Towards a nitrogen budget for different forests types of the central Congo Basin

Marijn BAUTERS[1,2], Hans VERBEECK[2], Landry CIZUNGU[3] and **Pascal BOECKX**[1]

[1] Isotope Bioscience Laboratory – ISOFYS, Ghent University, Coupure Links 653, 9000 Gent, Belgium
[2] CAVElab, Computational and Applied Vegetation Ecology, Department of Applied Ecology and Environmental Biology, Ghent University, Coupure Links 653, 9000 Gent, Belgium
[3] Faculty of Agronomy, Université Catholique de Bukavu, Avenue de la mission, BP 285, Bukavu, DR Congo.
† E-mail: Pascal.Boeckx@UGent.be

Abstract
Recent data analyses and modelling activities have shown that the CO_2 uptake by terrestrial ecosystems strongly depends on site fertility, i.e. nutrient availability. Accurate projections of future net forest growth and terrestrial CO_2 uptake thus necessitate an improved understanding on nutrient cycles and how these are coupled to the carbon cycle. This holds especially for tropical forests, since they represent about 40–50% of the total carbon that is stored in terrestrial vegetation. Central African forests are very poorly characterized and their role in global change interactions shows distinct knowledge gaps. Research in the Congo Basin region should combine assessments of both carbon stocks and the underlying nutrient cycles, which directly impact the forest productivity. We set up a monitoring network for carbon stocks and nitrogen fluxes in different forest types in the Congo Basin, which is now operative. Preliminary data show an atmospheric N deposition of 20-30 kg N ha^{-1} yr^{-1} with N mainly derived from fires and different N dynamics in mixed vs. mono-dominant forests, whereby the N economy of ectomycorrhizal fungi is likely the driving force for establishment mono-dominant forest ecosystems and nitrate leaching.

Key Words
Tropical forest, N budget, permanent monitoring, fluxes, global change

Introduction
Tropical forests are terrestrial ecosystems with the highest carbon stocks and fluxes globally. Hence, their role in the global carbon cycle and atmosphere-biosphere exchange processes is of vital importance. Because of the magnitudes of these exchange fluxes, it is highly likely that within-biome changes in dynamics or land-use have a high impact on the atmosphere, but also that ongoing global changes in the atmosphere have a severe impact on this biome. To better understand this interaction, researchers have increased their modelling efforts last decade, which has provided the scientific community with varying results. One of the most appealing outcomes of these efforts is the work by Bonan (2008), which has clearly shown that most of the current global models show a complete lack of nitrogen or nutrient biogeochemistry in their models, and he has shown that the model outcomes change strongly when implementing nitrogen. He concludes that nitrogen availability plays a key role in future atmosphere-biosphere interactions, and that it is a vital component for correct model predictions. Additionally, Galloway et al. (2004) has shown that reactive N deposition, and hence N availability, is likely to rise by ten-fold by 2050 in tropical regions, due to anthropogenic perturbation of the global N cycle. However, up to now, there is no empirical data underpinning these modelling results, as both Amazonia and the Congo Basin show a complete lack of N deposition and flux monitoring sites for forests (Jia *et al.* 2016). It is clear that we need to move forward to basic empirical work on N fluxes in tropical forests, to fully understand the ongoing exchange processes and their consequences for ecosystem dynamics and biogeochemistry. To do so, we have set up a permanent monitoring network for carbon stocks and nitrogen fluxes in different forest types in the Congo Basin. This allows us to close the nitrogen budget of the different forest types. The data of this network serves the scientific community with a fundamental empirical understanding of N input and output, N transformation and biogeochemical processes in the largely unknown forests of the Congo Basin. Additionally, these data will serve modelers worldwide, as it is the first large-scale permanent N flux network in tropical African forest biomes.

Methods

Study sites

The study sites are confined to the central Congo Basin. The monitoring sites were setup in 5 main forest types of the Congo basin, being: mixed lowland tropical rainforest (Yoko), monodominant *Gilbertiodendron* forest (Yoko), mixed montane forest (Kahuzi-Biéga), montane bamboo forest (Kahuzi-Biéga) and Miombo dry woodland (Lubumbashi) (Fig 1).

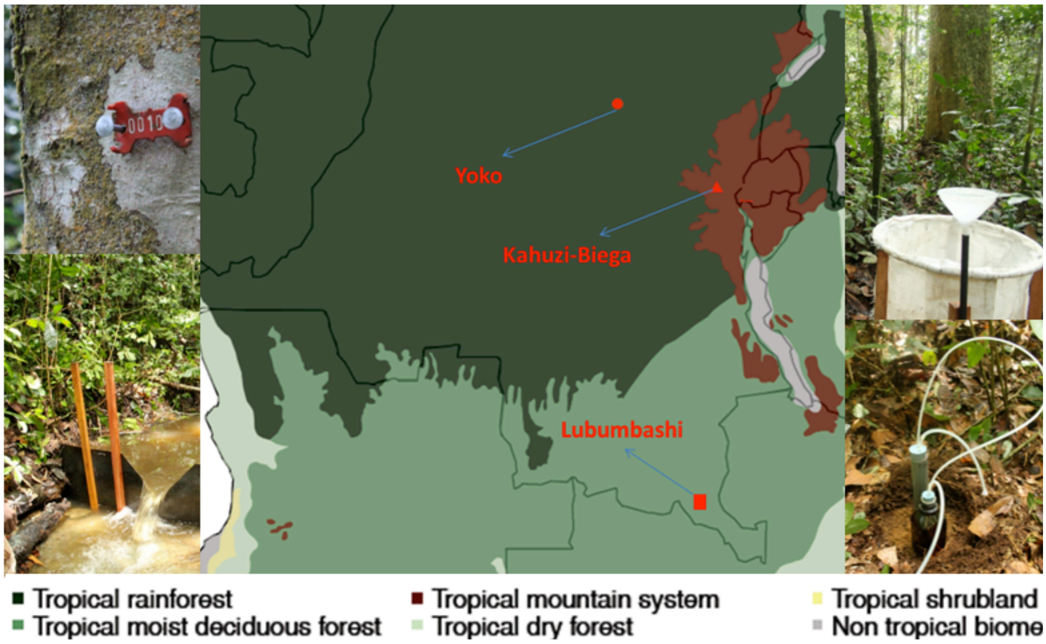

Figure 1: The tropical belt in Africa, with indication of the main vegetation types. Indicated on the map are the different study sites, with pictures of the experimental setup installed, showing the > 6000 tagged trees in the permanent monitoring plots, litterfall and throughfall collectors, lysimeters and the V-weirs; all sampled every two weeks by the local teams.

Sampling strategy

Throughfall and soil solution were sampled in all five forest types during a minimum of two years, along with bulk precipitation at the site. Each of the 15 plots (three per forest type) was equipped with eight throughfall collectors and twelve suction cup lysimeters, at three different depths (20, 40 and 80 cm) to collect soil solution water. This throughfall and the bulk precipitation was collected using collectors, consisting of polyethylene (PE) funnels (0.143 m diameter) supported by a wooden pole of 1.5 m height on which a polyethylene tube was attached and draining into 5-L PE container. A nylon mesh was placed in the neck of the funnel to avoid contamination by large particles. The container was partly buried in the soil and covered by leaves to avoid the growth of algae and to keep the samples cool. The throughfall collectors were set up in a systematic design (8 x 8 m; two lines of four collectors). Suction cup lysimeters consisted of a PVC tube fitted with a porous ceramic cup at a depth of 80 cm and connected to a buried opaque 1-L glass bottle by a PE tube. A pressure of -500 hPa was applied on each sampling occasion. Additionally, we installed 8 litterfall traps in the same design as the throughfall collectors. River water was sampled during two years at the outlet of the catchments, where a V-notch (90°) weir was installed to survey the river water flux and composition. The flow rate was estimated using a bucket and a stopwatch at every sampling occasion, and these data were coupled to the height recordings of a datalogger that took hourly height measurements before the V-notch. The total area of the PF catchment was calculated by analyzing a catchment-scale DTM by GIS.

All sampling was done fortnightly, and on each sampling occasion, the water volume in each collector was measured in the field, and recipients, funnels and mesh were replaced by others, rinsed and/or washed with distilled water. A volume-weighted composite sample per type of device per plot was made. After pH measurement, all samples were stored in a freezer and sent in batch to Belgium for chemical analysis.

Chemical analysis
The volume-weighted monthly composite samples were first filtered using a nylon membrane filter of 0.45 µm. Ammonium (NH_4^+) and nitrate (NO_3^-) were determined colorimetrically (AA3, Bran&Luebbe, Germany), while Na^+ and Cl^- were determined by atomic absorption spectrophotometry (Eppendorf, Netheler & Hinz GmbH Hamburg, Germany). We used alkaline persulfate oxidation for analysis of total dissolved N (TDN) in order to convert NH_4^+ and total dissolved N into NO_3^-). Dissolved organic nitrogen (DON) was determined as the difference between TDN and dissolved inorganic nitrogen (NH_4^+ and NO_3^-). When the concentration was below the detection limit we assumed the concentration to be half of the detection limit. When there was no or not enough sample (e.g. during the dry season), the concentration concerned was set at zero. Values presented here are averages and standard deviations calculated from three plots except for the bulk precipitation.

2.4. Data processing and analysis
The average throughfall water flux was obtained by dividing the average water volume by the surface area of the collector. Element deposition was calculated by multiplying the water volume with the element concentration in that volume. The net total effect of the canopy on depositions was obtained by subtracting the bulk precipitation deposition from throughfall deposition and is designated as net throughfall water (NTF). The canopy budget model (Staelens *et al.* 2008) was used to estimate the contribution of dry deposition and canopy leaching or uptake to net throughfall water. We calculated the deposition quantity of net throughfall water (NTW, kg ha^{-1} yr^{-1}) to obtain the total effect of the canopy on deposition in the forest:

$$NTF = TF - BD = DD + CE;$$

where BD= bulk deposition, TF= throughfall, DD = dry deposition, and CE = canopy exchange (with canopy leaching if CE > 0 and canopy uptake if CE < 0). In the canopy budget method, Na^+ is assumed to be inert with respect to the canopy, i.e. neither uptake nor leakage occurs.

The leaching flux at the level of the suction cup lysimeters was calculated using the Chloride Mass Balance (CBM) method. This method is based on the assumption of conservation of mass between the input of atmospheric chloride and the chloride flux in the subsurface.

Results
In this paper, we present preliminary results, based on data of 4 months flux monitoring in the two lowland sites, but more data will be available. The data of these 4 months have been extrapolated to yearly data and are shown in Table 1. There are clear differences in throughfall between both forest types, where mixed lowland showed a higher net throughfall than the monodominant forest. The monodominant forest predominantly leaches nitrate, whereas the mixed lowland forest shows the largest losses for organic nitrogen. Total losses in the upper layers are comparable between the two forest types. Both forest types showed a clear decrease in N leaching at 80 cm depth, especially for nitrate, indicating subsoil denitrification. Overall, while the total amounts of N leaching at the deepest layer were comparable, the monodominant forest had a relatively higher loss due to leaching.

Table 1: Preliminary results of both lowland forest types. These results are based on 4 months of sampling and were extrapolated for one year.

	Mixed Lowland				Monodominant			
	NH_4^+	NO_3^-	N_{org}	TDN	NH_4^+	NO_3^-	N_{org}	TDN
INPUT (kg ha^{-1} yr^{-1})								
Throughfall	5.4	11.5	17.5	34.4	5.2	9.1	5.7	20.0
Bulk Deposition	2.3	3.0	1.4	6.7	2.3	3.0	1.4	6.7
Net throughfall	3.1	8.5	16.1	27.7	2.9	6.1	4.3	13.3
LEACHING (kg ha^{-1} yr^{-1})								
At 20 cm	2.5	5.5	9.9	17.9	3.9	17.1	1.6	22.6
At 40 cm	6.1	8.6	3.5	18.2	3.5	13.9	2.9	20.2
At 80 cm	1.5	2.5	2.0	6.1	1.1	5.6	1.1	7.8
LEACHING LOSS	28%	22%	11%	18%	20%	62%	20%	39%

Discussion

The decreased dry deposition in the monodominant forest is without doubt due to the more homogenous canopy with large leafs in the monodominant forest. Contrary to the mixed forest, which is structurally far more complex, and where the total leaf area, and hence contact surface, is bigger. The leaching data suggest that the microbial communities of both ecosystems deal with N input in a different way. In the monodominant topsoil, almost all nitrogen that enters the system is converted to nitrate, while nitrate and ammonium are more balanced in the mixed lowland forest. This is in concordance with recent findings that a differing ectomycorrhizal (*i.e. Gilbertiodendron* is a species associated with ectomycorrhizal) nitrogen economy might be at the base of monodominance in tropical forests. We will look deeper into this using a ^{15}N-tracing experiment. Perhaps the most striking result from Table 1 is the high N deposition load in both ecosystems. Modelling efforts pointed out that these remote forests are expected to show levels of 10 kg N ha^{-1} yr^{-1} by 2050 (Galloway *et al.* 2004). Instead, we empirically showed that N deposition load is already two- to threefold higher. In contrast to Europe or the United States, these high deposition levels cannot be explained by high fertilizer use or high livestock levels in the surroundings. Instead, the omnipresence of fires in Africa, caused by slash-and-burn practices, is far more likely to cause this high N deposition. We checked the fire loads of the winds arriving at our monitoring sites, using the same methodology as Boy et al. (2008), using NOAA's HYSPLIT model and fire detection data from MODIS' Terra and Aqua satellite. The combined result with N deposition shows a similar pattern over time (Fig. 2).

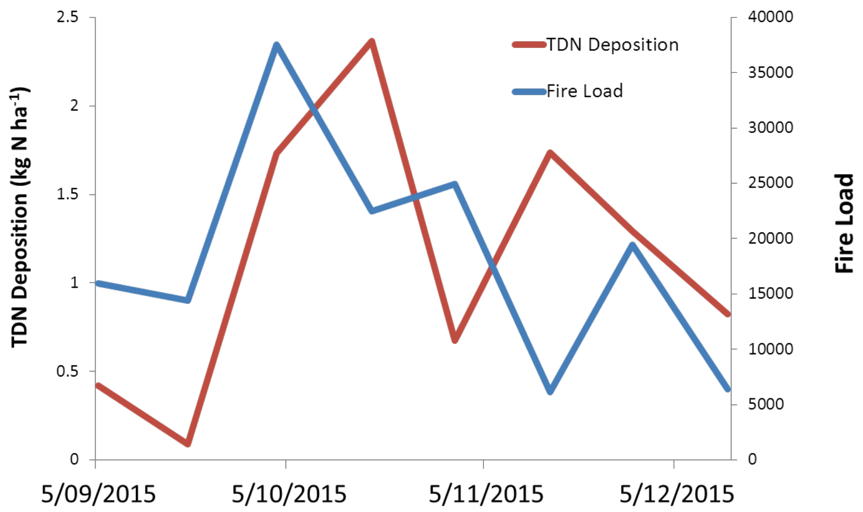

Figure 2 The total N deposition in the mixed forest over time, along with the modelled fire load of the arriving winds. Fire load stands for the number of fires that were passed by one-week-backwards trajectory of winds.

Our preliminary conclusion is hence that fires in the savannah and forest zone on the African content are fertilizing the natural undisturbed forests with N. These high N depositions loads are likely to affect the long-term nutrient dynamics and ecology of this forest and hence carbon budgets.

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