



ISSN: 0976-3376

Available Online at <http://www.journalajst.com>

ASIAN JOURNAL OF  
SCIENCE AND TECHNOLOGY

Asian Journal of Science and Technology  
Vol. 17, Issue, 05, pp. 14261-14268, May, 2026

## RESEARCH ARTICLE

# ANALYSIS OF SPATIO-TEMPORAL VARIATION OF REACTIVE NITROGEN (Nr) DRY DEPOSITION AND BIOGEOCHEMICAL Nr-EMISSION PROCESSUS ALONG THE AFRICAN ECOSYSTEM TRANSECT: DRY SAVANNA-WET SAVANNA- FOREST

Moussa Ouma\*<sup>1</sup>, Dungall Laouali<sup>2</sup> and Yacoubou Mahamadou<sup>3</sup>

<sup>1</sup>Graduate School of Education, Department of Physics, PO Box 10963, Abdou Moumouni University, Niamey, Niger

<sup>2</sup>Faculty of Science and Technology, Department of Physics, PO Box 10662, Abdou Moumouni University,

Niamey, Niger<sup>3</sup>Department of Physics, Faculty of Sciences of Education, Andre Salifou University, Zinder 656, Niger

### ARTICLE INFO

#### Article History:

Received 11<sup>th</sup> February, 2026

Received in revised form

29<sup>th</sup> March, 2026

Accepted 14<sup>th</sup> April, 2026

Published online 30<sup>th</sup> May, 2026

#### Key words:

Transect, Ecosystem, Concentration, Gases, Reactive Nitrogen, Savannah, Forest.

#### \*Corresponding author:

Moussa Ouma

### ABSTRACT

This article presents an analysis of dry reactive nitrogen (Nr) deposits measured between 1998 and 2013 at five sites in INDAAF network, in West and Central Africa, representative of different African ecosystems: dry savannas, wet savannas and equatorial forest. Monthly, seasonal, and annual concentrations of nitrogen gases (NH<sub>3</sub>, NO<sub>2</sub>, HNO<sub>3</sub>) are determined, and the variation in dry reactive nitrogen (Nr) deposits is studied. The results show that dry gaseous-Nr deposits largely dominate total-Nr deposition (approximately 97 to 99%), with maximum ratio in equatorial forest (Zoétélé) and minimum ratio in dry savanna (Banizoumbou). Conversely, the contribution of particulate-Nr deposits remains low (1 to 3%) and varies little between sites. Dry gaseous-Nr deposits increase gradually along the ecosystem transect: dry savanna – wet savanna – equatorial forest during the dry season. In the wet season, they increase in dry savanna but decrease in wet savanna and forest. Particulate-Nr deposits is generally higher during the dry season. These results highlight the major influence of climatic conditions of each ecosystem on the variability of dry reactive nitrogen deposition.

**Citation:** Moussa Ouma, Dungall Laouali and Yacoubou Mahamadou. 2026. "Analysis of Spatio-Temporal Variation of Reactive Nitrogen (NR) Dry Deposition and Biogeochemical NR-Emission Processus along the African Ecosystem Transect: Dry Savanna-Wet Savanna- Forest.", *Asian Journal of Science and Technology*, 17, (05), 14261-14268.

Copyright©2026, Moussa Ouma et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

## INTRODUCTION

During the nitrogen cycle, atmosphere, soil and water, each one plays a dual role, that of reservoir and sink of nitrogen compound. The latter have advantages especially in improving the yields of agricultural production (Vitousek, 1997). Biological fixation is the main input of atmospheric nitrogen in the cycle of its transformation (Chen *et al.*, 2010). It is carried out by bacteria living in symbiosis with certain plants such as legumes. Man, through his activities manages to increase the quantity of reactive nitrogen. It thus exerts a great influence on the nitrogen cycle by amplifying some of its links compared to others and generating an imbalance (Galloway *et al.*, 2004). Plants assimilate nitrogen preferentially in the NO<sub>3</sub><sup>-</sup> or NH<sub>4</sub><sup>+</sup> forms depending on the availability of the one or the other of these two forms, the nature of the soil, the plants and the climatic conditions. Thus, these compounds are synthesized in the soil during the processes of ammonification, nitrification (nitritation and nitration) and denitrification. Audoi (1991) states that the soil behaves like a complex purifying system towards the elements it receives, which undergo physical, hydrodynamic, physico-chemical and biological phenomena. These processes are accompanied by the emission of other reduced (NH<sub>x</sub>) or oxidized (NO<sub>x</sub>) nitrogen compounds. Under certain conditions, these compounds are detrimental to the environment, climate and health. Cellier *et al.*, 2013 express that, when reactive nitrogen returns to its inert form

(N<sub>2</sub>), it has necessarily passed through several excessive forms, and consequently has contributed to various environmental impacts. Intermediate nitrogen compounds have specific impacts on the environment. Those of NH<sub>3</sub> are consecutive to its deposit in ecosystems in the form of dissolved gases, ammonium salts (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> and NH<sub>4</sub>NO<sub>3</sub> formed by neutralization of H<sub>2</sub>SO<sub>4</sub> and HNO<sub>3</sub>. These additional reactive nitrogen inputs can increase soil fertility but also have disastrous consequences (disruption of ecosystems, forest degradation, acidification of soils, rainwater and waters) when the nitrogen quantity threshold is exceeded. These processes lead to the modification of the fauna and flora. In the soil, NH<sub>4</sub><sup>+</sup> replaces basic cations (Ca<sup>2+</sup>, K<sup>+</sup> and Mg<sup>2+</sup>) of the humic clay complex and thus causes acidification. These ions are carried towards the waters. Nitrogen is involved in the enrichment of the soil in the form of ammoniacal nitrogen, which develops nitrification as well as soil acidity (Binkley and Richler, 1987). An excessive supply of nitrogen to the soil (over-fertilization) can have harmful effects on health (Duchemi, *et al.*, 1988, Foulhouz, 1988). NO<sub>2</sub><sup>-</sup> and NO<sub>3</sub><sup>-</sup> can be absorbed directly through water and vegetables. Iron oxidizes from the ferrous state to the ferric state under action of NO<sub>2</sub><sup>-</sup> and loses its ability to transfer oxygen to the tissues of the body. This situation is accompanied by the following signs: headache, dizziness, polypnea, asthenia, primary and secondary hypertension. In forest ecosystems, nitrogen pollution is accompanied by leaching of NO<sub>3</sub><sup>-</sup> from the soil, leading to its progressive acidification, nutrient depletion and release of toxic aluminum ions. Moreover, the NO<sub>3</sub><sup>-</sup>

formed by bacteria and which exceeds the storage capacity of the soil, are either taken directly by plants (terrestrial eutrophication), or drawn into groundwater or surface water (water eutrophication) (Mariotti, 1994). The excess NO<sub>3</sub><sup>-</sup> contained in groundwater makes the water unfit for consumption and causes public health problems (WHO standard for the potability of drinking water < 50mg NO<sub>3</sub>/L). The excess nitrates contained in surface waters constitute a source of environmental degradation for much lower concentrations, of the order of 10mgNO<sub>3</sub>/L (Audoi, 1991).

NO<sub>2</sub> causes inflammatory manifestations in the respiratory tract and intensifies the irritating effects of allergens and cardiac arrhythmias. When the NO<sub>2</sub> load in the outside air increases, a higher number of deaths and hospitalizations for respiratory tract diseases are recorded in the short term, heart rhythm disorders are also frequent. Children, elderly and asthmatics are the most vulnerable. An increase in the quantity of fine dust formed by neutralization of HNO<sub>3</sub> by NH<sub>3</sub> (Moussa *et al.*, 2018b) leads to an increase in cardiovascular and respiratory pathologies and reduces life expectancy. By photochemical reaction, NO<sub>x</sub> and VOCs give rise to tropospheric ozone, which is a greenhouse gas. Nitrous oxide (N<sub>2</sub>O) is emitted during nitrification and/or denitrification reactions. N<sub>2</sub>O is the third greenhouse gas after CO<sub>2</sub> and CH<sub>4</sub>. It has a global warming potential about 300 times greater than that of CO<sub>2</sub>. Indeed, nitrous oxide is the main anthropogenic substance that depletes the stratospheric ozone layer (Ravishankara *et al.*, 2009).

HNO<sub>3</sub> in ambient air has an influence in the atmosphere and soil acidification (Ferm *et al.*, 2005) and control the levels of photooxidants (Gupta *et al.*, 2003). Nitrogen is accumulated in soils during the dry season and emitted as large pulses of NO at the beginning of the rainy season (Austin *et al.* (2004), Jaegle *et al.* (2004). By photochemical reactions, NO is converted to high quantities of NO<sub>x</sub> in the atmosphere, contributing to increase ozone formation. Several studies on atmospheric gases have been made along the African ecosystems transect (Al-Ourabi and Lacaux (2002), Delon *et al.* (2008), Delon *et al.* (2010), Delon *et al.* (2015), Adon *et al.* (2010), Adon *et al.* (2013), Ossohou *et al.* (2019), Moussa *et al.* (2018a)). They have allowed to quantify the concentrations, the dry gaseous depositions and to estimate the contributions of the different sources of gases and aerosols. The aim of this study is to analyze nitrogen deposition over the period (1998 to 2013) in each of the three main African ecosystems, and then to compare the results obtained with those of Adon *et al.*, (2010) in order to characterize the trends in concentrations and the predominant processes of the nitrogen cycle.

## MATERIALS AND METHODS

**Presentation of measurement:** The INDAAF long term monitoring network is composed by 8 stations in West and Central Africa (Mali, Niger, Ivory Coast, Senegal, Benin, Congo, and Cameroun) and 5 partner sites (4 in South Africa and 1 in Tunisia). These 8 West and Central African sites are located to represent a transect of ecosystems, dry savannas (Banizoumbou, Katibougou) - wet savannas (Djougou, Lamto) - equatorial forests (Zoetele, Bomassa). Dry savannas are characterized by a long dry season from October to May and a short-wet season from June to September. In wet savanna, wet season extends from April to October and from March to November in forests; the other months represent the dry season. A detailed description of INDAAF monitoring stations can be found in Adon *et al.*, (2010). NO<sub>2</sub>, NH<sub>3</sub> and HNO<sub>3</sub> have been monitored since 1998.

### Principle of operation of the passive samplers

**The operating principle of the passive samplers is based on the following two phenomena:**

- The physical phenomenon of molecular diffusion;
- The chemical reaction between the molecules of the gas studied and those of the substance of which the cellulose filter is impregnated.

The gas which concentration is to be determined is carried passively into the passive sampler by molecular diffusion. It is chemically trapped on a filter impregnated with a substance dissolved in a volatile solvent (methanol). The product of the reaction is recovered by extraction in a small volume of deionized water) before being analyzed by ion chromatography (ammonium, nitrates, and sulfates). The dose thus measured is proportional to the concentration of the gas in the ambient air determined by the formula (1):

$$C = (L/A \cdot X \cdot R \cdot T) / (t \cdot D \cdot P) \quad (1) \text{with:}$$

**C:** concentration of the gas considered in the air in ppb.

**X:** the quantity of molecules collected on the cellulose filter in  $\mu\text{mol}$  (corrected with the white).

**R:** the perfect gas constant ( $R = 0.08206 \text{ L}\cdot\text{atm}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$ ).

**T:** the average ambient temperature during the exposure period in Kelvin (K).

**P:** the mean atmospheric pressure during the exposure period of the passive samplers (atm).

**D:** the molecular diffusion coefficient of the gas in the air ( $\text{m}^2\cdot\text{s}^{-1}$ ).

**t:** the exposure time of the passive samplers in second (s).

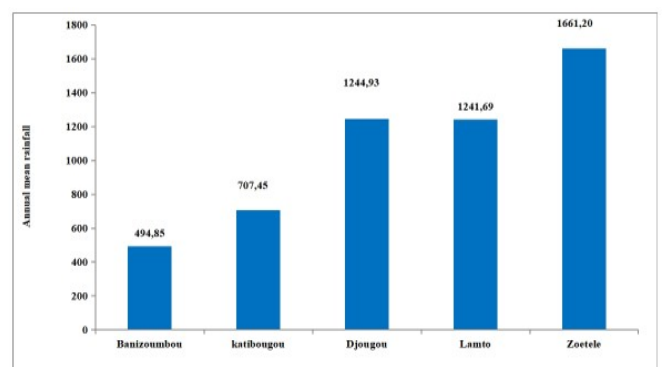
$L / A = 47.5 \text{ m}^{-1}$ , coefficient of air resistance (Al-Ourabi and Lacaux 2002).

The passive samplers are differentiated by a color code: gray for NO<sub>2</sub>, white for NH<sub>3</sub> and black for HNO<sub>3</sub>. Before and after exposure (one month), passive samplers are stored in the refrigerator in the laboratory or on the site, trying to minimize the time between exposure and analysis. All passive samplers (including "blanks"), after sampling on the sites, are sent back to the Laboratory of Aerology at Toulouse for analysis.

**Analysis method for passive samplers:** In passive samplers, the impregnated filter which traps the gas must have a complete reactive efficiency. For the different gases studied, the chemical capture is carried out by reactions. The product of the reaction is recovered by ultrasonic extraction in a small volume of milli-Qwater (deionized water). The desorption volume is 10 ml for the black and gray passive samplers filters and 5 ml for the white one. The solution obtained is analyzed by ion chromatography for the trapped ions: NO<sub>2</sub><sup>-</sup> for NO<sub>2</sub>, NO<sub>3</sub><sup>-</sup> for HNO<sub>3</sub>, and NH<sub>4</sub><sup>+</sup> for NH<sub>3</sub>.

## RESULTS AND DISCUSSION

The figure 1 presents the annual average of rainfall at each one of the five stations.



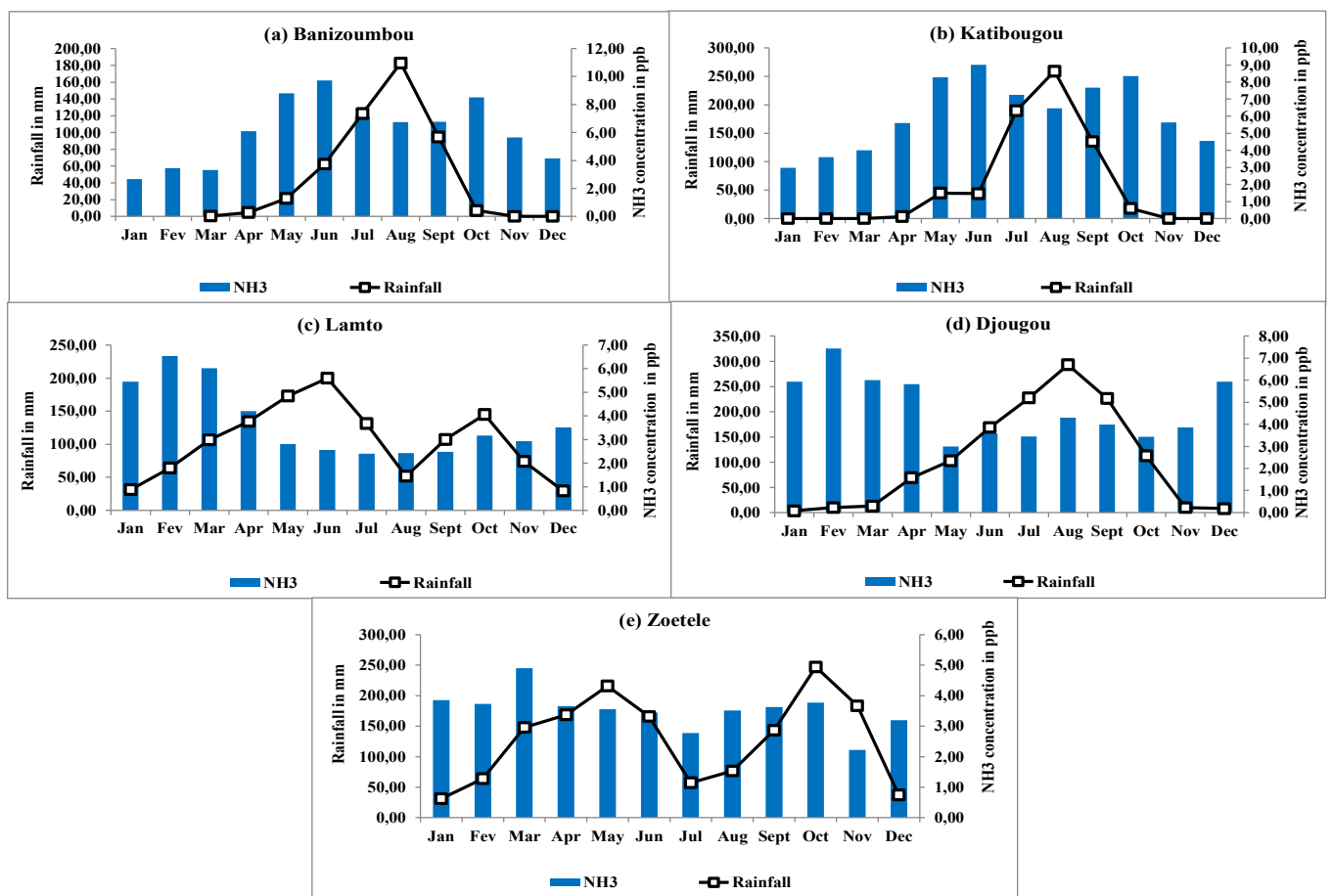
**Figure 1. Annual average of rainfall at of the five stations**

The total rainfall in annual average follows a positive gradient along the transect of dry savanna – wet savanna – equatorial forest ecosystems in West and Central Africa. The latter varies from 494,85 at Banizoumbou in dry savanna to 1661.20mm (i.e. 3,35 times that of Banizoumbou) in Zoétélé in the equatorial forest (1998 - 2013). Also, this annual average rainfall is down compared to the values indicated by Al Ourabi, (2002) for the period (1998 – 2000): Banizoumbou (548mm), Katibougou (868mm), Lamto (1264mm), Zoétélé

(1896mm) and those indicated by Adon, (2011) for the period (1998 – 2007): Banizoumbou (497mm), Katibougou (814mm), Agoufou (359mm), Lamto (1277mm), Djougou (1205mm) and Zoétélé (1595mm). The only station with rising cumulative rainfall is Djougou. However, with the exception of this station, the average annual accumulation of precipitation over the years (1998 – 2013) shows a downward trend in the three major ecosystems. This fact has main consequences on the emission-deposition processes of gases and aerosols on a spatio-temporal scale along the African ecosystems transect.

**Study of the variation of cumulative rainfall and the concentrations of nitrogen gases in the three major African ecosystems:** Figures 2(a - e) to 4(a - e) present the variation of the average monthly concentrations of  $\text{NH}_3$ ,  $\text{HNO}_3$ , and  $\text{NO}_2$  associated with those of the monthly average rainfall. In Banizoumbou and Katibougou, the concentration variation of  $\text{NH}_3$  and  $\text{NO}_2$  show two maximums: the first one in June and the second in October. These two concentration peaks correspond to the beginning and the end of the rainy season (June-July-August-September) in dry savanna. During this wet period, the concentration of  $\text{NH}_3$  and that of  $\text{NO}_2$  are important although reduced by the leaching of the atmosphere through the aqueous phase of clouds and precipitation in which these dissolved gases take the forms  $\text{NH}_4^+$  and  $\text{NO}_3^-$  respectively. This high concentration at the beginning and throughout the wet season is due to the porosity and humidity of the soil which is accompanied by the hydrolysis of animal excreta, the bacterial decomposition of animal and plant debris by ammonification, nitrification and denitrification because the frequency of dry days (successive days without rain) is high in dry savanna.

$\text{NH}_3$  and  $\text{NO}_2$  are relatively low. The concentration peaks of these gases in October result to the emissions from fertilized soils, biomass fires, the decomposition of crop residues, emissions from vegetation and the combustion of domestic firewood (Brocard *et al.*, 1996). For  $\text{HNO}_3$  in dry savanna at Banizoumbou and Katibougou, the figure 4 (a-e) shows a single concentration peak in June with a relatively high concentration from May to September. During this period, the precursors of this secondary gaseous pollutant including  $\text{NO}_x$  ( $\text{NO} + \text{NO}_2$ ) are important (Austin *et al.*, (2004), Jaegle *et al.*, 2004)). This concentration peak testifies the formation of nitric acid via photochemical reactions from  $\text{NO}_x$  and volatile organic compounds (VOCs) more available during this wet period characterised by high solar radiation. It coincides perfectly with the first  $\text{NO}_2$  concentration peaks obtained in June at the two stations in dry savanna (Banizoumbou and Katibougou). In the wet savanna (Djougou and Lamto) and in the equatorial forest (Zoétélé), for the three nitrogenous gases, the concentration is very low during the wet season. For each one of these humid ecosystems, the concentration during the rainy season gradually decreases from Djougou in the Sahelo-Sudanian savanna to Zoétélé in the equatorial forest via Lamto just at the doorstep of the forest zone. This fact is in perfect agreement with the strong influence of atmospheric leaching by precipitation, which frequency increases from Djougou to Zoétélé (Laouali *et al.*, 2017). The low concentration of these gases during the wet season (April to October) in the wet savanna and equatorial forest (March to November) is due to the density of the vegetation which prevents the spread of the chemical species locally emitted and to the atmospheric leaching by the quasi-permanent rainfall (Al Ourabi, 2002). From the analysis of figures 2(a-e) to 4(a-e), it appears that humidity leads to an increase in the concentration of nitrogenous



**Figure 2(a-e). Covariation of  $\text{NH}_3$  concentration and average monthly rainfall along the transect of African ecosystems: (a) Banizoumbou (1998-2013), (b) Katibougou (1998-2013), (c) Djougou (2005-2013), (d) Lamto (1998-2013) and (e) Zoétélé (1998-2013)**

Gaseous emissions from vegetation are also an important contributor. Indeed, Galy-Lacaux and Modi, (1998) state that the hydrolysis of urea from animalurine deposited in pastures is a considerable source of nitrogen compounds due to a high density of domestic animals in the Sahelian region. Outside of this wet period, the concentrations of

gases in dry savanna (Banizoumbou and Katibougou) while it causes a decrease of that concentration in the wet savanna (Lamto and Djougou) and in equatorial forest (Zoétélé). Indeed, humidity through precipitation is the origin of atmospheric leaching, it is also the cause

of hydrolysis of urea and biological processes of ammonification, nitrification and denitrification. Then, it can be deduced that:

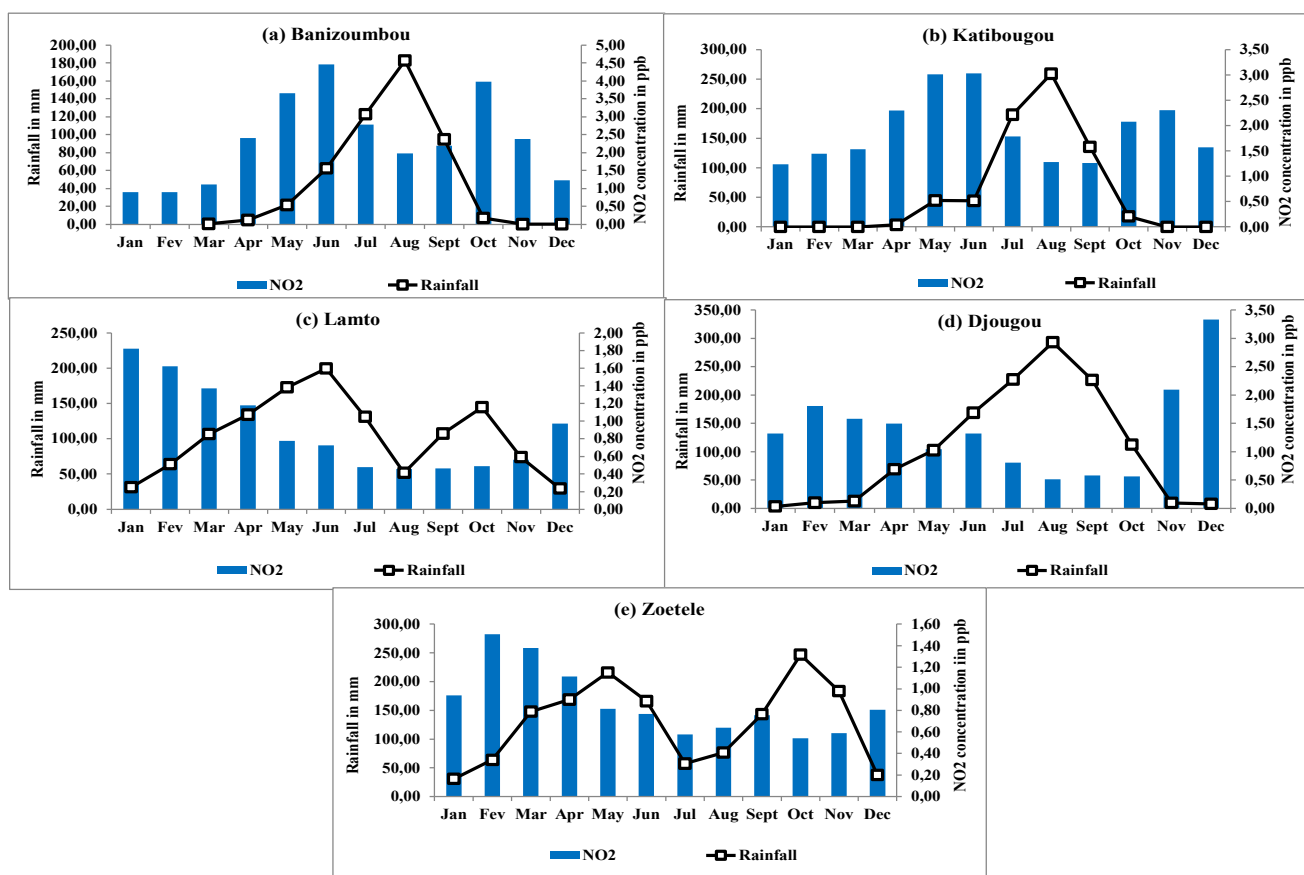
- In dry savanna, due to the irregularity of the rains (significant number of consecutive dry days) (Abassa *et al.*, 2024), the concentration of gases becomes high between two successive rainy events;
- In wet savanna and equatorial forest, the almost permanent precipitation means that the concentration of gases is continuously reduced by the leaching of the atmosphere. Thus wet deposition is very important in this area (Yoboué *et al.*, 2005; Laouali *et al.*, 2012).

**Annual average dry deposition of reactive nitrogen in the three major ecosystems:** Table 1 presents the values of the annual average dry deposition of reactive nitrogen in the form of gases and aerosols along the transect of dry savanna-wet savanna-equatorial forest ecosystems. Table 1 shows that the gaseous dry deposition of reactive nitrogen varying from 96.94% (Banizoumbou) to 98.68% (Zoétélé) has the most important contribution. The particulate form one is lower varying from 1.32% (Zoétélé) to 3.06% (Banizoumbou). No trend in the variation of the amount of total reactive nitrogen deposited (in the form of gases and aerosols) is observed. Thus, it seems obviously that the dry deposition of reactive nitrogen in an ecosystem depends on the meteorological conditions of the environment but above all on the natural and anthropogenic actions or processes that intervene in the nitrogen cycle.

agriculture, livestock, vegetation, biomass fires, domestic fires, soil microfauna activities, photochemical reactions). Our results on total reactive nitrogen deposition along the transect of dry savanna-wet savanna-equatorial forest ecosystems ( $3.98 \pm 0.20$ ;  $5.17 \pm 0.65$ ;  $4.50 \pm 0.18$  and  $7.17 \pm 0.20$   $\text{KgN}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ ) at Banizoumbou, Katibougou, Lamto and Zoétélé respectively are in agreement with those of Adon *et al.*, (2013) (4.0; 5.3; 4, 6 and  $8.0 \text{ KgN}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ ). However, the seasonal behavior relative to an ecosystem is a determining factor for the nitrogen cycle. The determination of seasonal average dry deposition of reactive nitrogen provides even more information on the influence of biological and physico-chemical sources and processes that impact the nitrogen cycle.

**Seasonal average dry deposition of reactive nitrogen in the three major African ecosystems:** From the values of the seasonal average deposition of the gaseous nitrogenous species including  $\text{NO}_2$ ,  $\text{NH}_3$  and  $\text{HNO}_3$  and those particulates mainly  $\text{NO}_3^-$  and  $\text{NH}_4^+$ , we determine the corresponding nitrogen masses. The results obtained are indicated in the following Table 2:

From Table 2, it can be deduce that the dry deposition of reactive nitrogen is mainly controlled by the gaseous dry deposition varying from  $2.69 \pm 0.38 \text{ KgN}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$  (Banizoumbou) to  $6.82 \pm 0.11 \text{ KgN}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$  (Zoétélé) during the dry season and from  $2.64 \pm 0.15 \text{ KgN}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$  (Lamto) to  $5.66 \pm 1.04 \text{ KgN}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$  (Katibougou) during the wet season.



**Figure 2(a-e). Covariation of NO<sub>2</sub> concentration and average monthly rainfall along the transect of African ecosystems: (a) Banizoumbou (1998-2013), (b) Katibougou (1998-2013), (c) Djougou (2005-2013), (d) Lamto (1998-2013) and (e) Zoetele (1998-2013)**

The dry deposition of reactive nitrogen in particulate form is approximately the same ( $0.12 \pm 0.04 \text{ KgN}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ ) in dry savanna (Banizoumbou and Katibougou) and in wet savanna (Lamto), but lower ( $0.09 \pm 0.03 \text{ KgN}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ ) in equatorial forest (Zoétélé). On the other hand, the gaseous dry deposit is greater at Zoétélé ( $7.08 \pm 0.20 \text{ KgN}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ ) then at Katibougou ( $5.05 \pm 0.65 \text{ KgN}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ ), Lamto ( $4.38 \pm 0.18 \text{ KgN}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ ) and finally lower in Banizoumbou ( $3.81 \pm 0.20 \text{ KgN}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ ). It appears that the importance of the dry deposition of gaseous and particulate reactive nitrogen is linked to the characteristics of the ecosystem (rainfall,

The ratios (dry season gaseous deposition/wet season gaseous deposition) are lower than unit in dry savanna (Banizoumbou (0.62) and Katibougou (0.83)) and higher than unit in wet savanna of Lamto (2.00) and in the equatorial forest of Zoétélé (1.40). During the dry season, this gaseous reactive nitrogen deposition follows a positive gradient on the dry savanna-wet savanna-equatorial forest transect. This is not the case in the wet season during which this deposit increases in dry savanna and decreases in wet savanna and equatorial forest. For the particulate deposit, it is greater in the dry season than in the wet season (Laouali *et al.*, 2017) with ratios greater than unit

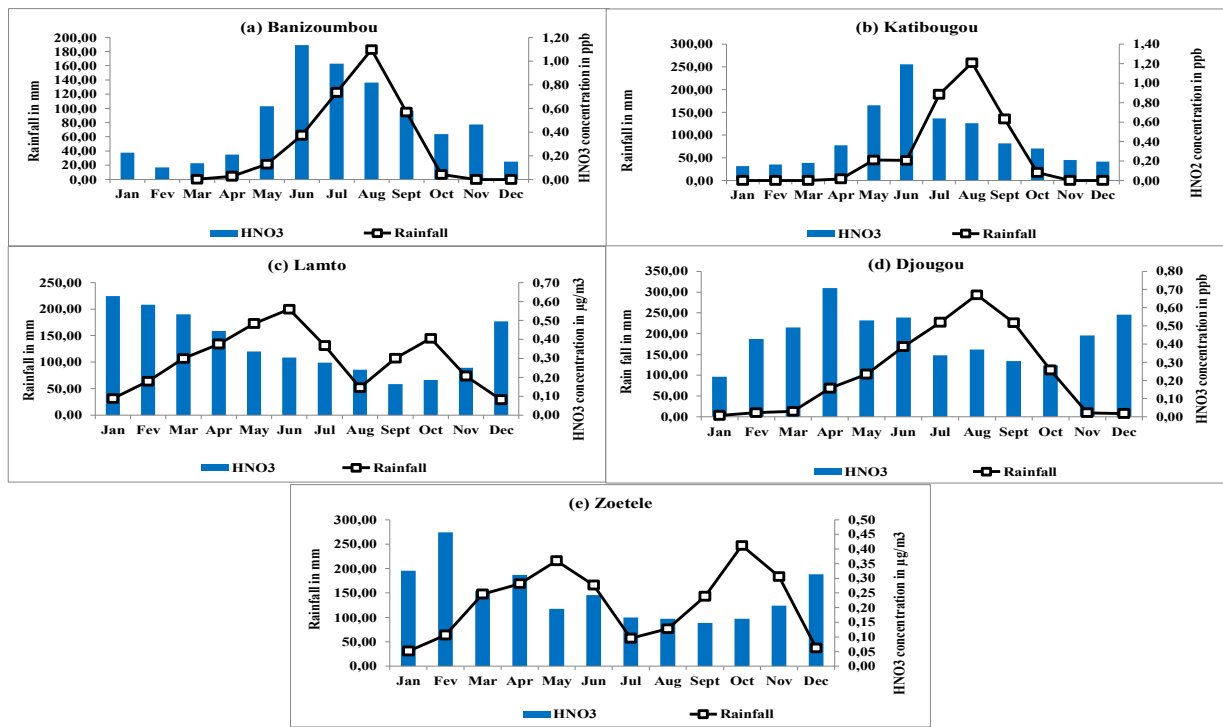


Figure 2(a-e). Covariation of HNO<sub>3</sub> concentration and average monthly rainfall along the transect of African ecosystems: (a) Banizoumbou (1998-2013), (b) Katibougou (1998-2013), (c) Djougou (2005-2013), (d) Lamto (1998-2013)) and (e) Zoetele (1998-2013)

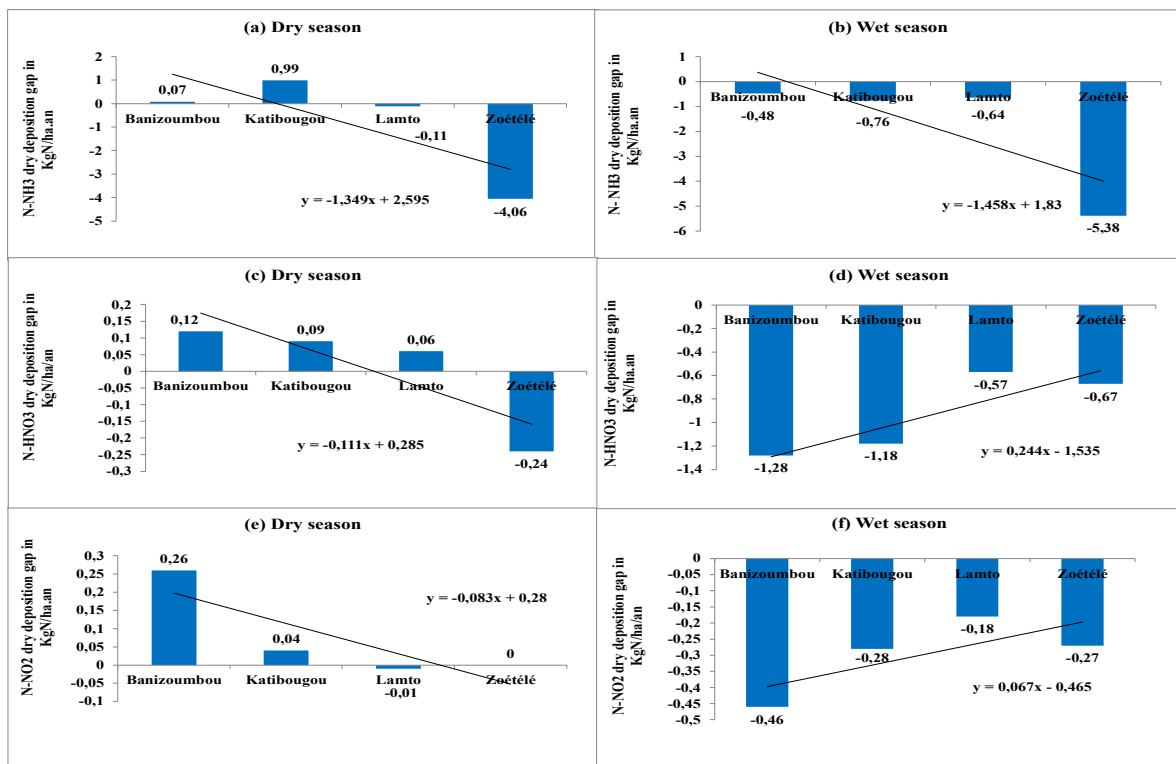


Figure 3(a-f). Variation of the gap between the Nrdry deposition for this work and for of Adon et al., (2013)

Table 1. Annual average dry deposition of reactive nitrogen to: (a) Banizoumbou (1996 - 2004), (b) Katibougou (1999 - 2003), (c) Lamto (1998 - 2005) and (d) Zoétélé (1999 - 2003)

Annual mean deposition in KgN.ha <sup>-1</sup> .yr <sup>-1</sup>	N-Total-gaz	N-Total-aerosols	N-Total	N-ratio-gaz (%)	N-ratio-aerosols (%)	Ratio (gaz/aerosols)
Banizoumbou	3.81 ± 0.20	0.12 ± 0.04	3.98 ± 0.20	96.94	3.06	31.63
Katibougou	5.05 ± 0.65	0.12 ± 0.04	5.17 ± 0.65	97.74	2.26	43.25
Lamto	4.38 ± 0.18	0.12 ± 0.04	4.50 ± 0.18	97.33	2.67	36.51
Zoetele	7.08 ± 0.20	0.09 ± 0.03	7.17 ± 0.20	98.68	1.32	25.01

**Table 2. Seasonal average dry deposition of reactive nitrogen in KgN.ha<sup>-1</sup>.year<sup>-1</sup> in: (a) Banizoumbou (1996 - 2004), (b) Katibougou (1999 - 2003), (c) Lamto (1998 - 2005) and (d) Zoétélé (1999 - 2003)**

Annual mean deposition in KgN.ha <sup>-1</sup> .yr <sup>-1</sup>	N-gaz dry deposition			N-particulate dry deposition			Total N-dry deposition (gaz + particule)		
	Dry Season (DS)	Wet Season(WS)	ratio: DS/WS	Dry Season (DS)	Wet Season (WS)	ratio: DS/WS	Dry Season (DS)	Wet Season (WS)	ratio: DS/WS
Banizoumbou	2.69 ± 0.38	4.32 ± 0.43	0.62	0.13 ± 0.01	0.09 ± 0.01	1.34	2.82 ± 0.40	4.41 ± 0.44	0.64
Katibougou	4.71 ± 0.26	5.66 ± 1.04	0.83	0.15 ± 0.02	0.08 ± 0.01	1.82	4.86 ± 0.28	5.74 ± 1.05	0.85
Lamto	5.29 ± 0.72	2.64 ± 0.15	2.00	0.15 ± 0.02	0.10 ± 0.01	1.54	5.44 ± 0.74	2.74 ± 0.16	1.99
Zoetele	6.82 ± 0.11	4.86 ± 0.07	1.40	0.05 ± 0.01	0.07 ± 0.01	0.78	6.87 ± 0.12	4.93 ± 0.08	1.39

**Table 3. Values of dry deposition of reactive nitrogen specific to each nitrogenous compound (KgN.ha<sup>-1</sup>.year<sup>-1</sup>), for this work and for Adon et al.**

N-deposition in KgN.ha <sup>-1</sup> .yr <sup>-1</sup>	season	Autors	Banizoumbou	Katibougou	Lamto	Zoetele
N-NH <sub>3</sub>	dry season	Adon	1.66 ± 0.69	2.64 ± 1.01	3.91 ± 1.29	8.86 ± 1.42
		This work	1.73 ± 0.29	3.63 ± 0.20	3.80 ± 0.54	4.80 ± 0.13
	wet season	Adon	4.21 ± 0.72	5.74 ± 0.96	3.07 ± 0.52	9.91 ± 2.35
		This work	3.73 ± 0.29	4.98 ± 0.82	2.43 ± 0.11	4.53 ± 0.38
N-HNO <sub>3</sub>	dry season	Adon	0.17 ± 0.09	0.36 ± 0.13	0.9 ± 0.29	1.66 ± 0.63
		This work	0.29 ± 0.04	0.45 ± 0.08	0.96 ± 0.07	1.42 ± 0.02
	wet season	Adon	1.4 ± 0.43	1.36 ± 0.52	0.59 ± 0.17	0.75 ± 0.23
		This work	0.12 ± 0.05	0.18 ± 0.10	0.02 ± 0.02	0.08 ± 0.03
N-NO <sub>2</sub>	dry season	Adon	0.41 ± 0.23	0.59 ± 0.16	0.54 ± 0.16	0.60 ± 0.19
		This work	0.67 ± 0.06	0.63 ± 0.03	0.53 ± 0.12	0.60 ± 0.19
	wet season	Adon	0.93 ± 0.25	0.78 ± 0.24	0.37 ± 0.15	0.52 ± 0.19
		This work	0.47 ± 0.09	0.50 ± 0.13	0.19 ± 0.02	0.25 ± 0.07

except at Zoétélé where this ratio is 0.78 (Table 2). From these results, it can be deduced that in dry savanna, the actions and processes leading to dry deposition of reactive nitrogen in the form of gas during the wet season (biological activities in the soil, agriculture and livestock) are more influential than those during the dry season (biomass fires). In wet savanna and equatorial forest, the opposite occurs. However, the processes leading to the formation of nitrogen aerosols (nucleation, suspension of terrigenous particles, condensation, coagulation) are more influential during the dry season.

**Contribution of each nitrogen compounds to the average seasonal deposition of reactive nitrogen in the three major African ecosystems:** Table 3 presenting the values of dry deposition of reactive nitrogen from each one of the nitrogenous compounds makes it possible to deduce the preponderant processes during the nitrogen cycle at the level of each ecosystem according to the seasons. Our results are also compared with those of Adon *et al.*, (2013). From these values, relative nitrogen deposition difference between the two results is determined. The variation of the gap is presented by figure 6(a - f). Results show that, the dry deposition of reactive nitrogen in its three forms (N-NH<sub>3</sub>, N-HNO<sub>3</sub> and N-NO<sub>2</sub>) has increased in dry savanna and decreased in wet savanna and equatorial forest except for N-HNO<sub>3</sub> at Lamto. The difference in dry deposition of reactive nitrogen decreases along the transect of dry savanna-wet savanna-equatorial forest ecosystems for the three forms. During the wet season, for all stations studied and for all the three forms (N-NH<sub>3</sub>, N-HNO<sub>3</sub> and N-NO<sub>2</sub>), the deposition of gaseous reactive nitrogen decreased. All deviations are negative and decreasing for N-NH<sub>3</sub>, increasing for N-HNO<sub>3</sub> and N-NO<sub>2</sub> along the transect of African ecosystems. In particular, the difference of dry deposition of reactive nitrogen is globally negative at Zoétélé, especially for N-NH<sub>3</sub> for which a difference of -4.06 and -5.38 KgNha<sup>-1</sup>.year<sup>-1</sup> during the dry season and the wet season respectively is obtained. These results are in agreement with those of Ossouhou *et al.*, (2019) showing a downward trend in NO<sub>2</sub> concentration over the period (1998 - 2015).

**Seasonal influence on nitrogen cycle processes in each ecosystem:** For each of the three forms of reactive nitrogen deposition, we present the predominant processes by ecosystem based on the results obtained.

**N-NH<sub>3</sub> dry deposition:** The ratio (N-NH<sub>3</sub> dry deposition in the dry season / N-NH<sub>3</sub> dry deposition in the wet season) are low in the dry savanna (Banizoumbou: 0.43; Katibougou: 0.73) whereas they are

1.56 and 1.06 in Lamto and Zoétélé respectively. Thus in dry savanna the dry deposition of N - NH<sub>3</sub> is greater during the wet season, which is the opposite in wet savanna and equatorial forest. The reasons for these significant depositions of ammoniacal nitrogen in its molecular form (N - NH<sub>3</sub>) would mainly be the following:

**In dry savanna including Banizoumbou and Katibougou, an agropastoral areas, during the wet season:**

- The volatilization of NH<sub>3</sub> from the degradation of animal excreta and urea but also from fertilizers used for crops;
- The emission of the excess ammoniacal nitrogen adsorbed by clay humic complex from the wet soil.
- The decomposition of crop residues by mineralization (transformation into NO<sub>3</sub><sup>-</sup>, NH<sub>3</sub> and NH<sub>4</sub><sup>+</sup>) of the nitrogen constituting the micro-organisms and plant sheets by the microfauna of the soil. It can be deduced that, in this region, the transformation of organic nitrogen goes from ammonification to nitrification;
- The velocity of deposition is also greater during the wet season (Adon *et al.*, 2013), therefore increasing the quantity of nitrogen deposited in dry form.
- On the other hand, during the dry season, biomass fires for the preparation of crop fields (Al Ourabi, 2002) are responsible for the emission and therefore the deposition of nitrogen in the N-NH<sub>3</sub> form.

**In wet savanna (Lamto) and equatorial forest (Zoétélé), areas with high density of vegetation and permanent humidity:**

- during the dry season, there is a significant emission of NH<sub>3</sub> by bush fires, soils and vegetation;
- during the wet season, the use of industrial nitrogen fertilizers for crops, the mineralization of organic matter.

Thus, the excess of humidity in these two ecosystems causes soil aeration to become insufficient and consequently leads to the reduction of nitrogen in the ammoniacal form.

**N- NO<sub>2</sub> dry deposition:** The dry deposition of reactive nitrogen in N-NO<sub>2</sub> form comes after that of N-NH<sub>3</sub>. During the dry season, this form of nitrogen deposition is in the same order of magnitude in the three major ecosystems but a little higher in Banizoumbou (0.67 ± 0.06 kg.ha<sup>-1</sup>.year<sup>-1</sup>) and Katibougou (0.63 ± 0.03 kg.ha<sup>-1</sup>.year<sup>-1</sup>) in dry

savanna compared to wet savanna at Lamto ( $0.53 \pm 0.12 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ ) and equatorial forest at Zoétélé ( $0.60 \pm 0.11 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ ). The same situation is obtained during the wet season with lower values. Indeed, the ratios (N-NO<sub>2</sub> - dry season/ N-NO<sub>2</sub> - wet season) are: Banizoumbou (1.43), Katibougou (1.26), Lamto (2.78) and Zoétélé (2.4). The influence of NO<sub>x</sub> emission processes (NO and NO<sub>2</sub>) seems to be approximately equivalent during the two seasons in dry savanna and more predominant in the dry season than in the wet season at wet savanna (Lamto) and equatorial forest (Zoétélé). These main processes are:

#### During the dry season

- Larger biomass fires in wet savanna and forest;
- Higher emissions of nitrogen compounds by fertilized soils in dry savanna.

#### During the wet season

- Oxidation of atmospheric nitrogen by lightning;
- The emission by the soil through bacterial nitrification (in aerobiosis) of ammoniacal nitrogen which is a more active process in dry savanna where the soil is more aerated;
- The emission by bacterial denitrification of NO<sub>2</sub> and NO<sub>3</sub><sup>-</sup> in anaerobiosis which is a more active process in wet savanna and equatorial forest where the stagnation of water from permanent rains makes the soil less aerated.
- The deposition velocity is higher during the wet season (Adon, 2011).

**N-HNO<sub>3</sub> dry deposition:** Dry deposition of reactive nitrogen in the N-HNO<sub>3</sub> form is relatively the lowest of the three forms. The values of this deposit define a negative gradient along the dry savanna – wet savanna – equatorial forest transect of West and Central African ecosystems. Nitric acid is a secondary pollutant, its concentration depends on:

- The availability of NO<sub>x</sub> in the atmosphere, oxidizing radicals and solar radiation which modulates its formation by photo-oxidation. This process is more important in dry savanna with high solar radiation;
- The concentration in the atmosphere of alkaline species, especially NH<sub>3</sub> (NH<sub>4</sub><sup>+</sup>) and Ca<sup>2+</sup>, which neutralize it and form particulate species. This process considerably reduces the concentration of HNO<sub>3</sub> during the dry season, a period during which the concentration of terrigenous species (Ca<sup>2+</sup>) is the highest in dry savanna (Laouali *et al.*, 2017);
- The importance of N-HNO<sub>3</sub> dry deposition in wet savanna and equatorial forest is due to its significant deposition velocity in these humid ecosystems (Adon *et al.*, 2013).

**N-NH<sub>4</sub><sup>+</sup> and N-NO<sub>3</sub><sup>-</sup> particulate deposition:** The dry deposition of reactive nitrogen in particulate form (N-NH<sub>4</sub><sup>+</sup> and N-NO<sub>3</sub><sup>-</sup>) is very low. The neutralization of HNO<sub>3</sub> and H<sub>2</sub>SO<sub>4</sub> by alkaline species is the origin of this deposition. Thus, the size of the particles obtained during this neutralization process (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> and NH<sub>4</sub>NO<sub>3</sub> can grow rapidly and be deposited on the ground in the form of dry deposition or more often serve as condensation nuclei for water vapor and be eliminated from the atmosphere as wet deposition during the rainy season (Laouali *et al.*, 2017) reflecting the abundance of NH<sub>4</sub><sup>+</sup> in the rains (Galy Lacaux and Modi, 1998; Yoboué, 2005).

## CONCLUSION

This study reports measurements of reactive nitrogen deposition along the transect of dry savanna-wet savanna and equatorial forest ecosystems in West and Central Africa. The concentration and deposition flux of NH<sub>3</sub>, HNO<sub>3</sub>, NO<sub>2</sub> (for gases) and NH<sub>4</sub><sup>+</sup>, NO<sub>3</sub><sup>-</sup> (for particles) are determined. From these compounds, reactive nitrogen is also analyzed. Results show that: The gaseous dry deposition of reactive nitrogen varying from 96.94% (Banizoumbou) to 98.68% (Zoétélé) mainly controls the total dry deposition of reactive nitrogen.

The particular form represents only a small contribution varying from 1.32% (Zoétélé) to 3.06% (Banizoumbou) and is greater during the dry season than in the wet season. The gaseous reactive nitrogen deposition follows a positive gradient along the dry savanna-wet savanna-equatorial forest transect during the dry season. However, in the wet season, this deposit increases in dry savanna and decreases in wet savanna and equatorial forest. The dry N - NH<sub>3</sub> follows a positive gradient along the transect of African ecosystems studied. The dry N-NO<sub>2</sub> deposition is of the same order of magnitude in the three major ecosystems but a little higher in Banizoumbou in dry savanna compared to wet savanna at Lamto and equatorial forest at Zoétélé. The same situation is obtained during the wet season with lower values. The dry N-HNO<sub>3</sub> deposition follows a negative gradient along the dry savanna – wet savanna – equatorial forest transect of West and Central Africa and is less important. All these situations revealed by our results show dependence on variations over time and space in solar radiation, vegetation cover, precipitation patterns, soil types, human activities, and the advance of desertification. Future work could explore this dependence in greater depth.

## REFERENCES

- A. T. Austin, L. Yahdjian, J. M. Stark, J. Belnap, A. Porporato, U. Norton, D. A. Ravetta, and S. M. Schaeffer. *Oecologia* 141 (2004) 221–235.
- Abassa, Y. M. Ouma, B. Abdou Latif b and D. Laouali. 2024. Long-Term Estimation of Rainfall Acidity in Major African Ecosystems. *International Journal of Environment and Climate Change*, Volume 14, Issue 10, Page 674-690, ISSN: 2581-8627.
- Adon, Attoh Marcellin 2011. Etude des concentrations de gazatmosphériques et estimation des flux de dépôt sec à l'échelle des principaux écosystèmes africains. Thèse de doctorat, Université Toulouse III-Paul Sabatier & Université de Cocody-Abidjan
- Al-Ourabi, H. and Lacaux, J. P. 2002. Dry and wet deposition for nitrogen and sulfur at seven IDAF stations in Tropical Africa, *International Global Atmospheric Chemistry (IGAC), Symposium, Crete, Greece, 18–25 September*,
- Audoi, L. N, 1991. Rôle de l'azote et du phosphore dans la pollution animale. *Rev. sci. lech. Off. int. Epiz.*, 10 (3), 629-654
- Binkley, D. et Richler. 1987. Nutrient cycles and H<sup>+</sup> budgets of forest ecosystems, *Adv. Ecol. Res.*, 16, 1-51.
- Brocard, D., Galy-Lacaux, C, J. P. Kouadio, G., and Yoboué, V. 1996. Emissions from combustion of biofuels
- C. Delon, C. E. Reeves, D. J. Stewart, D. Serça, R. Dupont, C. Mari, J.-P. Chaboureaud and P. Tulet. *Atmos. Chem. Phys* 8(2008) 2351–2363.
- C. Delon, C. Galy-Lacaux, A. Boone, C. Liousse, D. Serça, M. Adon, B. Diop, A. Akpo, F. Lavenu, E. Mougin, and F. Timouk. *Atmos. Chem. Phys.* 10 (2010) 2691–2708.
- Cellier P, Rochette P, Hénault C. 2013. Les émissions gazeuses dans le cycle de l'azote à différentes échelles d' territoire : une revue, *Cahiers Agricultures*, n° 22, p. 258-271.
- Chen, Y., Randerson, J.T., Van Der Werf, G.R., Morton, D.C., Mu, M., Kasibhatla, P.S., 2010. Nitrogen deposition in tropical forests from savanna and deforestation fires: FIRE EFFECTS ON TROPICAL N FLUXES. *Glob. Chang. Biol.* 16, 2024–2038. <https://doi.org/10.1111/j.1365-2486.2009.02156.x>.
- Delon, E. Mougin, D. Serça, M. Grippa, P. Hiernaux, M. Diawara, C. Galy-Lacaux, and L. Kergoat. *Biogeosciences* 12 (2015) 3253–3272.
- Duchemi N J., Dufil S J. & Pari S M. 1988. Nitrates et santé. *Tech. Sci. Munic.* 4, 181-191. Echelles. 9
- Ferm M. 1991. A Sensitive Diffusional Sampler. IVL publication B-1020, Swedish Environmental Research Institute Box 47086, 402 58 Goteborg, Sweden.
- Foulhouze, R. 1998. Nitrates et eaux d'alimentation. *Tech Sci. Munie.* 4, 171 - 176.
- Galloway JN, Dentener FJ, Capone DG. (2004). Nitrogen cycles: past, present, and future. *Biogeochemistry*, n° 70, p. 153-226.

- Galy-Lacaux C. and Modi A. I. 1998. Precipitation chemistry in the Sahelian savanna of Niger, Africa. *Journal of atmospheric chemistry*, 30(3), 319-343.
- Gupta, A., Kumar, R., Kumari, K.M., Srivastava, S.S., 2003. Measurement of NO<sub>2</sub>, HNO<sub>3</sub>, NH<sub>3</sub> and SO<sub>2</sub> and related particulate matter at a rural site in Rampur, India. *Atmos. Environ.* 37, 4837–4846.
- H. Al-Ourabi and J. P. Lacaux. International Global Atmospheric Chemistry (IGAC) Symposium Crete, Greece 18–25 September (2002).
- L. Jaegle, R. V. Martin, K. Chance, L. Steinberger, T. P. Kurosu, D. J. Jacob, A. I. Modi, V. Yoboué, L. Sigha-Nkamdjou, and C. J. Galy-Lacaux. *Geophys. Res.* 109 (2004) D21310, doi:10.1029/2004JD004787.
- Laouali, D., Galy-Lacaux, C., Diop, B., Delon, C., Orange, D., Lacaux, J. P., Akpo, A., Lavenue, F., Gardrat, E., and Castera, P. 2012. Long term monitoring of precipitation chemical composition and wet deposition over three Sahelian savannas, *Atmos. Environ.*, 50, 314–327.
- Laouali, D., Moussa, O., Galy-Lacaux, C. 2017. Characterizing Aerosols Chemistry in the Great African Ecosystems. *J. Mater. Environ. Sci.*, Volume 8, Issue 5 Page 1644-1653 in western Africa, in *Global Biomass Burning*, edited by: Levine. J. S., MIT Press, Cambridge, Mass, 350 - 360.
- M. Adon, C. Galy-Lacaux, C. Delon, V. Yoboué, F. Solmon, and A. T. Kaptue Tchuenta. *Atmos. Chem. Phys.* 13 (2013) 11351–11374.
- M. Adon, C. Galy-Lacaux, V. Yoboué, C. Delon, J. P. Lacaux, P. Castera, E. Gardrat, J. Pienaar, H. Al Ourabi, Laouali, B. Diop, L. Sigha-Nkamdjou, A. Akpo, J. P. Tathy, F. Lavenue, and E. Mougouin. *Atmos. Chem. Phys.* 10(2010)7467–7487
- Mariotti, A. 1994. Dénitrification in situ dans les eaux souterraines : processus naturels ou provoqués : unerevue, in *Hydrogéologie*, vol. 3, pp. 43-68.
- Moussa O, Laouali D, Adon M. 2018a. Measurement of atmospheric gases in the West and Central African ecosystems. *J. Mater. Environ. Sci.*, 2018, Volume 9, Issue 10, Page 2812-2821
- Moussa O., Laouali D., Akpo A. B. 2018b. Chemical characterization of PM<sub>2.5</sub> and PM<sub>10</sub> collected in dry savanna of Banizoumbou in Niger and wet savanna of Djougou in Benin. *Int. Res. J. Environmental Sci.* Vol. 7(9), 1-15.
- Ossouhou, M., Galy-Lacaux, C., Yoboué, V., Hickman, J. E., Gardrat, E., Adon, M., Darras, S., Laouali, D., Akpo, A., Ouafou, M., Diop, B., Opepa C. 2019. Trends and seasonal variability of atmospheric NO<sub>2</sub> and HNO<sub>3</sub> concentrations across three major African biomes inferred from long-term series of ground-based and satellite measurements, *Atmospheric Environment* 207 (2019) 148–166.
- Vitousek, P.M., 1997. Human domination of earth's ecosystems. *Science* 277, 494–499. <https://doi.org/10.1126/science.277.5325.494>.
- Yoboué, V., Galy-Lacaux, C. 2005. Rainwater Chemistry and Wet Deposition over the Wet Savanna Ecosystem of Lamto (Côte d'Ivoire), *J. Atmos. Chem.* 117 - 141.

\*\*\*\*\*