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Modelling the effect of soil moisture and organic matter degradation on biogenic NO emissions from soils in Sahel rangeland (Mali)

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Abstract

This work is an attempt to provide seasonal variation of biogenic NO emission fluxes in a sahelian rangeland in Mali (Agoufou, 15.34° N, 1.48° W) for years 2004, 2005, 2006, 2007 and 2008. Indeed, NO is one of the most important precursor for tropospheric ozone, and the contribution of the Sahel region in emitting NO is no more considered as negligible. The link between NO production in the soil and NO release to the atmosphere is investigated in this study, by taking into account vegetation litter production and degradation, microbial processes in the soil, emission fluxes, and environmental variables influencing these processes, using a coupled vegetation–litter decomposition–emission model. This model includes the Sahelian-Transpiration-Evaporation-Productivity (STEP) model for the simulation of herbaceous, tree leaf and fecal masses, the GENDEC model (GENeral DECompositon) for the simulation of the buried litter decomposition, and the NO emission model for the simulation of the NO flux to the atmosphere. Physical parameters (soil moisture and temperature, wind speed, sand percentage) which affect substrate diffusion and oxygen supply in the soil and influence the microbial activity, and biogeochemical parameters (pH and fertilization rate related to N content) are necessary to simulate the NO flux. The reliability of the simulated parameters is checked, in order to assess the robustness of the simulated NO flux. Simulated yearly average of NO flux ranges from 0.69 to 1.09 kg(N) ha^{-1} yr^{-1}, and wet season average ranges from 1.16 to 2.08 kg(N) ha^{-1} yr^{-1}. These results are in the same order as previous measurements made in several sites where the vegetation and the soil are comparable to the ones in Agoufou. This coupled vegetation–litter decomposition–emission model could be generalized at the scale of the Sahel region, and provide information where little data is available.

1 Introduction

In the continental biosphere, most of the N cycle is accomplished through internal processes such as mineralization/assimilation, because N is mostly assimilated in the biosphere from its mineral form (nitrates NO_3^-, ammonium NH_4^+). These compounds come from the mineralization of organic matter through the bacterial and fungal decomposition of dead matter. N cycle in the soil is dominated by microbial transformations. Bacterial processes involve important reactive gaseous components, e.g. NO formation through nitrification and denitrification (Delmas et al., 1995). A significant fraction of these compounds can be released to the atmosphere. NO is one of the most important precursor for tropospheric ozone, and participates to the formation of nitric acide, participating in N deposition. NO_x ($NO_x = NO + NO_2$) are also involved in the abundance of the hydroxyl radical (OH) which determines the lifetime of some pollutants and greenhouse gases (Fowler et al., 2009).

Atmospheric NO_x is coupled to the earth's nitrogen cycle through complex interactions involving soil microbial activity, soil N content and N inputs to the soil, either from anthropogenic or atmospheric origin (Hudman et al., 2012; Parton et al., 2001). The processes of NO production in the soil have been studied through modelling, laboratory or field studies by several authors (Butterbach-Bahl et al., 2004a; Schindblacher et al., 2004; Li et al., 2000) for different types of soils and climates (Butterbach-Bahl et al., 2009; Kesik et al., 2005 for european soils, Feig et al., 2008; Meixner et al., 1997 for tropical soils as examples). Processes of emission in arid and semi arid soils are mainly governed by pulse events, produced when first precipitations shower long-dried soils at the beginning of the rainy season. Several studies have shown that pulse emissions of NO contribute strongly to the total emission (Yan et al., 2005; Hudman et al., 2010; Jaeglé et al., 2004), specifically in semi arid regions. In those regions, mineral and organic substrates tend to accumulate at the soil surface and in the soil during the long dry season, when there is little nutrient demand, leading to an excess of mineralization during the early phases of the wet cycle (Schwinning et al., 2004).

At the global scale, NO emissions from soils have been estimated to be approximately 21 Tg(N) yr^{-1} (Davidson and Kingerlee, 1997) at the ground level (below canopy), a portion of the NO being deposited within the canopy. Above canopy emissions were estimated to be 5.45 Tg(N) yr^{-1} by one of the first global modelling study on the subject (Yienger and Levy, 1995), and more recently up to 10.7 Tg(N) yr^{-1} (Hudman et al., 2012). At the scale of the sahelian region, Delon et al. (2010) have calculated a 0.5 ± 0.1 Tg(N) yr^{-1} above canopy NO_x emission flux, representing 5 to 10 % of the global budget according to Hudman et al. (2012) or Yienger and Levy (1995). Hudman et al. (2012) have shown that the largest pulsed enhancements in their model are predicted over this region during the monsoon onset (April to June), comprising 15 to 65 % of the simulated NO_2 column and increasing variability by a factor of 5. As a consequence, the contribution of the Sahel in emitting NO is no more considered as negligible. Though they are of high interest for the specific mechanisms taking place there, and for their relatively high contribution to the global N cycle, semi arid regions remain poorly investigated due to the remoteness of the sites and the complexity to run long term measurements in difficult conditions. Modelling is therefore a precious help to try to describe and understand processes leading to emission fluxes, without minimizing the need of measurements on the field to complete the study.

In this study, we propose a modelling approach of NO emissions from soils at the yearly and seasonal scale, to identify emission processes through organic matter decomposition in the soil leading to NO pulses in semi arid ecosystems. The main goal is to use a coupled vegetation–litter decomposition–emission modelling approach, by linking three existing models specifically developped for semi arid regions, which simulate, respectively the growth and degradation of the vegetation (STEP), the decomposition of the organic matter with microbial processes in the soil (GENDEC), and the emission of NO fluxes (NO emission) associated to environmental variables. Modelling results are compared to data collected in the northern Mali site of Agoufou for years 2004 to 2008. This new modelling tool has been developped for semi arid regions where specific processes need to be taken into account due to the climatic originality of those regions.

Firstly, the Agoufou site is presented, as well as the different measurements used for model comparison. Secondly, the three models, STEP, GENDEC and NO emission, are introduced. Finally, modelling results are discussed and compared to field measurements, and limitations and uncertainties are assessed.

2 Data source: Agoufou site

The Agoufou study site (Mali, 15.34° N, 1.48° W) is part of the African Monsoon Multi-disciplinary Analysis (AMMA) – Couplage de l'Atmosphere Tropicale et du Cycle Hydrologique (CATCH) site observatory located in the Gourma region. This region stretches, in northern Mali, from the loop of the Niger River southward down to the border region with Burkina-Faso (Mougin et al., 2009). Located towards the northern limit of the area reached by the West African Monsoon, the region experiences a single rainy season with most precipitation falling between late June and mid September. The rainy season is followed by a long dry season of approximately 8 months. At the Agoufou site, the soil is sandy, with 91.2 % of sand, 3.1 % of silt and 4.6 % of clay in the first 5 cm. The surface pH is 6.7. The hydrologic system is endorheic operating at short distance from dune slopes to inter-dune depressions within small adjacent catchments. The vegetation at Agoufou is an open woody savanna, typical of mid-Sahel sandy soil vegetation with an herbaceous layer almost exclusively composed of annual species, and scattered trees and shrubs with a 3.1 % crown cover (Hiernaux et al., 2009). The area is used as livestock grazing under communal access. Because of the proximity of the Agoufou permanent pond, the grazing pressure is high during the dry season. Agoufou can be considered as representative of sahelian dry savannas. A comprehensive description of the site can be found in Mougin et al. (2009).

2.1 Meteorological and vegetation data

At the Agoufou site, woody and herbaceous plant density and species composition are organised in facieses following finer topography and soils nuances or differences in land use practices and histories (Hiernaux and Le Houérou, 2006). The herbaceous layer has been monitored using a two-level stratified random sampling design, as described in (Hiernaux et al., 2009). Total and green vegetation cover (visual and digital photograph estimates in %, Mougin et al., 2014), standing and litter mass (destructive measure, with harvest, air drying and weighing) and species composition (list with visual estimates of contribution to bulk) are assessed in 1 × 1 m plots randomly sampled in each of the vegetated strata along the transect. Above ground green and dry masses and surface litter mass have been sampled during several years, but only the years 2004, 2005, 2006, 2007 and 2008 are used in this study to evaluate the performance of the model. Indeed, these years represent contrasted meteorological conditions, with low rainfall years (2004 and 2008) and years with normal rainfall for the region (2005, 2006, 2007).

A meteorological station has been installed from 2002 to 2010, giving data on rainfall, wind speed, relative humidity, air temperature and global radiation. Data on soil moisture at different levels and different places (top, middle and bottom locations of dune slope), and soil temperatures at different levels are also available, except for year 2004. A detailed description of the soil moisture network and methodology and of the meteorological station is given in De Rosnay et al. (2009) and Mougin et al. (2009).

2.2 NO flux data sampling

NO flux were determined at Agoufou during summers 2004 and 2005, from dynamic stainless steel chambers measurements made on the soil. The NO flux rate was computed from the slope of the initial linear increase in NO concentration in the chamber, following Davidson (1991) and Serça et al. (1994). During summer 2004 (from 30 June to 12 July), NO daily fluxes ranged from 0.78 to 3.58 $\mathrm{kg(N)\,ha^{-1}\,yr^{-1}}$ (mean = 2.11 ±

$0.77\,\mathrm{kg(N)\,ha^{-1}\,yr^{-1}}$, Delon et al., 2007). During summer 2005 (from 11 to 13 August), NO fluxes ranged from 0.57 to $1.01\,\mathrm{kg(N)\,ha^{-1}\,yr^{-1}}$ (mean = $0.72\pm0.25\,\mathrm{kg(N)\,ha^{-1}\,yr^{-1}}$, unpublished data). In the following simulations, NO fluxes were not measured at Agoufou during years 2006 to 2008. However, since NO flux data are scarce, these field measurements from 2004 and 2005 will be helpful to give an order of magnitude of NO emission at the beginning and during the wet season.

3 Model description

3.1 Modelling approach

Biogeochemically based model of instantaneaous trace gas production can be parameterized for individual sites, describing locally nitrification and denitrification processes responsible for emission, but more generalized models are needed for the calculation of temporally or regionally integrated models (Potter et al., 1996). In that purpose, a new approach for biogenic NO emissions from soils calculation has been developed by Delon et al. (2007), in order to use general environmental parameters easily available as inputs for the flux parameterization. This approach was used at the regional scale for pulse emission events in the Sahel (Delon et al., 2008) and at the yearly scale at several Sahelian sites (Delon et al., 2010; Laouali et al., 2012). This approach has been partly inspired by the hole-in-the-pipe (HIP) concept, developed by Firestone and Davidson (1989), presenting the environmental parameters which control the variation of trace-N-gases by nitrification and denitrification with different levels of regulation, from proximal (e.g. mineralization, immobilization, respiration, plant uptake) to distal (e.g. pH, soil porosity, soil type,...). Using two functions based on soil N availability and soil water content, the HIP model characterizes a large fraction of the observed variation of NO emissions from soils (Davidson et al., 2000).

The NO emission model will be described in the following sections, but one has to precise that in its previous version, (Delon et al., 2010), the N availability in the soil was driven by the surface input (organic and livestock fertilisation) and considered constant in time (a similar amount of N was injected each month). Now, the main difference between the previous version and the study presented here, is that the N availability in the soil is calculated from buried litter (vegetation and feces) decomposition and is no more prescribed. The link between vegetation, litter decomposition and NO emission is explained in the following sections.

The on line coupled models are presented here and used at the daily scale: the herbaceous and tree leaf masses are simulated using the Sahelian-Transpiration-Evaporation-Productivity (STEP) model (Mougin et al., 1995), the buried litter decomposition is simulated in GENDEC (Moorhead and Reynolds, 1991), and the NO flux to the atmosphere is simulated with the NO emission model (Delon et al., 2007).

A schematic view of the model imbrications is given in Fig. 1

3.2 STEP

STEP is an ecosystem process model for sahelian herbaceous vegetation. In its current version, tree phenology (leaf mass set-up and fall) is also described by considering six phenological types which proportions must be known. This model is defined to be used at local or regional scale in order to simulate the temporal variation of the main parameters and processes associated with vegetation functioning in sahelian savannas. In this study, the model will be used at the local scale. In previous studies, STEP has been coupled to radiative transfer models in the optical (Lo Seen et al., 1995) and active/passive microwave domain (Frison et al., 1998), allowing an indirect comparison of satellite observations and modeling results of the vegetation growth (e.g. Jarlan et al., 2002). The performance of the STEP process model in predicting herbage mass variation over time and herbage yield along a north-south bio-climatic gradient within the Sahel was tested along a 15 yr period, and gave high correlation coefficients between model and measurements when the model is calibrated for each site (Tracol et al., 2006). Modifications brought to the first version of the model have been given in Jarlan et al. (2008). A recent regional scale use of the model is illustrated in Pierre et al. (2012).

STEP is driven by daily standard meteorological data obtained from site measurements in Agoufou (precipitations, global radiation, air temperature, relative humidity and wind speed), prepared for years 2004 to 2008. Site specific parameters like sand and clay percentage, pH, C3/C4 percentage, initial green biomass, initial dry biomass and initial litter, number of soil layers, initial water content in each layer, livestock composition (between 6 different categories, cattle, sheep, goats, donkeys, horses, camels) and livestock total load are given as input parameters. The seasonal dynamics of the herbaceous layer, major component of the Sahelian vegetation, is represented. The processes simulated are: 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. Moreover, structural parameters such as vegetation cover fraction fCover, LAI (Leaf Area Index), and canopy height, are also simulated. A new development has been included in the model for the present study: soil temperatures are simulated from air temperature according to Parton (1984).

Total above-ground herbaceous mass is divided into three components: above-ground green mass, standing dead (or dry) biomass, and litter biomass. Green biomass variations are controlled by the balance between total photosynthetic inputs expressed by the gross photosynthesis and total outputs due to respiration losses and senescence. Dry biomass results from the senescence of green material, minus litter production, ingestion by animals and burned biomass. Litter biomass accumulation is the result of dead material falling down on the soil, due to trampling and to climate conditions like rain, wind, and air temperature, minus litter burying and ingestion by animals, litter burning and litter decomposition due to insects, small mammals and climate conditions (rain kinetic energy, soil humidity, air temperature and wind). Green vegetation growth starts at seedling emergence with an initial above ground biomass. The date of emergence is estimated from the number of days required for germination when the moisture content of the soil surface layer is above wilting point. The quantity of fecal matter is calculated from the livestock total load given as input parameter.

The quantity of carbon in the soil is calculated from the total litter input (from fecal and herbal mass), which is 50 % of the buried litter mass. The quantity of nitrogen in the soil is derived from the quantity of carbon using the C/N ratio. A more detailed description of STEP can be found in Mougin et al. (1995); Tracol et al. (2006) and Jarlan et al. (2008). Information such as the quantity of fecal and herbal masses are transfered as inputs to GENDEC, the litter decomposition model.

3.3 GENDEC

GENDEC (for GENeral DEComposition) is a general, synthetic model, which aim is to examine the interactions between litter, decomposer microorganisms, and C and N pools, and to explore the mechanisms underlying observed patterns of decomposition in arid ecosystems. The general modelling approach is based on fundamental decomposition processes. Six pools of C and N are used in this model, representing dead organic matter (labile materials with high N content and rapid decomposition rate, celullose and related materials with an intermediate decomposition rate and very little associated N, very slowly decomposing recalcitrant compounds with moderate levels of physically associated N, and dead microbiota with high N content and rapid decomposition), living microbial biomass (final pool of organic matter), and soil N for the nitrogen submodel (Moorhead and Reynolds, 1991). C/N ratio is different for each of these compartments, and is set to 10, 1000, 34, 8, 25 and 9, respectively for labile compounds, holocellulose, resistant compounds, dead microbial biomass, living microbial biomass and nitrogen pools, based on Moorhead and Reynolds (1991) and experimental results from the Agoufou site detailed below. Flows between these pools are driven by empirical relationships according to characteristics of the microbial community. Climatic parameters such as soil moisture and soil temperature are important drivers for C and N dynamics, intimately associated through the nutrient control of C mineralization, with microbial turnover providing the N required for utilizing holocellulose, and wetting-drying events increasing the turnover of microbial biomass and stimulated C mineralization.

GENDEC is driven by organic matter input coming from four different boxes in STEP: buried litter (herbs and tree leaves), trees, fecal matter, and dry herb roots. It is also driven by soil temperature and soil water potential calculated in STEP. Input parameters include the assimilation efficiency and the microbial mortality rate. The first step is to calculate the substrate decomposition depending on C/N ratio for each pool, and to obtain the quantity of total C and N released by the litter decomposition, as well as the quantity of mineral nitrogen ($NH_4^+ + NO_3^-$, mentionned as mineral N in the rest of the text). The second step is to describe microbial dynamics (growth, death and respiration), taking into account C and N availability calculated in the first step, for each compartment. At last, mineral nitrogen, total quantities of C and N, respiration are obtained for each box (buried herbaceous litter, buried leaf trees, dry roots and fecal matter). The addition of these four contributions gives access to the total C and N in the soil. Organic carbon is assumed to be the sole source of energy and substrate for heterotrophic microbial growth. Organic matter mineralization driven by heterotrophic activity of soil microorganisms releases mineral nitrogen. This is the starting point for the calculation of nitrogen transformations in soils (Blagodatsky et al., 2011). The mineral nitrogen is then used as an input in the NO emission module described below.

3.4 NO emission

An emission algorithm, derived from a neural network, has been developed for the calculation of NO biogenic emissions from soils (Delon et al., 2007). In this algorithm, NO fluxes depend on soil moisture, soil temperature at two depths (5 and 20–30 cm), wind speed, soil pH, sand percentage, and fertilization rate (quantity of nitrogen given as input to the soil). In the first versions of this parameterization, the fertilization rate was given as a constant value, decorrelated from the vegetation dynamics at the surface.

In this study, we use a new approach, based on the one of Potter et al. (1996), who have developed an extended version of the CASA (Carnegie Ames Stanford) model, where potential emission of total nitrogen trace gases ($N_T = NO + NO_2 + N_2O + N_2$) at the soil surface is treated as a given percentage (2 %) of gross mineralized nitrogen at any given time step (this corresponds to the definition of the emission factor). This version of the simple conceptual model is not designed to distinguish between nitrification and denitrification as sources of N gases. In order to adapt this approach to our own study, we made the assumption that the sandy soil texture in Agoufou favours predominantly aerobic conditions and subsequently nitrification processes (Li et al., 2000; Blagodatsky et al., 2011). Furthermore, the Water Filled Pore Space (WFPS) remains below 20 % (soil moisture below 10 %), and according to Davidson (1991) the total oxidized N emitted would be composed of 95 % to 100 % of NO.

In the present work, we have adapted the concept developed in CASA in a different way: the fertilization rate (i.e. N available for NO emission) is 2 % (same percentage as in Potter et al., 1996) of the mineral N content in the soil (mineral N, which depends both on N input and N content) available as an output from STEP-GENDEC calculations. The main difference between Potter et al. (1996) approach and the one of this study lies in the fact that in the present study the NO emission is modulated by additional parameters such as pH and wind speed, as well as soil moisture and temperature which have an impact on both mineralization and emission. In this NO emission model, if the value of mineral N is 0, it takes a minimum value of 0.01 g m^{-2} in the NO emission module to avoid null values of NO emission. Indeed, very little is known about mineral N dynamics and subsequent NO emission at low soil moisture, but experimental studies show low emission even during the dry season (Scholes et al., 1997).

The principal advantage of this NO parameterization is to depend on different factors at two levels. The first level concerns climatic impacts and environmental parameters, such as precipitations, soil texture and pH, temperatures, wind speed, and the second level concerns intrinsic processes of N turnover in the soil, through the organic matter degradation from vegetation and livestock. The majority of the first level variables are easily available on site or/and from atmospheric model reanalysis and global databases, the second level is a sophistication of the model, making it possible to add the organic matter dynamics in this parameterization of NO emission.

4 Results and discussion

Several parameters, included in the NO emission module, play an important role in modulating emission. These parameters can be classified in two categories: physical parameters (soil moisture and temperature, wind speed, sand percentage) which affect substrate diffusion and oxygen supply in the soil and influence the microbial activity (Skopp et al., 1990), and biogeochemical parameters (pH and fertilization rate related to N content). In this paragraph, we will discuss the reliability of the simulated variables, in order to assess the robustness of the simulated NO flux.

4.1 Soil moisture

Soil moisture has a strong influence on NO emission from soils, particularly in hot and dry regions, as reported in the literature until today, from studies at the global, regional, or local scale (Williams et al., 1992; Yienger and Levy, 1995; Meixner et al., 1997; Hartley and Schlesinger, 2000; Yan et al., 2005; Feig et al., 2008; Hudman et al., 2012). This variable needs to be well reproduced by the model in order to calculate reliable fluxes of emission. Soil moisture is calculated by STEP at different soil layers, using a tipping bucket approach. Figure 2 shows the soil moisture calculated by STEP between 0 and 2 cm from 2004 to 2008, compared to the soil moisture measured at Agoufou at 5 cm depth in 2005, 2006, 2007 and 2008. From 2006 to 2008, these measurements are actually an average of 3 datasets from soil moisture probes operating at the top, middle and bottom locations of dune slopes. In 2005, only bottom slope data were available.

The comparison between STEP and measurements in Fig. 2 is not direct, because depths are not exactly equivalent. Despite this, the comparison gives satisfying results from 2005 to 2008. In the surface layer, the measurements reach 10 to 12 % during summers and show lower values during the dry season than those calculated by STEP. A threshold at 8 % is observed on the STEP plot. This value corresponds to the field capacity calculated by STEP. In reality, this theoretical value may be overstepped, and water is not systematically transfered to the layer underneath. In the model, when the field capacity is reached, the excess water is transfered to the second layer, between 2 and 30 cm. For all years, the model is consistent and correctly reproduces the temporal dynamics, the increase and decrease of the soil moisture are well in phase, and the filling and emptying of the surface layer is reasonably well represented. The determination coefficient between model and measurements R^2 is 0.70 for all years.

4.2 Soil temperature

Soil temperature is also an important variable for modelling NO emissions from soils. In tropical regions, emissions are mostly driven by soil moisture, but temperature influence has to be taken into account, especially during the dry season when soil moisture is very low (Butterbach-Bahl et al., 2004b; Yao et al., 2010). Figure 3 shows the soil temperature calculated in the two first STEP layers and compared to measurements at 5 and 30 cm at Agoufou from 2005 to 2008. Temperatures at both levels are needed because, as explained in the NO emission model description, the equation derived from the neural network approach uses both surface and deeper soil temperature as input parameters. The seasonal cycle is well reproduced by the model, with some missing high frequency variations due to rain events during the wet season. The determination coefficient R^2 between the simulated and measured temperatures in the surface layer is 0.86, and 0.82 in the 30 cm layer, showing a good representation of temperature at both levels in the model.

4.3 Aboveground and litter vegetation

The temporal variation of the green living biomass, dry standing biomass (or standing straw), surface litter and buried litter is simulated and compared to measurements at Agoufou (except for buried litter because no measurements are available). Green biomass begins to increase between 20 to 25 June for years 2004 and 2005, and between 10 to 15 July for years 2006 to 2008, when the surface soil moisture is above the wilting point during 5 consecutive days (green in Fig. 4). In 2004, 2005, 2006, 2007 and 2008, respectively, the cumulative rain is 191, 418, 376, 286, and 227 mm. The maximum of green biomass simulated by STEP is 80, 205, 192, 161 and 104 g(d.m.) m^{-2} (d.m. = dry matter), when the respective measurements give 47, 224, 174, 150 and 82 g(d.m.) m^{-2} in 2004, 2005, 2006, 2007 and 2008. In 2004, two distinct growing phases are simulated, corroborated by measurements. Indeed, the first green biomass growth is interrupted due to a lack of rainfall, and starts again later in the season. The maximum simulated green biomass value seems to be slightly late in 2006 and 2007, and early in 2008, compared to measurements, whereas the seedling emergence is correctly simulated for these three years. In 2008, the quantity of precipitation is lower, but the soil moisture is sufficient to trigger seedling emergence in the model. Overall, simulations and measurements are in good agreement with $R^2 = 0.72$ for green biomass for the five years.

The change over time of the herbaceous standing mass is driven by mechanical and biological degradation, influenced, among other causes, by livestock grazing. Forage consumption and trampling by livestock have major effects on herbage offtake, decay and decomposition including seed dispersal (Tracol et al., 2006). The STEP model allows the drying from green to dry standing biomass, and the degradation of the dry biomass by livestock. The minimum value for the initialization of dry standing biomass in 2004 is 10 g(d.m.) m^{-2}. The increase of the senescent aboveground biomass at the end of the wet season is well reproduced by the simulation (light blue in Fig. 4). R^2 between simulations and measurements is 0.56 for dry standing biomass for the five years of simulation. The maximum of dry standing biomass is underestimated in 2006 and 2008 and well reproduced in 2004 (despite a particular feature) and 2007. No measurements were available for year 2005.

The minimum value for the initialization of the surface litter in 2004 (red in Fig. 4) is 30 g(d.m.) m^{-2}. The maximum value is encountered in December–January (end of November in 2004). Litter decay is sharper in the measurements than in the simulation, with minimum occuring in the middle of the wet season. R^2 between simulations and measurements is 0.5 for litter for the five years of simulation.

The evolution of simulated buried litter (dark blue in Fig. 4) is closely linked to that of surface litter. The first days of rain induce a sharp decrease of buried litter, which is rapidly decomposed. The minimum is observed in september (August in 2004), when it begins to increase again with the surface litter accumulation. That accumulation feeds the C and N pools, and is the N resource for soil mineral N and N losses to the atmosphere.

The evaluation of the model in terms of vegetation dynamics, quantity, and production of surface litter seems to be reliable, despite time lags in some cases. Therefore, the quantity of organic matter (via the buried litter), likely to be degraded and to produce N in the soil, can be considered as correctly reproduced by the model.

4.4 N content in the soil

The N content calculated by the model has been compared to N content analysis made on 35 different soil samples in Agoufou (sampled in July 2004). Results from soil samples give a mean total N content of $0.20 \pm 0.14\,\mathrm{g\,kg^{-1}}$ (or 0.02 %), with a mean C/N ratio of 9.80 ± 1.11. Diallo and Gjessing (1999) have mentioned 0.011 % of total N in sandy soils of the Gourma region, where Agoufou is situated. However, the few studies performed on arid or semi arid soils showed that high microbial metabolism and high turnover rates of little nutrients might be major explanatory factors of the observed NO fluxes (Meixner and Yang (2006) and references therein). In the model, the total soil N content is the sum of mineral N, organic N and microbial N (Fig. 5). To convert the model output in g(N) m^{-2} to percentage, we assume a density of 1500 kg m^{-3} for the soil, according to De Rosnay et al. (2009), and we apply this value to the first 2 cm of the soil (first layer in the model). Yearly means range from 0.016 % in 2004, 0.023 % in 2005, 0.030 % in 2006 to 0.035 % in 2007 and 2008. To compare directly to measurements, we have calculated the average for the 15 first days of July in the model, and obtained 0.020 % in 2004, 0.022 % in 2005, 0.031 % in 2006 to 0.037 % in 2007 and 2008, values that are representative of the beginning of the wet season, and very close to measurements at the same dates. It is rather difficult to find direct comparisons to ensure the model initializations in terms of N content and N dynamics in the region of the Sahel. However, some studies like De Bruin et al. (1989) and Krul et al. (1982) show from incubation results that after the long dry season the soil contains approximately 14 kg(N) ha^{-1} (approximately 0.005 %, lower than our results) in the first 10 cm, and the nitrogen flush after the intensive first rains is about 7 to 8 kg(N) ha^{-1}. In the next paragraph, we will see that our results imply the same kind of emission fluxes at the beginning of the wet season, which gives confidence on the robustness of the N dynamics reproduced by GENDEC.

4.5 NO emission from soil to the atmosphere

4.5.1 Seasonal and yearly cycle of NO emissions

As explained above, the quantity of N due to the decomposition of buried litter and fecal biomass is calculated in GENDEC, and therefore used to parameterize the NO emissions from soil (see Fig. 6a for 2004 to 2008 and Fig. 6b for comparison with measurements in 2004 and 2005). Yearly and wet season (from 1 June to 30 September) averages are reported in Table 1. The largest peaks (up to 6 kg(N) ha^{-1} yr^{-1}) of emission occur at the beginning of the wet season. Indeed, as shown in Fig. 6a and b, the first rains induce a sharp increase in soil surface moisture until saturation, followed by a subsequent drying out of the surface layer until the following rain event. The organic matter, brought by the buried litter, is suddenly decomposed when the soil moisture is sufficient, and produces a NO pulse of emission to the atmosphere. This kind of process has already been highlighted by e.g. Butterbach-Bahl et al. (2004b) in a rain forest where a huge amount of litter that had accumulated during the long-lasting dry period of the year before was intensively decomposed with the onset of rainfall.

After these peaks, in the core of the rain season, though additional rainfall events, less N is released to the atmosphere and NO emissions decrease. Figure 7 shows the mineral N behaviour together with the rainfall amount. First rains and rains after a short break lead to a sharp increase in mineral N content (in $\text{g}\,\text{m}^{-2}$), whereas frequent rains in the core of the wet season do not stimulate mineral N in the same proportion. Furthermore, Krul et al. (1982) have shown that when the soil moisture is sufficient to allow the growth of the vegetation, the mineral N in the soil is taken by the plants (not numerically represented in this version of the model), in competition with the assimilation by microbes, and therefore less released to the atmosphere.

After the end of the wet season, when the maximum of green biomass is reached, the vegetation starts to dry out while still standing, then falls on the surface and begins to decompose since the soil surface moisture is still relatively high. The vegetation decomposition at that moment is responsible for the peak of emission observed in the late wet/early dry season. Afterwards, the soil surface moisture decreases, leading to low NO emissions. During the dry season, emissions are reduced, but still present, and mostly driven by surface temperature. Actually, the influence of temperature also exists during the wet season, but is dominated by soil moisture effect.

Though the strong dependance of NO fluxes on soil moisture, the total rainfall amount in a year does not appear to be essential for the amplitude of the fluxes. Indeed, though 2008 rainfall amount is less important than in 2005, 2006 and 2007, the annual and wet season NO flux averages are larger in 2008. This is not the case in 2004, and could be attributed to the fact that 2008 wet season begins earlier and ends later than in the other years, allowing more efficient and more frequent pulse events.

Some wet season measurements performed at Agoufou in July 2004 and August 2005 are reported in Table 1, and shown in Fig. 6b with modelled fluxes. The model underestimates the measurements in 2004 (10 points), and overestimates them in 2005 (3 points). However, modelled fluxes are in the range of measured fluxes. In Table 1, they are compared to other measurements made in other types of semi arid ecosystems, and to wet season measurements in Banizoumbou (Niger), situated in a dry savanna site and presenting the same type of vegetation (Delon et al., 2012). Data from this study are also compared to other simulations done with the ISBA model (Interactions Soil Biosphere Astmosphere) used to simulate emission and deposition N fluxes in dry savannas in a previous study (Delon et al., 2010 and Delon et al., 2012), where the N input (fertilization rate) was constant in time, and equivalent to 5.5 kg(N) ha^{-1} yr^{-1}.

These results show that the coupled STEP-GENDEC-NO model gives fluxes in the order of known experimental or simulated data, while not exactly equivalent to measurements at the Agoufou site in 2004 and 2005. Several studies have shown different ranges of NO fluxes, but always with a strong link to the soil moisture. As a comparison, Butterbach-Bahl et al. (2004b) found average fluxes of 18 kg(N) ha^{-1} yr^{-1} in tropical forests soils at the transition between dry and wet season, where the quantity of decomposed litter is far greater than in dry savanna sites of the Sahel, and where the nutrient content of the soil is far larger, since semi arid soils are generally nutrient poor.

The ratios of fluxes from wet to dry seasons in this study are 2.5, 3.3, 2.8, 3.7 and 3.5, respectively for the years 2004, 2005, 2006, 2007, 2008, in the (lower) range of what has been reported in the literature (Meixner and Yang, 2006), but showing undoubtedly the difference between the two periods in terms of emission.

4.5.2 Sensitivity tests

To highlight the effects of soil temperature, soil humidity, and mineral N content on the NO flux to the atmosphere, several sensitivity tests have been performed in the NO emission module. The sensitivity of the emission to deep soil temperature and wind speed will not be shown here, because less important than for surface soil temperature, moisture and mineral N content. In the first example (Fig. 8), soil moisture is set successively to a low (2 %) and a high (10 %) value, associated, respectively to a low (0.01 $\mathrm{g\,m^{-2}}$) and a high (0.1 $\mathrm{g\,m^{-2}}$) value of mineral N content in the soil. The associated high and low values of mineral N with soil moisture have been chosen according to realistic outputs given by the GENDEC model (see Fig. 7), and corresponding to dry and wet season quantities. The results are shown for year 2006, to lighten the figures, because 2006 is a standard year in terms of pluviometry, and the same conclusions would appear anyway for the other years. When the soil moisture is low and constant (associated to low and constant mineral N content), the NO fluxes are only driven by the soil temperature at high (diurnal) frequency. Pulses usually linked to soil moisture variation do not occur and the mean value of the flux remains low. When the soil moisture is high (associated to a high value of mineral N content), the mean value of the flux is larger, directly resulting from high mineral N content. The seasonal cycle of the fluxes is not correlated to the seasonal cycle of the soil temperature, as already found by Meixner and Yang (2006) (low frequency variation), whereas their diurnal cycle are correlated, in accordance with previous studies. As an example, Ludwig et al. (2001) have stated that soil temperature fluctuations can explain short term variations of NO fluxes.

In the second example (Fig. 9), soil moisture and mineral N content are not forced, soil surface and bottom temperatures are set successively to both a low (33 °C and 32 °C, respectively) and a high (48 °C and 47 °C, respectively) values, for the year 2006. These temperatures correspond to possible values encountered during the dry and wet seasons. At the beginning of the year, during the dry season, the soil moisture is low, and fluxes are constant if the soil temperature is constant. During both seasons, the highest value of soil temperature leads to the lowest values of NO fluxes, although differences are reduced between mean annual fluxes (1.08 vs 0.69 $\mathrm{kg(N)\,ha^{-1}\,yr^{-1}}$ for $T = 33$ and $T = 48$ °C, respectively) despite a large temperature difference (15 °C). Temperature effect on NO emissions has been studied in other circumstances, and is still under debate still no clear conclusion could be raised. Contrasted results have been found in tropical and temperate regions: most studies have shown that NO emissions increase with increasing temperature as reported for example in Martin et al. (1995); Meixner and Yang (2006), and Van Dijk and Meixner (2001), other studies do not find any clear tendance (Cardenas et al., 1994; Sullivan, 1996), while Butterbach-Bahl et al. (2004b) find a linear relationship during only certain periods of the year in a tropical rain forest. Temperature effect in our study is moderate in dry season, and almost not visible in wet season.

In addition, soil pH effects have also been tested (not shown here), within a reasonable range of pH from 6.1 to 8. Pulse effects and modulation by soil temperature present the same feature as in the reference case, with a slight decrease of the base level when pH increases. Serça et al. (1994) and Yan et al. (2005) have also found the same kind of variation, with decreasing emissions while increasing pH in tropical soils.

Sensitivity tests of the NO emission module used in this study have already been explored in Delon et al. (2007) for the elaboration of the module. The most straightforward conclusion from these tests is that soil moisture is the main driver for NO fluxes in the particular conditions of semi arid soils (with immediate effect on soil N content), modulated by soil temperature effect (mostly visible during the dry season) and adjusted by soil pH and wind effects.

5 Limitations and uncertainties

Estimating the NO fluxes in semi arid regions through modeling studies remains a difficult exercise, considering the scarcity of data. The uncertainties in the calculation of NO fluxes in the model are related to the uncertainties on the main drivers of the fluxes, i.e. soil moisture, and mineral N. Furthermore, the mineral N concentration in the soil is also driven by soil moisture. The uncertainty on the NO flux has been estimated around 20 % when calculated with the present algorithm, derived from a neural network algorithm (Delon et al., 2010). Despite the scarcity of validation flux measurements, and of data on N cycle in the soil, this work gives results that can be added to the existing knowledge on emission processes. Simulated fluxes are in the order of magnitude of previous measurements performed in the same semi arid region. As mentioned in Davidson et al. (2000), a model based on regression parameters between NO emissions and nitrogen cycling in the ecosystem will have only order of magnitude prediction accuracy. The temporal variation of the quantity of live and dry biomass (straw and litter) have been accurately compared to measurements, but the case is different for the seasonal cycles of the N pools in the soil. Comparisons have been made with the available experimental data at a given time, but do not give access to the whole yearly cycle. Concerning the mineral N concentration in the soil, used as input in the calculation of the NO fluxes, the model gives a zero value during the dry season, but was set to a non zero value for the calculation of NO fluxes in this work. This value should be moderated and readjusted according to experimental results of available nitrogen in the soil during the dry season.

In this study, all initial parameters are calibrated and validated at the Agoufou site. However, it could be possible to generalize this coupled vegetation-nitrogen-emission model to at least the Sahel region by making approximations, concerning for example biomass, livestock, N and C pools. Considering the need of information in this region of the world, it would be conceivable to simulate such processes of emissions at a larger scale. The challenge is worth to be done, knowing that NO emissions participate at a larger scale to the production of tropospheric ozone.

6 Conclusions

The present work is an attempt to estimate NO fluxes in the semi arid region of the Sahel. Simulations are performed at the site of Agoufou (Mali), with a coupled vegetation–litter decomposition–NO emission model, for years 2004, 2005, 2006, 2007 and 2008. The vegetation model STEP correctly reproduces the temporal dynamics of the soil moisture in the first layer of the model (layer involved in the N cycle in the soil), as well as the increase and decrease, and the filling and emptying of the surface layer.

The temperature in the first two layers of the model are also in accordance with measurements. The green and dry biomass calculated by STEP show a correct feature when compared to measurements in terms of vegetation growth, vegetation quantity, decay and production of litter, despite slight time lags in the peak of geen biomass for the years 2006 and 2008. The quantity of N is calculated in GENDEC, and is directly derived from organic matter and C contents, both quantities calculated from litter degradation. Sahelian soils are usually considered as N poor, and the comparison of the N content in the soil calculated in GENDEC (around 0.2–0.3 %) is well in accordance with experimental values, and with the few references found in the literature. The coupling between the three models is successfull, and well adapted to the specific functionning of semi arid ecosystems.

The quantity of N in the soil is the consequence of the presence of vegetation and livestock at the surface, and mineral N constitutes the N pool available for N release to the atmosphere, in the form of NO (and other compounds). The NO flux calculated by the model is of course highly dependent on soil moisture, as well as on mineral nitrogen, and a 2 % fraction of this pool is used as input to calculate the NO emission, modulated by the effect of environmental parameters such as wind speed, soil moisture and temperature, pH and sand percentage. The simulated NO emissions during the wet season are in the same order as previous measurements made in several sites where the vegetation and the soil are comparable to the ones in Agoufou. Very few measurements have been made during the dry season, which complicates the validation of the modelling results for that season. However, the annual budget of emissions is mostly dominated by emissions occuring during the wet season, as already highlighted in different studies in semi arid regions.

This modelling study has been strengthened at each step of the calculation process by comparison with experimental values. It would be necessary to obtain more measurements through field campaigns, especially for the N content in the soil, the grazing pressure, the soil N uptake by plants, and the concentrations and fluxes of N compounds in the atmosphere. Taking into account the difficulty of organizing field campaigns in these remote regions, modelling is an essential tool to link N cycles both in the soil and in the atmosphere, and to understand the specific processes of emission involved in semi arid regions. This study is a step forward in the evaluation of the response of soils to meteorological forcing, in terms of emissions, and it contributes to increase the knowledge of NO emissions processes in semi arid regions.

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Table 1. Comparison of experimental and simulated NO fluxes (daily scale) during various wet seasons in dry savanna sites. The model used are indicated in parenthesis. No model specified means experimental data.

Site name	NO flux (kg(N) ha^{-1} yr^{-1})	Period	Reference
Banizoumbou	1.92 ± 0.83	Wet season 1992	Le Roux et al. (1995)
Agoufou	2.11 ± 0.77	Wet season 2004	Delon et al. (2007)
Agoufou	0.72 ± 0.25	Wet season 2005	Unpublished
South Africa	1.7–2.5	Wet season 1993	Otter et al. (1999)
Chihuahuan desert	0.76	Watered soils 1993	Hartley and Schlesinger (2000)
Agoufou (STEP)	1.16 ± 1.10	Wet season 2004	This work
Agoufou (STEP)	1.82 ± 1.61	Wet season 2005	This work
Agoufou (STEP)	1.70 ± 1.52	Wet season 2006	This work
Agoufou (STEP)	1.81 ± 1.51	Wet season 2007	This work
Agoufou (STEP)	2.08 ± 1.90	Wet season 2008	This work
Agoufou (ISBA)	2.52 ± 1.14	Wet season 2006	Delon et al. (2010)
Agoufou (STEP)	0.69 ± 0.72	Year 2004	This work
Agoufou (STEP)	0.98 ± 1.13	Year 2005	This work
Agoufou (STEP)	0.97 ± 1.15	Year 2006	This work
Agoufou (STEP)	0.93 ± 1.08	Year 2007	This work
Agoufou (STEP)	1.09 ± 1.35	Year 2008	This work

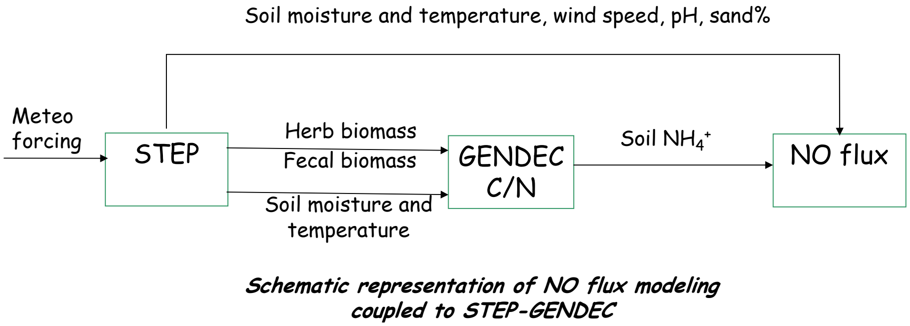

Figure 1. Schematic view of links between the models STEP, GENDEC and NO emission module.

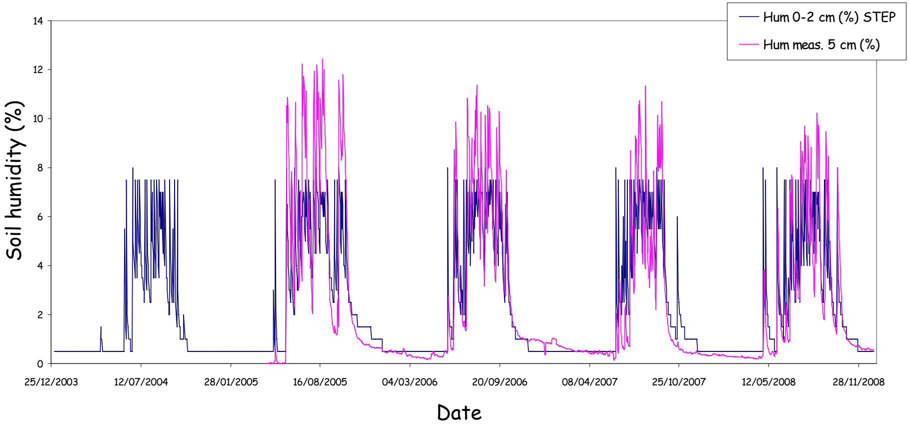

Figure 2. Soil moisture calculated by STEP at the surface layer (0–2 cm) in blue, mean soil moisture measured at 5 cm in pink, for years 2004 to 2008 at Agoufou.

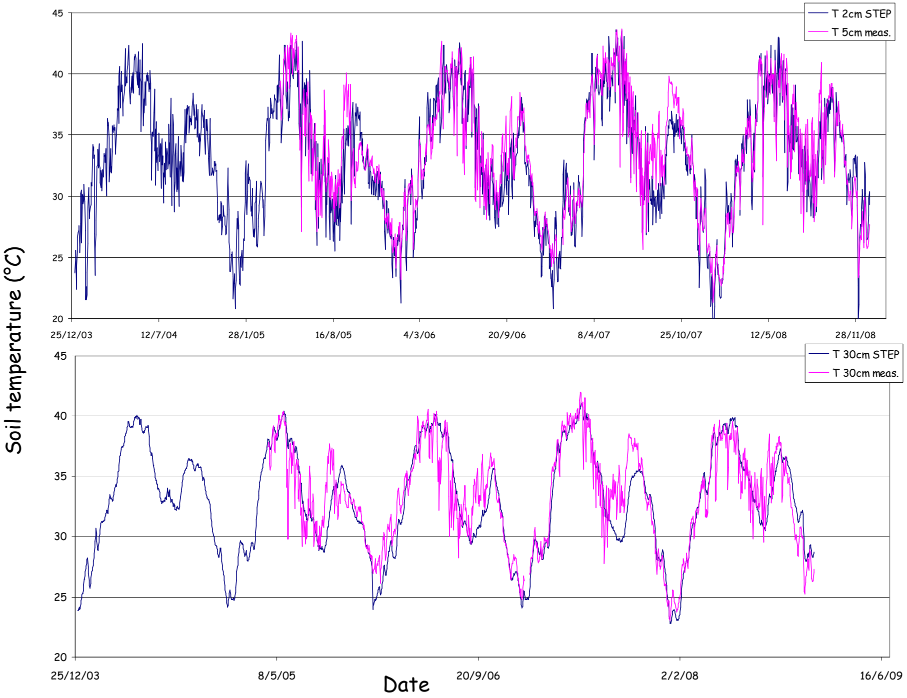

Figure 3. (a) Soil temperature measured at 5 cm at the low slope station (in pink), soil temperature simulated at the surface layer in blue; **(b)** Soil temperature measured at 30 cm at the low slope station (in pink), soil temperature simulated at the second layer (2–30 cm) in blue, for years 2004 to 2008 at Agoufou.

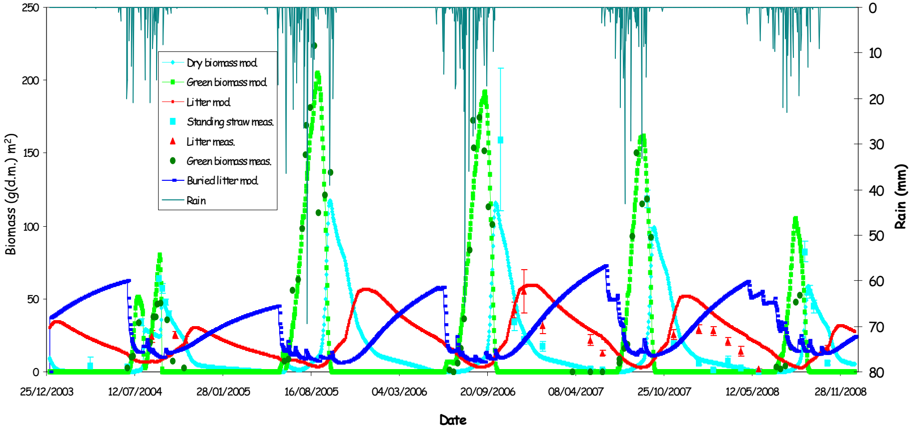

Figure 4. Green biomass in green, dry biomass in light blue, surface litter in red, buried litter in dark blue (line for the model, dots for measurements), in g(d.m.) m^{-2}. Standard deviations are indicated for the measurements. Rain in blue-grey in mm, for years 2004 to 2008 at Agoufou.

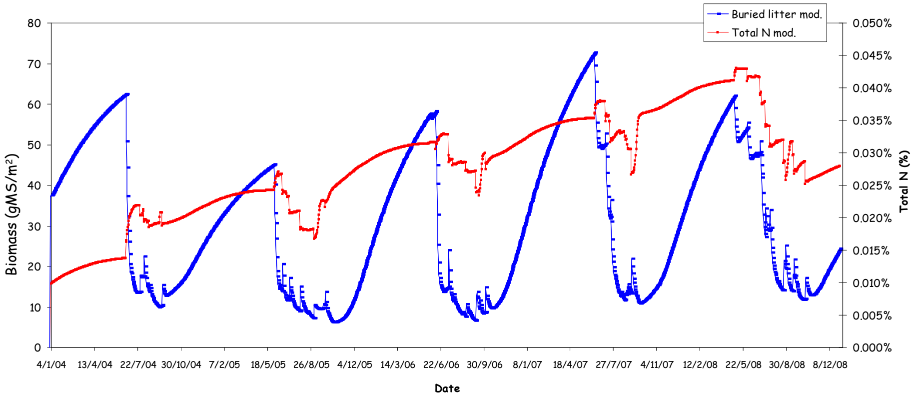

Figure 5. Simulated buried litter in g(d.m.) m^{-2} in dark blue and total N content in the soil in %, for years 2004 to 2008 at Agoufou.

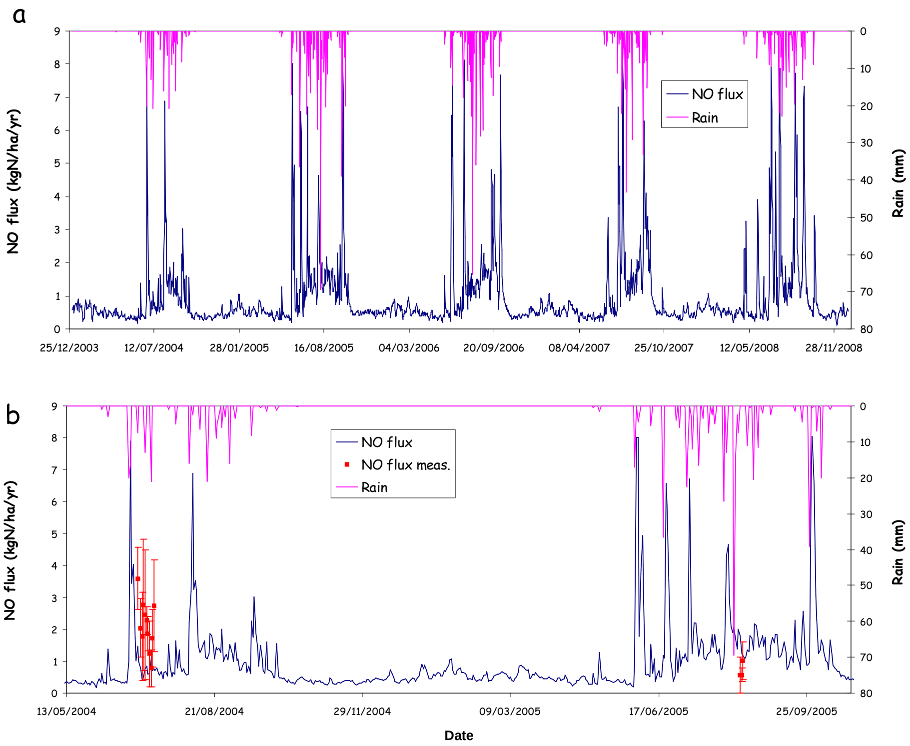

Figure 6. Simulated NO flux in kg(N) ha^{-1} yr^{-1} and rain in mm, for years 2004 to 2008 at Agoufou.

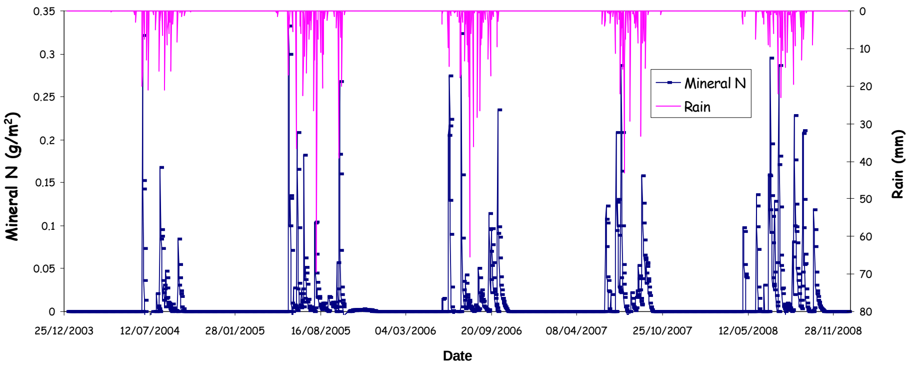

Figure 7. Simulated mineral N in $g\,m^{-2}$ and rain in mm for years 2004 to 2008 at Agoufou.

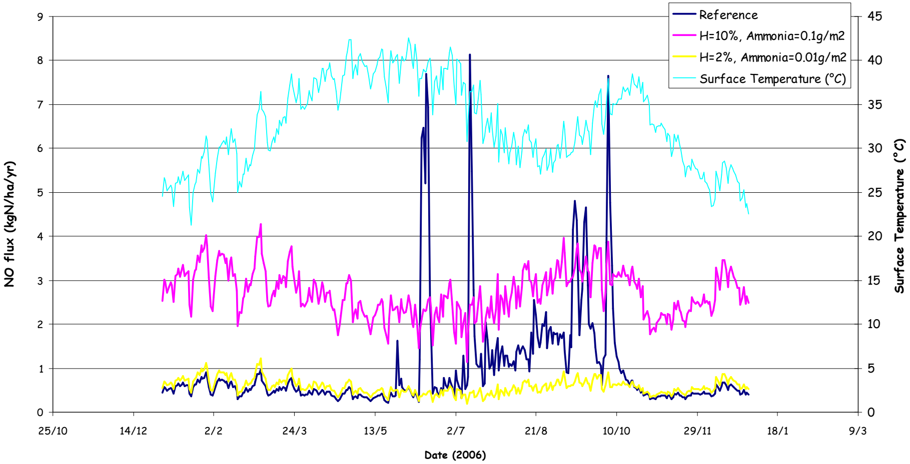

Figure 8. Sensitivity test. In dark blue: reference NO flux in kg(N) $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$, in yellow: NO flux with H = 2 % and mineral N = 0.01 $\mathrm{g\,m}^{-2}$, in pink: NO flux with H = 10 % and mineral N = 0.1 $\mathrm{g\,m}^{-2}$, in light blue: surface temperature in °C, for year 2006.

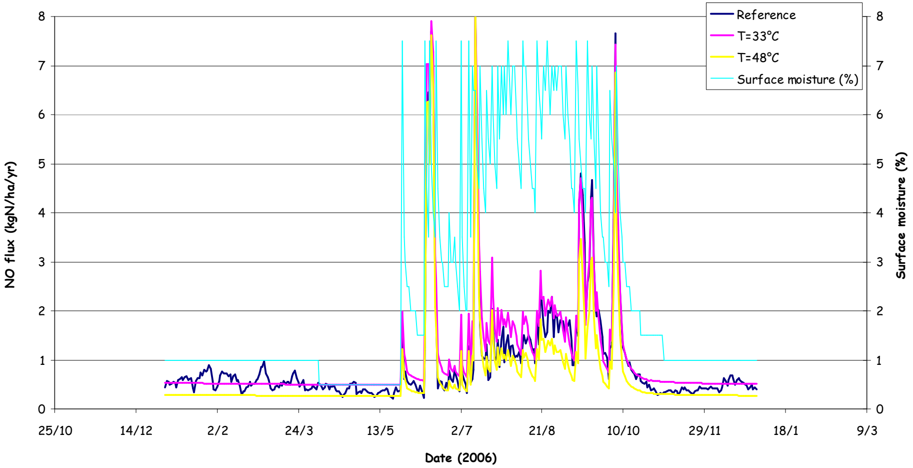

Figure 9. Sensitivity test. In dark blue: reference NO flux in kg(N) ha^{-1} yr^{-1}, in yellow: NO flux with $T = 48\,^{\circ}$C, in pink: NO flux with $T = 33\,^{\circ}$C, in light blue: surface moisture in %, for year 2006.