Surface atmosphere exchange of NO and CO_2 in a grazed semi-arid ecosystem: comparison of measurements and model predictions

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Abstract
This paper presents a comparison between measurements and model predictions of biogenic nitric oxide emissions and respiration (CO_2 emissions) from soils in a Sahelian grazed ecosystem in Senegal (Dahra site, 15.2°N, 15.2°W). Nitric oxide (NO) and CO_2 emissions are large at the beginning of the wet season when the first rains fall on dry soils (pulse emissions), due to microbial and biological processes reactivated in the soil when moisture conditions are favourable. The model shows a correct representation of pulses of NO and CO_2, but underestimates fluxes in the drier periods between rain events and after the wet season. We hypothesize that in the drier periods the model over-predicts the death rate of microbes, involving a lag between mineral N content availability and N emissions. Spatial heterogeneity of soil and vegetation characteristics and presence of livestock also involve differences between modelled and measured fluxes.

Key Words
Semi-arid region, soil biogenic NO emissions, soil respiration, soil carbon and nitrogen turnover, livestock

Introduction
NO contributes to the formation of tropospheric ozone and modifies the oxidative capacity of the atmosphere. In remote areas, where anthropogenic emissions are negligible, the soil emission of biogenic NO plays an essential role in regional atmospheric chemistry (Pilegaard et al., 2013). In semi-arid zones, the exchanges of trace gases are strongly (but not only) influenced by hydrologic pulses. In the West African Sahel wet and dry seasons alternate and drive the responses of carbon and nitrogen biogeochemical cycles (Austin et al., 2004, Shen et al., 2016). Drastic changes in soil water availability strongly affect all ecosystem compartments, especially microbial and biogeochemical processes (Wang et al., 2015). The short wet season (3-4 months) experiences the necessary moisture conditions for microbial activity to start in the soil after the long inhibition period induced by dry conditions. The first rainfalls have significant impacts on nitrogen production and consumption processes in the soils, and on nitrogen and carbon exchange fluxes with the atmosphere, leading to strong pulses of CO_2 and NO (Shen et al., 2016, Delon et al., 2015). Semi-arid zones have been shown to contribute significantly to N emissions at the global scale (Hudman et al., 2012), due to punctual high emissions occurring on large areas, even if soils are known to hold limited amounts of nutrients (C, N), a consequence of rapid turnover in these regions leading to low nutrient accumulation. In that context, three field campaigns were carried out in a semi-arid Sahelian rangeland in Dahra (Ferlo, Senegal), two at the beginning of the wet season in July 2012 and July 2013, and one in November 2013 at the end of the wet season. NO and CO_2 (respiration) fluxes from soils were measured by dynamic chambers. Soil temperature and moisture were measured throughout the year by an automatic meteorological station set in the field. The Sahelian Transpiration Evaporation and Productivity – GENeral DEComposition – NOFlux (STEP-GENDEC-NOFlux) model was used to simulate temporal variation of CO_2 and NO fluxes from soil, based on local meteorology for 2012 and 2013. Model and experimental results are compared. The objectives of this study are to quantify NO and CO_2 emissions to the atmosphere with model predictions and to understand the underlying biogeochemical processes in the soil in a semi-arid region.

Methods
Sampling site and field campaigns
Measurements were made in Dahra, Ferlo, Senegal (15°24'10"N, 15°25'56"W), from 11 to 17 July 2012

(J12), from 11 to 18 July 2013 (J13) and from 29 October to 7 November 2013 (N13). This site is a semi-arid woody savanna grazed rangeland. The wet season extends from mid-July to mid-October. Annual rainfall was 515mm in 2012 and 356mm in 2013 (to be compared to 400±147mm as the mean for the period 2002-2013). Mean soil moisture was 9.2%, 5% and 3.5% respectively in J12, J13 and N13, and cumulative precipitation calculated 5 days before the campaign was 66 mm in J12, 0.15 mm in J13 and N13. Air and soil temperatures were respectively 29 and 34°C in J12, 30 and 37°C in J13, 30 and 34°C in N13. This site has been comprehensively described in Tagesson et al. (2015).

NO fluxes and soil respiration (CO_2 emission) measurements

NO fluxes were measured with Teflon manual closed dynamic chambers (non-steady-state through-flow chambers, Pumpanen et al. 2004, dimension 200 mm width x 400 mm length x 200 mm height), connected to a Thermoscientific 17C analyzer in J12, and a Thermoscientific 17I analyzer (ThermoFischer Scientific, MA, USA) in J13 and N13. The calculation of fluxes is based on an equation adapted from Davidson et al. (1991). The rate of increase in NO mixing ratios is calculated by linear regression during the first 180 to 300s following the installation of the chamber on the soil. A different system was used for CO_2 fluxes. They were measured using a manual closed dynamic chamber (SRC-1 from PP-systems, 150 mm height x 100 mm diameter) coupled to a non-dispersive infrared CO_2/H_2O analyzer EGM-4 (PP-Systems). The chamber was placed on bare soil to ensure only roots and microbes respiration. CO_2 fluxes were measured close to NO fluxes (30 cm). Results of NO and CO_2 fluxes are presented as daily means with daily standard deviations.

Model STEP-GENDEC-NOFlux (Mougin et al., 1995, Moorhead & Reynolds, 1991, Delon et al., 2015)

The STEP-GENDEC-NOFlux coupled model is a 1 dimensional (1D) model forced by daily meteorological data (air temperature and humidity, rainfall, global radiation, wind speed). Data on vegetation and livestock were also given as input data. The autotrophic respiration was calculated from growth and maintenance respirations by living roots and green biomass. The heterotrophic respiration was calculated from the growth and death of microbes in the soil depending on the available carbon from buried litter, roots and animal faeces. Biogenic NO fluxes from soils (which equation was obtained from a neural network algorithm) were calculated from soil temperature and moisture, sand percentage, N input, wind speed, and soil pH. N input to the soil came from buried litter, animal faeces and roots. Model outputs were given at daily scale, and compared to daily means from measured data.

Results

Soil respiration (CO_2 fluxes).

Figure 1 shows heterotrophic (microbes) and autotrophic (roots only) respiration calculated by the model, and CO_2 fluxes measured at Dahra (no fluxes in J12). A comparison between modeled and measured fluxes in J13 and N13 is presented in Table 1. The larger fluxes in J13 both in model and measurements (compared to N13) are explained by the rapid response of the soil decomposers to the increase in soil moisture at the beginning of the wet season (June-July)leading to a rapid decomposition of the litter buried during the preceding dry season. Enzymes are located in the soil during the dry season and ensure decomposition with the first rains even when microorganisms are not yet totally developed. Measured respiration fluxes appear to be larger than modeled fluxes during J13 because the model over-predicts the death rate of microbes and also during N13 probably because of persistent microbe respiration and residues of roots despite low soil moisture, whereas in the model all microbes are dead, and roots have disappeared. Simulated respiration of microbes and roots and soil moisture in the 2-30cm layer are significantly correlated (R^2=0.4, p<0.01).

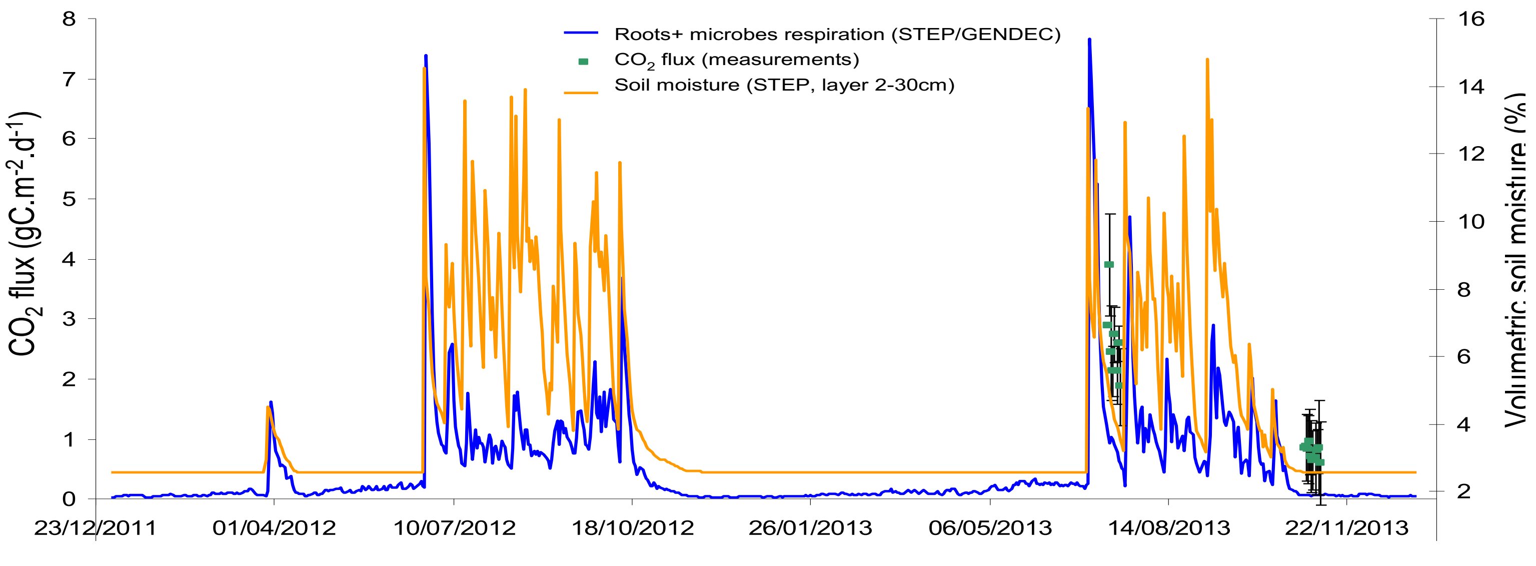

Figure 1. Modeled roots and microbes respiration (blue line), soil measured CO_2 fluxes (green squares, standard deviation in black) in 2012 and 2013 in Dahra, and modeled soil moisture in the layer 2-30cm (orange line).

Table 1. Mean values and standard deviations of measured and modeled CO_2 and NO fluxes during J12= 11-17 July 2012, J13= 11-18 July 2013, N13 = 29 October-7November 2013. All periods = J12+J13+N13.

		J12	J13	N13	All periods
CO_2 ($gC.m^{-2}.d^{-1}$)	Measured		2.58±0.63	0.78±0.11	1.58±1.01
	Modeled		0.87±0.19	0.07±0.007	0.42±0.43
NO ($ngN.m^{-2}.s^{-1}$)	Measured	4.94±2.74	4.30±1.92	3.45±1.97	4.14±2.19
	Modeled	4.00±1.92	3.07±0.45	1.88±0.22	2.85±1.34

Biogenic NO fluxes from soils

Figure 2 shows the comparison between measured and modeled NO fluxes with N input by animals faeces and litter decomposition, and N uptake by vegetation included. Table 1 gives both model and measurements means and standard deviation for J12, J13 and N13. Mean values are larger in J12 than in other periods in both model and measures due to higher soil moisture levels explained by rain events before the campaign (*cf* sampling site paragraph). The model underestimates measured NO fluxes by 20%, 30% and 50% respectively in J12, J13 and N13. This could be due to several reasons: a) mineral nitrogen (not shown) is underestimated in the model by 90% involving an underestimation of released N, especially at the beginning of the wet season when pulses of NO occur due to the mineralization of organic matter accumulated during the long dry season. b) in N13, 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. During the wet season, the available soil mineral nitrogen is used by growing plants(N uptake, accounted for in the model) and emissions to the atmosphere decrease, as shown in Fig.2. c) 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. Modeled NO fluxes are significantly correlated with measured soil moisture at 5 cm depth (Fig 1, R^2=0.37, p<0.01).

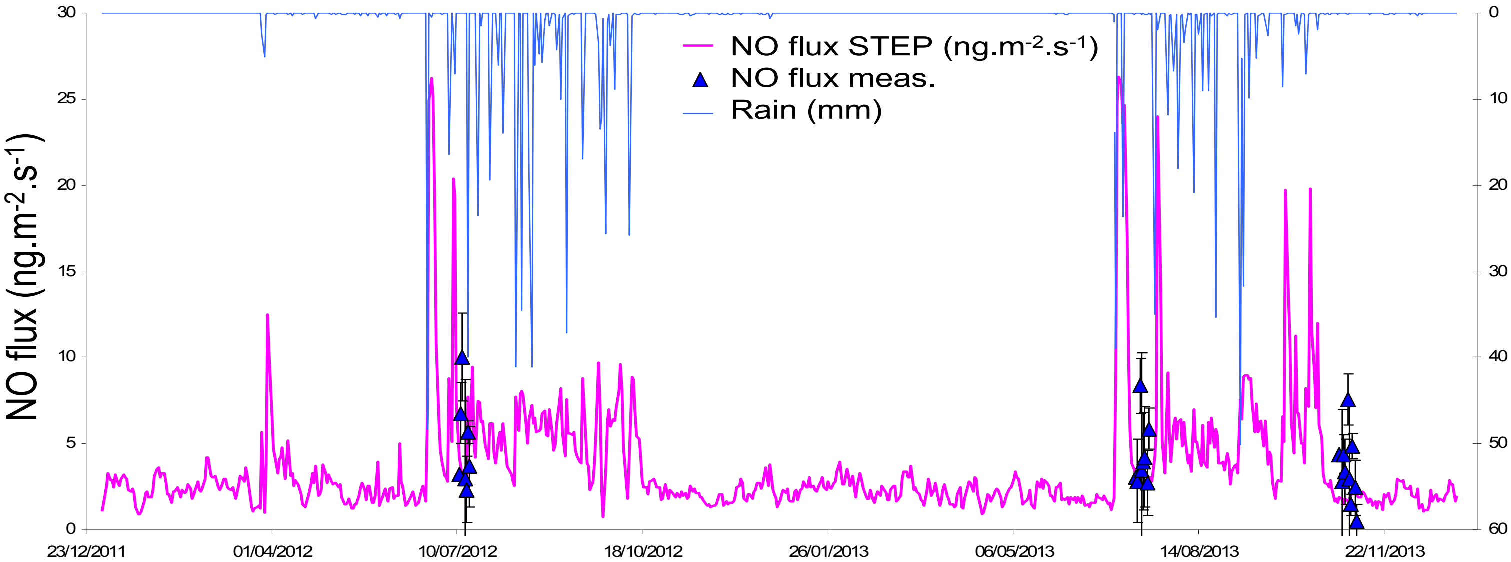

Figure 2: Biogenic NO fluxes from soils modeled by STEP (pink line) and measured in the field (blue triangles with standard deviation in black). Rain is plotted in blue line, in 2012 and 2013 in Dahra (Sahel, Senegal).

Respiration and soil NO fluxes are significantly correlated in the model (R^2=0.75, p<0.005). These relationships were not observed in the measurements, probably due to the reasons (points a, b and c) stated above. However, in J13, if NO fluxes are shifted by 1 day (i.e. CO_2 is in advance), R^2=0.6 (p=0.03), highlighting probably a light discrepancy in model predictions. In N13 soil respiration is too low in measurements to retrieve this lag. Soil respiration and nitrification processes (causing NO release) are closely linked by microbial processes: soil microorganisms trigger soil respiration and decomposition of soil organic matter (Xu et al., 2008).

Conclusion

CO_2 and NO emissions, related to microbial processes of C and N production in the soil, are underestimated by the model but remain in the same range and are well correlated to soil moisture. One may hypothesize that a possible underestimation of soil mineral N content could drive subsequent underestimation of N release. Possible discrepancies may exist between model and reality concerning N input by livestock, faeces deposit during the wet season following herbage consumption by cattle, and on spatial heterogeneity of driving parameters (soil pH, soil texture, N input), as well as possible overestimated mortality of microbes in the model. Dry and wet atmospheric deposition of N compounds, representing 8 $kg.ha^{-1}.yr^{-1}$ (Galy-Lacaux & Delon, 2014) has also to be introduced as N input the model, mostly during the wet season. Furthermore, additional emission of NO by litter is not taken into account by the model, but seems to be an important contributor to yearly means as indicated by measurements at the end of the wet season. The beginning of the wet season leads to strong pulses of NO and CO_2 because water is the main relevant parameter to re-start microbial processes after a long dormancy occurring during the dry season, as highlighted by increases in emissions in the model when the first rains fall.

NO and CO_2 emissions to the atmosphere are significantly correlated together in the model, and are both correlated with soil moisture during 2012 and 2013. In the measurements, this correlation is shifted by one day. These results highlight the relationship between CO_2 and NO and the underlying mechanisms (coupling biogeochemical, ecological and physico-chemical approaches), which are very important in improving our understanding of carbon and nitrogen cycling in semi-arid regions of the Sahel. The contrasted ecosystem conditions due to drastic changes in water availability in semi-arid regions have important non linear impacts on the biogeochemical nitrogen cycle and ecosystem respiration, and may affect the atmospheric chemistry if changes in precipitation regimes occur due to climate change in less dry regions, and also in case of increasing demographic pressure leading to increases in livestock pressure.

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