# Nitrogen Emission and Deposition Budget in Africa

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**Abstract**

Atmospheric nitrogen concentrations depend on land surface exchanges of nitrogen compounds. In Africa, deposition and emission fluxes of nitrogen compounds are poorly quantified, and are likely to increase in the near future due to land use change and anthropogenic pressure. This work is part of the long term deposition monitoring project IDAF initiated in the 1990s. IDAF (IGAC/DEBITS/Africa) is the African contribution to study deposition in the IGAC/DEBITS programme and contributes to the WMO-GAW programme. This work proposes an estimate of an atmospheric N compounds budget in Africa, along an ecosystem transect, from dry savanna to wet savanna and forest, for the years 2000 to 2007. The budget takes into account: (1) gaseous dry deposition fluxes estimated by considering N compounds concentrations at the monthly scale and modeling of deposition velocities at the IDAF sites, (2) wet deposition fluxes calculated from measurements of ammonium and nitrate chemical content in precipitations and (3) N emission sources taking into account simulated NO biogenic emission from soils, $NH_3$ emission by volatilization and NOx and $NH_3$ emission from biomass burning and domestic fires. This regional N emission deposition budget should give the present status at the scale of the main African ecosystems and should help to quantify the processes that may contribute to the changing levels of N deposition.

**Keywords**

Atmospheric Deposition, Reactive Nitrogen, Emission, Africa, budget.

## Introduction

Reactive nitrogen (Nr) compounds in the oxidized form ($NO_x$) and the reduced form ($NH_x$) play an important role in the chemistry of the atmosphere as well as the functioning of aquatic and terrestrial ecosystems. Nr inputs to ecosystems have considerably increased since pre-industrial times and are still accelerating to support the food and fuel needs of a growing human population (Galloway et al, 2008). Regional Nr assessments are available for the European Union, North America and China. However, major uncertainties remain for the developing world. Africa remains a region with too little reactive nitrogen inputs. Insufficient Nr leads to food insecurity in developing regions of the world, specifically in Sub Saharan Africa (SSA). SSA represents - at the global scale - one of the best case studies to investigate the ongoing challenges created by "too little N," and the on-going African Green Revolution that emphasizes overcoming soil nutrient depletion through provision of more nutrients through subsidized fertilizers, combined with improved cropping practices and a better water management. If in the « industrialized world », reducing Nr creation and its harmful impacts is of critical importance, the initial challenge in SSA remains to increase Nr to produce more food while minimizing nutrient losses and subsequent environmental damages (Sutton et al, 2011).

The work is part of the international program Deposition of Biogeochemically Important Trace Species (DEBITS) started in 1990 as part of the IGAC/IGBP core project. For tropical Africa, the IDAF (IGAC/DEBITS AFRICA) project started in 1994 and had the mission of establishing a long-term measuring network to study the atmospheric composition and wet- and dry- atmospheric deposition processes. IDAF activity is based on high quality measurements of atmospheric chemical composition data. This project implemented ten monitoring sites distributed in the major African ecosystems over West and Central Africa and South Africa: dry savanna (Niger, Mali, South Africa), wet savanna (Côte d'Ivoire and Benin) and equatorial forest (Cameroon, Congo). The work presented in this abstract starts in the context of the regional African assessment in the framework of the International Nitrogen Initiative (INI) (Galy-Lacaux and Delon, 2014) and of the global WMO GAW assessment on atmospheric deposition (Vet et al, 2014).

We present in this paper an atmospheric nitrogen budget including nitrogen emissions and deposition regionally representative of major African ecosystems. We propose a compilation of IDAF wet and dry nitrogen deposition fluxes monitored at various times since the late-1990s and an estimate of atmospheric nitrogen emissions representative of specific climate zones and vegetation types around each studied ecosystem.

## Methods

*Wet deposition*

An automatic precipitation collector designed for the IDAF network has been installed at all stations. Each rainfall event was analyzed for pH, conductivity and major inorganic and organic ions. Analytical procedures are given in Galy-Lacaux & Modi (1998) and on the web site http://idaf.sedoo.fr. We estimate the global uncertainty of the wet deposition fluxes to be about 10%.

*Dry N deposition*

Dry deposition fluxes at the African sites were estimated using the inferential technique for calculating dry deposition velocities and measured concentrations of gaseous and particle nitrogen species. Monthly-integrated concentrations of $NO_2$, $NH_3$, and $HNO_3$ were obtained through passive sampling and concentrations of water soluble p-$NH_4^+$ and p-$NO_3^-$ through filter-based sampling (Adon et al, 2013). We assume that the uncertainties on dry nitrogen deposition fluxes are larger than 30%.

*N emission sources*

The N emission sources take into account simulated NO biogenic emission from soils, $NH_3$ emission by volatilization and $NO_x$ and $NH_3$ emission from biomass burning and domestic combustions.

*NO biogenic emission from soils – $NH_3$ emission by volatilization*

Biogenic NO emissions from soils are derived from the method presented in Delon et al., 2008. The fertilization rate provided to the model is based on the calculation of N released by organic fertilization for 23 countries of West and Central Africa based on the N quantity released by livestock, and the number of animals per $km^2$ in each country from the FAO GLiPHA (http://kids.fao.org/glipha/). The overall uncertainty applied on $NH_3$ volatilization is estimated at 50%.

*$NO_x$ and $NH_3$ emission from biomass burning and from domestic fires*

Global biomass burning inventories for gases and particles are available from January 2005 to December 2006 on the Lab. d'Aerologie website (http://www.aero.obs-mip.fr:8001/) (Liousse et al., 2010). The total uncertainty for both $NH_3$ and $NO_x$ fluxes from biomass burning is 54%. Combustion of biofuel, used for cooking in West and Central Africa, represents a constant emission all year long and is a potential source of trace gases. The total uncertainty applied to domestic fires is 60%.

## Results

*N deposition budget*

*Wet deposition of N*. The multi-year average (2000-2007) precipitation-weighed mean concentrations of N in west and central Africa and 1986-1999 in South Africa ranged from 0.4 to 0.6 mg N/L in dry savannas to 0.2 mg N/L in forests, with higher values in dry savannas in accordance with high $NO_x$-N biogenic soil emissions combined with high $NH_3$-N emissions from livestock. Measurement data were combined with ensemble-mean model global modeling results for N deposition (Coordinated Model Studies Activities of the Task Force on Hemispheric Transport of Air Pollution – UNECE LRTAP) to provide nitrogen emission/deposition budgets and to assess the contribution of dry and wet deposition to total deposition of N (Vet et al, 2014). $N_{oxidized}$ wet deposition fluxes ranged from 0.7 to 2.0 kg N/ha/a. The lower deposition fluxes occurred in the rural dry savannas of West Central and South Africa and the highest fluxes in the industrial dry savanna area of South Africa. In the wet savanna and forested areas, the wet deposition fluxes were generally around 1.5 kg N/ha/a. The multi-year average wet deposition fluxes of $N_{reduced}$ ranged from 0.5 to 3.8 kg N/ha/a. Higher values of $N_{reduced}$ deposition were measured in west and central Africa.

The multi-year average total wet deposition fluxes ($N_{oxidized}$+$N_{reduced}$) ranged from 1.0 to 5.3 kg N/ha/a. At the dry savanna sites, $N_{oxidized}$+$N_{reduced}$ wet deposition varied from 1.7 to 3.4 kg N/ha/a. In the wet savannas and forested areas, the wet deposition fluxes ranged from 3.6 to 5.3 kg N/ha/a. N wet deposition in West Central Africa is dominated by N in the form of $NH_4^+$, which represents around 63 to 70% of the $N_{oxidized}$+$N_{reduced}$ wet deposition measurements at the paired IDAF stations (dry and wet savannas). In South African dry savannas, N wet deposition varies from 1.0 kg N/ha/a in Skukuza to 1.7 kg N $ha^{-1}$ $a^{-1}$ at Louis Trichardt (LT) to a maximum of 4.4 kg N/ha/a in the industrialized area of South Africa (Amersfoort site). In West and Central Africa including dry ecosystems, we observe that in spite of very low industrial and transportation emission sources, nitrogenous compounds in precipitation are in the same range as in the industrialized region of South Africa, albeit at the lower end.

*Dry deposition of N.* Combining dry deposition fluxes of N coming from the gaseous and the particulate phase, the total dry N deposition fluxes for the period 2002-2007 are estimated to be in the range of 4.2 to 5.3kg N/ha/a in dry savannas, 3.8 to 4.1 kg N/ha/a in wet savannas and 7 to 8 kg N/ha/a in forested ecosystems. In South African dry savannas, dry N deposition fluxes vary from 2.4 in LT to 5.0 kg N $ha^{-1}$ $a^{-1}$ in Amersfoort.

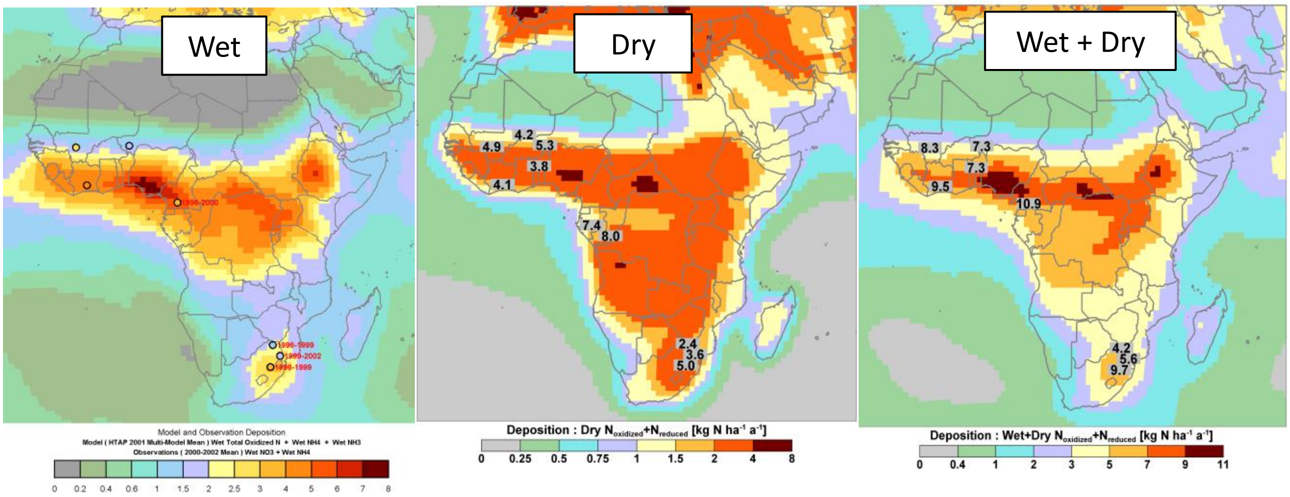


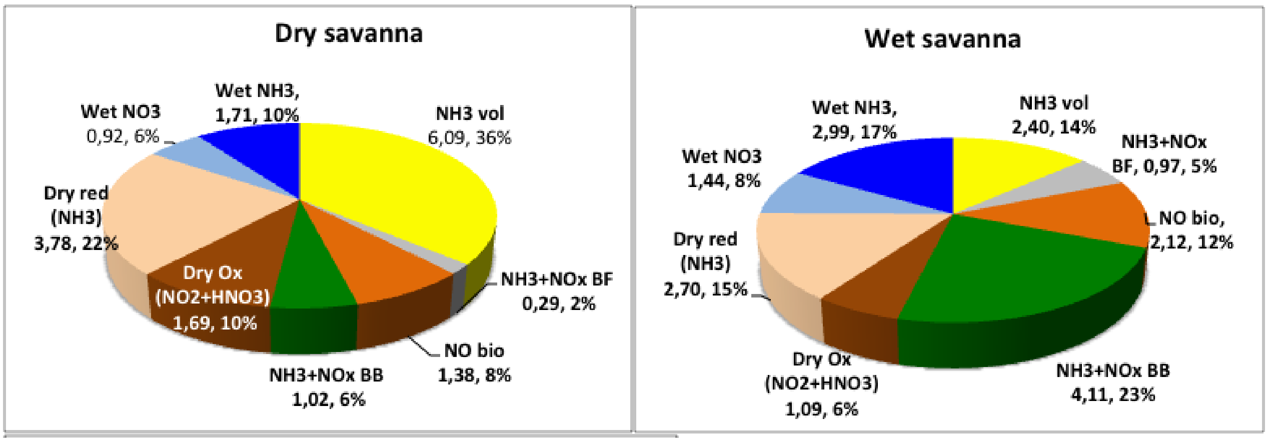

Figure 1: IDAF measurement-based wet N deposition and inferential estimates of dry N deposition from 2000 to 2007 superimposed on 2001 HTAP modeled wet, dry and wet+dry deposition of Noxidized + Nreduced (Vet et al, 2014).

*Total deposition of N.* The measurement-based multi-year total deposition of N is estimated at approximately 7-8 kg N/ha/a, 7-9 kg N/ha/a and 11 kg N/ha/a, in the dry savanna, humid savanna and forested areas, respectively. At the South African sites, total deposition of N at Amersfoort is estimated to be around 10 kg N /ha/a. Louis Trichardt and Skukuza presents lower values between 4 and 6 kg N/ha/a. Globally, model results underestimate total deposition of N in forested and dry savanna ecosystems in west and central Africa. The measurement-based estimates indicate the major importance of dry deposition in west central Africa, especially for nitrogenous gaseous compounds (Figure 2) (Galy-Lacaux and Delon, 2014). The combined model-measurement results for dry $N_{oxidized}$+$N_{reduced}$ deposition show an underestimation of dry deposition fluxes over West and Central Africa ecosystems, from 25% in wet savannas and forest to 50% in dry savannas and quite good agreement with dry N deposition fluxes measured in South Africa. This indicates that N-$NH_3$ sources taken into account are also mainly related to anthropogenic emission sources. We assume that the difference between model results and measurements representative of the African ecosystems rely on (1) the underestimation of N-$NH_3$ emissions from livestock and from agricultural activities and (2) the underestimation of dry deposition rates over forested ecosystems.

*N emission/deposition budget*

Figure 2 presents the results of the annual N emission/deposition budget at the regional scale of the west and central African ecosystems including all the different estimated contributions. The estimation of mean annual emissions including biogenic NO from soils, NOx and $NH_3$ from biomass burning and domestic fires, and $NH_3$ from volatilization are presented in Figure 2 according to the three main types of ecosystems. Dry savannas ecosystems are dominated by natural emissions of $NO_x$ from soils and $NH_3$ volatilization from animal excreta. In wet savannas, contributions of natural and biomass burning nitrogen compounds sources are in the same order of magnitude. In forested ecosystems, biomass burning sources become dominant (72% of the total emission) and $NH_3$ from volatilization remains low. Biomass burning emissions of $NH_3$ and $NO_x$ increase along the latitudinal transect dry savanna/wet savanna/forest. Results shows that emission sources of nitrogen compounds are in equilibrium with deposition fluxes in dry and wet savannas, with respectively 7.4 (±1.9) deposited and 9.01 (±3.44) kg N/ha/a emitted in dry savanna, 8.38 (±2.04) kg N/ha/a deposited and 9.60 (±0.69) kg N/ha/a emitted in wet savanna. In forested ecosystems, the nitrogen budget is dominated by wet + dry deposition processes (14.75 ± 2.36 kg N/ha/a), compared to emission processes (8.54±0.50 kg N/ha/a). Equatorial forests could be influenced by emissions coming from the both hemispheres, especially by savanna fires emissions transported further equator ward. This equatorward transport pattern was not unique to Africa and has been retrieved in Southeast Asia and South America. In addition, equatorial forests are well known to be a strong sink of compounds in term of dry deposition processes. Wet deposition fluxes are also assumed to be large considering the high amount of rain above this ecosystem. An important result highlighted by this budget is the importance of dry deposition processes in west and central Africa for N gaseous compounds. In dry savanna and forest, the relative contribution of dry deposition is between 63% and 76 %, in wet savanna around 50 %. In the deposition part of the budget, the dry deposition of ammonia is dominant for all the ecosystems representing 34 % to 53 % of the total.

In addition, the wet deposition of ammonium represents the second predominant contribution accounting for 14% to 36% of the total deposition.  N reduced deposition should be mainly related to the emission through the volatilization of $NH_3$ that represents 62%, 25% and 24 % in dry, wet savannas and forests, respectively. In dry and wet savanna, the oxidized N compounds in the emission and deposition part of the budget are in the same order of magnitude.



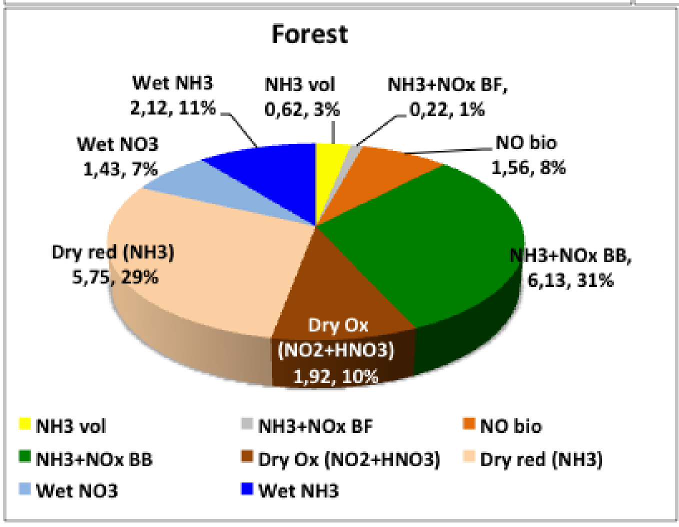




Figure 2: N emission and deposition budget for the major ecosystems in west and Central Africa, Wet: wet deposition, Dry: dry deposition, bio: biogenic emissions, BB: biomass burning emissions, BF: biofuel emissions, vol: volatilization.

## Conclusion

In this study, we have taken into account the contribution of major N compounds to establish and document the annual atmospheric Nr budget at the regional scale for three main types of ecosystems in Africa. This work brings a new insight in deposition and emission regional budgets in remote areas in Africa. Our results show that in the current situation, atmospheric N deposition fluxes represent a significant nutrients input to the African ecosystems (from 8 to 14 $kg.ha^{-1}.yr^{-1}$). However, substantial uncertainties remain, in particular concerning the importance of organic compounds in wet deposition. $NH_3$ remains the largest contributor to the total budget, both for emission and deposition processes, in the three types of ecosystem. Big differences however are to be noted in the source of emission, largely dominated by $NH_3$ volatilization from animal excreta in dry savanna, and by biomass burning in wet savanna and forests. The consequence on deposition is that $NH_3$ is the most important compound involved in deposition processes.

Our work on generating an atmospheric nitrogen budget, regionally representative of the main African ecosystems, represents an important contribution for “low N input regions”, which could be taken (1) as a baseline for quantities of N exchanged between the soil and the atmosphere and (2) as a way to discriminate the importance of different sources of N depending on the type of ecosystem of Western Africa. This contribution should be taken into consideration in future integrated nitrogen management system for Africa as a reference point before possible anthropogenic perturbations such as substantial N losses to the atmosphere and aquatic environments.

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