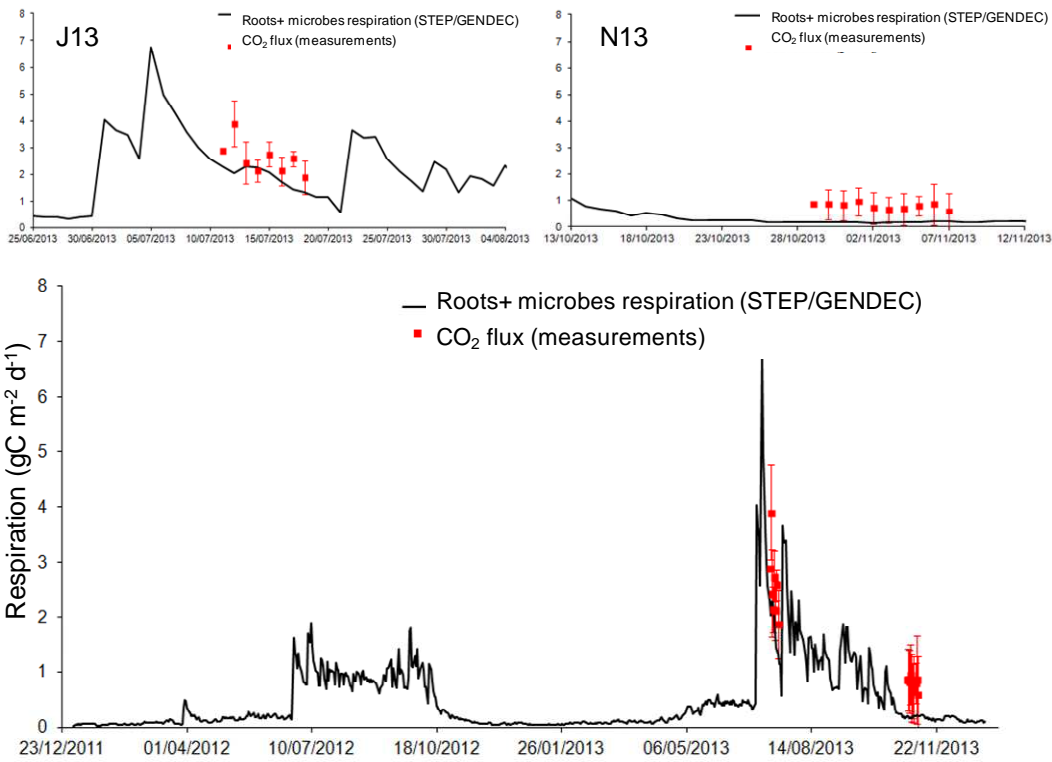


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Figure 6: Daily Ammonium simulated by STEP-GENDEC (% blue-black line) and daily averaged measured-ammonium measurement (pink-red squares) during the field campaigns. Error bars in pink-red give the standard deviation at the daily scale for measurements. The upper panel is a focus of J12.

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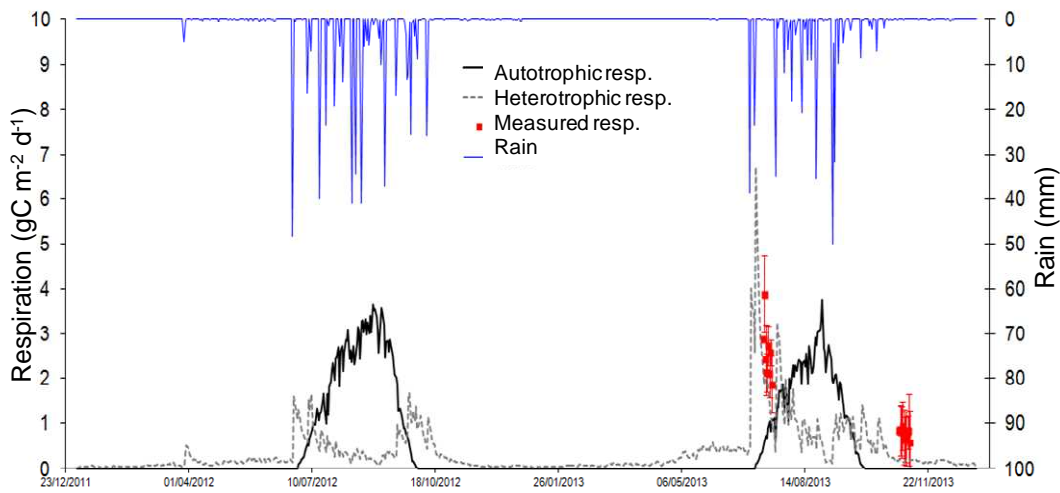
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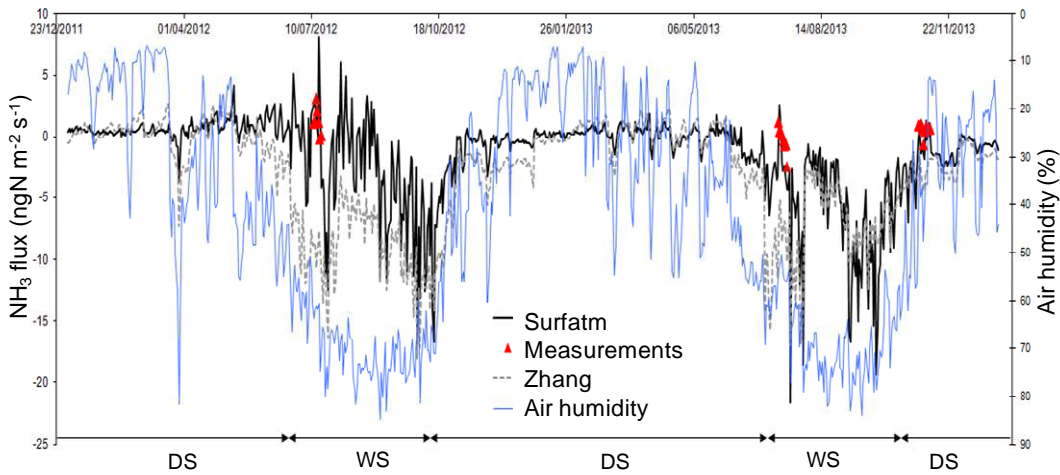
10 Figure 7: Daily Roots and microbes respiration in $\text{mgC}_m^{-2}\text{d}^{-1}$ simulated by STEP-GENDEC (black line), and daily averaged soil respiration measurements (grey-red squares) during 2 field campaigns. Error bars in grey-red give the standard deviation at the daily scale. Upper panels give a focus of J13 and N13 field campaigns.

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Figure 8: **Daily Autotrophic** (roots + green vegetation, black line) and **daily heterotrophic** (microbes, grey dashed line) respiration in $\text{mgC} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ and rain (blue line) in mm. **Averaged daily measurements of soil respiration in grey-red squares, with standard deviation.**



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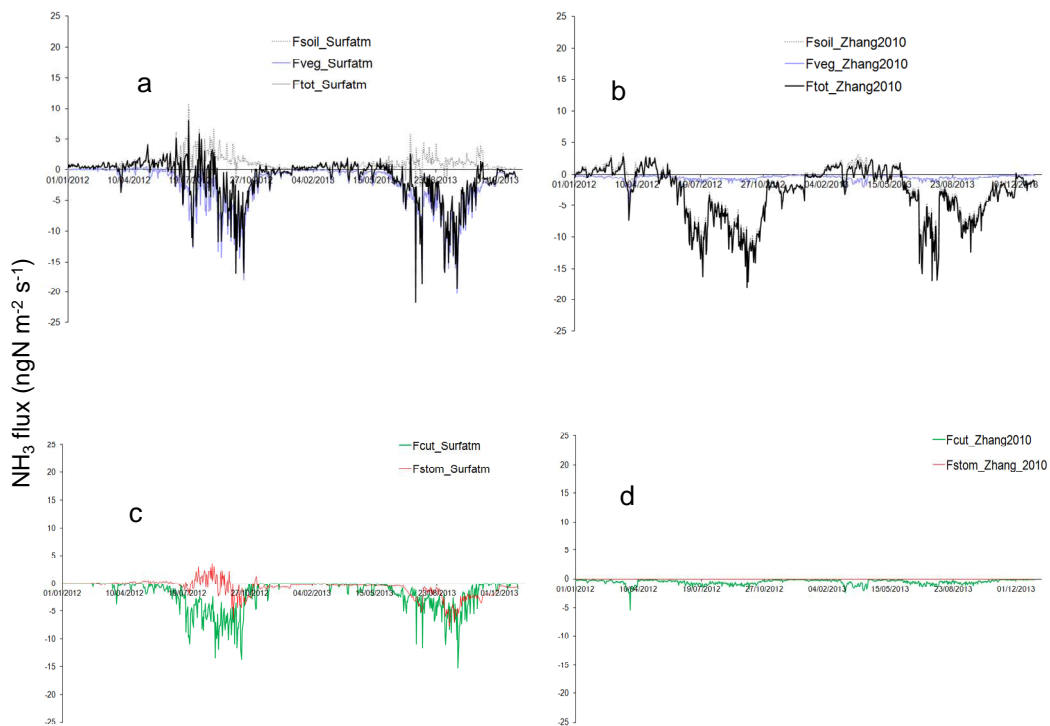
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Figure 9: Daily NH_3 flux (in $\text{ngN} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) simulated by SurfAtm (black line) and Zhang et al. (2010) (grey dashed line) and daily averaged NH_3 flux measurements during 3 field campaigns (grey-red triangles). Error bars in grey-red stand for standard deviation at the daily scale. Air humidity in % (blue line). DS = Dry Season; WS = West Season.

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Figure 10: Daily NH_3 flux (in $\text{ngN} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) partitioned between soil and vegetation. Black line is for total net flux (F_{tot}), grey dashed line is for soil flux (F_{sol}) and blue line is for vegetation flux (F_{veg}) for SurfAtm in (a), and for Zhang2010 in (b). Red line is for stomatal flux (F_{stom}) and green line is for cuticular flux (F_{cut}) for SurfAtm in (c) and for Zhang2010 in (d).