1. Introduction

Nitrogen (N) cycle is disrupted by anthropogenic activities, and the detailed knowledge of the processes responsible for N-cycling is thus required. Three anaerobic metabolisms are responsible for nitrate (NO$_3^-$) or nitrite (NO$_2^-$) reduction, with different impacts on N cycle:

- **Canonical denitrification (N loss, N$_2$O production), which can occur with different electron donor, such as organic matter or HS:**
  
  \[ \text{NH}_4^+ + \text{OM} \rightarrow \text{N}_2 + \text{CO}_2 \]

- **Anoxic ammonium oxidation (anammox) (N loss):**
  
  \[ \text{NH}_4^+ + \text{NO}_2^- \rightarrow \text{N}_2 + \text{SO}_4^{2-} \]

- **Dissimilatory reduction of nitrate to ammonium (DNRA) (N retention):**
  
  \[ \text{NO}_3^- + \text{OM} \rightarrow \text{NH}_4^+ + \text{CO}_2 \]

Knowledge on the regulation of these competing processes is crucial for predicting, modeling, and managing the N-cycle, but they remained understudied in tropical freshwaters. We thus investigated one of the East-African Great Lakes, Lake Kivu (Rwanda-Democratic Republic of the Congo), a deep meromictic lake characterized by:

- Anoxic deep waters rich in NH$_4^+$, carbon dioxide, and methane ($\text{CH}_4$).
- A nitrous zone at the base of the mixed-layer, forming in rainy season ($\sim 3$), where N$_2$O accumulates ($\sim 1$).
- A zone of sulfate ($\text{SO}_4^{2-}$) reduction below the oxic-anoxic interface, leading to HS$^-$ accumulation to up to 200 $\mu$mol L$^{-1}$ in the anoxic waters ($\sim 0$).

2. Abstract

We investigated anaerobic nitrogen (N) cycling in the water column of Lake Kivu, a deep meromictic tropical lake in East Africa. Data were collected at one station in the Northern Basin and one in the Southern Basin, during two sampling campaigns (June 2011—dry season, and February 2012—rainy season). Short-term incubations of sulfide-free water with $^{15}$N-labeled substrates revealed high potential denitrification and dissimilatory nitrate reduction to ammonium (DNRA) rates (up to 300 and 36 $\mu$mol N produced L$^{-1}$ h$^{-1}$, respectively), while anaerobic ammonium oxidation (anammox) was lower (up to 3.3 $\mu$mol N produced L$^{-1}$ h$^{-1}$). However, anammox rates were 15 $\mu$mol N produced L$^{-1}$ h$^{-1}$ when $^{15}$NH$_4^+$ was added at depths where NH$_4^+$ concentrations were very low ($<1 \mu$mol L$^{-1}$). With the addition of 5 $\mu$mol L$^{-1}$ of $^{15}$NO$_3^-$ and 20 $\mu$mol L$^{-1}$ of H$_2$S, denitrification and anammox were stimulated in the Northern Basin, while the increase of DNRA rates was not notable. In the Southern Basin, the addition of H$_2$S decreased denitrification rates, probably because of competition with DNRA, which increased, while no effect was observed on anammox. This study puts into evidence the co-occurrence of denitrification, anammox and DNRA, for the first time in a great tropical lake, and underlines the spatial heterogeneity of these processes. Contrary to numerous reports in literature, we show that anammox can significantly occur in presence of H$_2$S, suggesting that the contribution of anammox in the N cycle may be underestimated.

3. Hypotheses and objectives

Three hypotheses:
1. Upward fluxes of HS$^-$: from deep waters to nitrosonitrogenous zone could support denitrification coupled to HS$^-$ oxidation, and HS$^-$ is a source of energy for anammox.
2. Upward fluxes of NH$_3$: from deep waters to nitrosonitrogenous zone could support anammox.
3. Competition could occur between the three processes:
   - To test the effect of HS on anammox.
   - To identify the competitive relationships.

4. Material and methods

Two different stable labeling experiments were performed:
1. Determination of denitrification, anammox and DNRA by amending water with $^{15}$NO$_3^-$.
2. Determination of denitrification, anammox and DNRA by amending water with $^{15}$NO$_3^-$ + H$_2$S.

For both experiments, a time course was established by arresting samples at 6h, 12h, 24h, 48h, and 72h.

5. Results and conclusions

5.1 Co-occurrence of denitrification, anammox and DNRA, and stimulating effect of HS$^-$

Dashed line = oxic-anoxic interface

5.2 Competitive relationships

5.3 Conclusions

Our results show:
1. The co-occurrence of denitrification, anammox and DNRA in the water column of a tropical lake.
2. The link between denitrification and HS$^-$ oxidation, probably when organic matter is limiting.
3. The occurrence of anammox with HS$^-$, and even a stimulation of anammox by the addition of HS$^-$.
4. That anammox is not stimulated in the presence of DNRA in the water column of Lake Kivu, probably because NH$_4^+$ is not limiting.
5. That anammox is favored in the presence of denitrification, probably because denitrification create a detoxified zone for anammox microorganisms.