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RESEARCH ARTICLE

# Nitrogen mineralization and eutrophication risks in mangroves receiving shrimp farming effluents

Hermano Melo Queiroz[1,2] · Tiago Osório Ferreira[1] · Carlos Alberto Kenji Taniguchi[3] · Diego Barcellos[1] · Juliana Costa do Nascimento[1] · Gabriel Nuto Nóbrega[4] · Xosé Luis Otero[5] · Adriana Guirado Artur[2]

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## Abstract

Nitrogen (N) inputs originated from shrimp farming effluents were evaluated for potential changes in the net N mineralization for mangrove soils from Northeastern Brazil. Our study provides notable information and assessment for the potential enhancement of N mineralization in preserved and shrimp-impacted semi-arid mangrove soils of the Jaguaribe River estuary, which is one of the largest shrimp producers of Brazil, using an analytical and daily tidal variation experimental approach. Nitrogen-rich effluents promoted a significant ($p$ value < 0.001) increase of the total soil N content (1998 ± 201 mg kg$^{-1}$ on average) compared with the preserved sites (average: 1446 ± 295 mg kg$^{-1}$). The effluents also increased the N mineralization in the shrimp-impacted sites (N-min: 86.6 ± 37.5 mg kg$^{-1}$), when compared with preserved mangroves (N-min: 56.5 ± 23.8 mg kg$^{-1}$). Over a daily tidal variation experiment, we found that just 30% (36.2 ± 20.6 mg kg$^{-1}$) of mineralized N remains stored in the soil, whereas 70% (102.9 ± 38.8 mg kg$^{-1}$) was solubilized in tidal waters. Therefore, the N mineralization process may trigger eutrophication by increasing N inorganic bioavailability in mangrove soils receiving N-rich effluents from shrimp ponds, which in turn might increase primary producers' activity. This approach has not been studied so far in semi-arid mangroves, where the shrimp farming activity is one of the most important economic activities.

**Keywords** Inorganic nitrogen · Mangrove soils · Soil pollution

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✉ Hermano Melo Queiroz
hermanomelo@usp.br

1 Luiz de Queiroz College of Agriculture, University of São Paulo (ESALQ-USP), Av. Pádua Dias 11, 13418-900, Piracicaba, São Paulo, Brazil

2 Departamento de Ciências do Solo, Universidade Federal do Ceará, UFC, Av. Mister Hull 2977, Campus do Pici, Fortaleza, Ceará 60440-554, Brazil

3 Embrapa Agroindústria Tropical, Rua Dra. Sara Mesquita Street, 2270, Planalto Pici, Fortaleza, Ceará 60511-110, Brazil

4 Programa de Pós-Graduação em Geociências (Geoquímica), Departamento de Geoquímica, Universidade Federal Fluminense, Rua Outeiro São João Baptista s/n, Centro, Niterói, Rio de Janeiro 24020-141, Brazil

5 Departamento de Edafoloxíe e Química Agrícola, Facultade de Bioloxía, Universidade de Santiago de Compostela, Santiago, Spain

## Introduction

Nitrogen (N) is an essential nutrient for thriving mangrove ecosystems. However, excessive exogenous N amendments may pose serious environmental risks in these ecosystems, such as eutrophication (Feller 1995; Boto 2017). For example, the discharge of high loads of nutrients (including N) into mangroves by anthropogenic activities affects the behavior and function of these ecosystems (Kauffman et al. 2018; Queiroz et al. 2019; Barcellos et al. 2019), which can turn them into an important source of greenhouse gases (GHG) (Chen et al. 2016; Roughan et al. 2018; Queiroz et al. 2019). Other natural factors such as changes in land use, hydrological regimes, storms, tidal levels, sea-level rise, and deforestation may also affect N dynamics and bioavailability (Alongi 2018).

At the northeastern coast of Brazil, shrimp farming is an important economic activity, producing over 90,000 tons of shrimp per year (Queiroz et al. 2013; Nunes 2015). Shrimp production at the NE coast of Brazil is characterized by low technological investments and high rates of water reutilization (5–10%), from where the N-enriched effluents are directly disposed into the mangroves (Mole and Bunge 2002; Jackson et al. 2003; Nóbrega et al. 2013; Suárez-Abelenda et al. 2014). Then N-enriched effluents from shrimp ponds may enhance N content in mangrove soils/water and may alter N mineralization rates (Briggs and Fvnge-Smith 1994; Molnar et al. 2013; Keuskamp et al. 2015; Tian et al. 2019). However, poorly is known about the lability of these N compounds in affected soils and how distinct climatic conditions drive the biogeochemical process related to N dynamics. In fact, soils from semi-arid mangrove forests may present distinct conditions when compared with those located in more humid climate (Nóbrega et al. 2019; Kauffman et al. 2018). Thus, to better understand the impacts in mangroves receiving N-rich effluents, it is important to evaluate N-related process in mangroves influenced by specific environmental conditions.

Nitrogen mineralization (N-min) in mangrove soils is a microbial-induced process that transforms organic-N into inorganic-N, including nitrate ($NO_3^-$) and ammonium ($NH_4^+$) species (Cartaxana et al. 1999; Inoue et al. 2011; Basyuni et al. 2014; Craft 2016; Lin et al. 2016). Besides N-min, other important biogeochemical processes associated with N cycle occur in mangroves soils, such as biological nitrogen fixation, gaseous losses of N (e.g., denitrification, $N_2O$ emissions), fluxes of N across the sediment-water interface, tidal fluctuation and export, and assimilation by mangrove plants (Reis et al. 2017). Considering the N budget in mangroves, only 10% of N is stored in the soil, whereas 40% is recycled within the fauna and flora, and the remainder is exported (Alongi 2002).

Tidal fluctuations impact N mineralization by submerging soils with tidal water, affecting oxygenation and redox reactions (oscillating between oxic, suboxic, and anoxic conditions) and influencing anaerobic microbial metabolism (Alongi 2005). In mangroves, N mineralization rates are mainly influenced by anaerobic pathways (e.g., nitrate reduction, iron reduction, and sulfate reduction), which result in lower decomposition rate and N-min, favoring the storage of organic nitrogen into the soil (Canfield et al. 1993; Kristensen et al. 2000; Donato et al. 2011).

Despite the slow N-min rates in mangroves soils, this process may be enhanced by N inputs leading to increased microbial activity and the "priming effect" (Muñoz-Hincapié et al. 2002; Bianchi 2011). The "priming effect" is defined as a vigorous/short-term degradation of the organic matter in the presence of readily degradable organic compounds (Fontaine et al. 2003; Chen et al. 2014). The intensification of organic matter degradation caused by priming effect may result not only in higher N mineralization and a decrease in soil organic matter content (Suárez-Abelenda et al. 2014) but also in environmental impacts such as eutrophication and greenhouse gases emissions (especially $N_2O$) (Zhang et al. 2012; Guenet et al. 2014; Li et al. 2015).

Previous studies in terrestrial ecosystems reported priming effect by the addition of labile compounds to soils, promoting a release of soil-derived carbon and nitrogen. However, in marine ecosystems (especially in mangroves), few studies reported this effect and the potential environmental impacts, even though mangroves are one of the ecosystems most impacted by the discharge of N-rich effluents and labile compounds (Páez-Osuna et al. 1999; Jackson et al. 2003; Blagodatskaya and Kuzyakov 2008; Bianchi 2011; Suárez-Abelenda et al. 2014; Keuskamp et al. 2015). Few studies reported effects on mangrove soils receiving N-rich effluents from shrimp ponds, and all were performed in mangroves affected by humid climates, with mean rainfall above 1200 mm, and smaller shrimp farm areas compared with the northeastern coast of Brazil (Trott et al. 2004; Molnar et al. 2013; Tian et al. 2019).

This study aimed to (i) assess the potential increase of nitrogen content in mangrove soils impacted by the disposal of shrimp farming effluents compared with the soils from pristine mangroves and the potential for environmental impacts and to (ii) quantify changes in net nitrogen mineralization in both soil conditions. To pursue our objectives, we analyzed nitrogen forms in soils from shrimp-impacted and preserved mangroves in an estuary largely influenced by N-rich effluents from shrimp production of NE-Brazil (Ceará State) and also conducted a controlled experiment simulating tidal fluctuations (by submerging and draining soils daily) and monitoring the fate of nitrogen in soil/water compartments.

## Material and methods

### Site characterization

The studied mangrove forest covers 762 ha and is located in the Jaguaribe River estuary (NE-Brazil; Godoy and de Lacerda 2015). This region is one of the largest shrimp production centers in the Ceará State, corresponding for more than 33% of the Brazilian shrimp production with approximately 3300 ha of shrimp ponds (Queiroz et al. 2013; Tahim and de Araújo Junior 2014), highlighting the importance of the studied site (Fig. 1). The local shrimp industry generates a huge amount of effluents, for example, a standard pond of 30,000 $m^2$ discharges on average 27,000 $m^3$ of effluents into the Jaguaribe River (de Figueirêdo et al. 2006; Meireles et al. 2007). According to Lacerda et al. (2006), in the state of Ceará, the aquaculture on average generates about 0.47 kg $ha^{-1}$ $day^{-1}$ of N resulting in an annual discharge of about 110 kg $ha^{-1}$ into mangroves.

The climate at the Jaguaribe River estuary is a tropical semi-arid, with low rainfall (983 mm annual average) and high evapotranspiration (favoring the occurrence oxic conditions in the soil), presenting an irregular wet (from January to

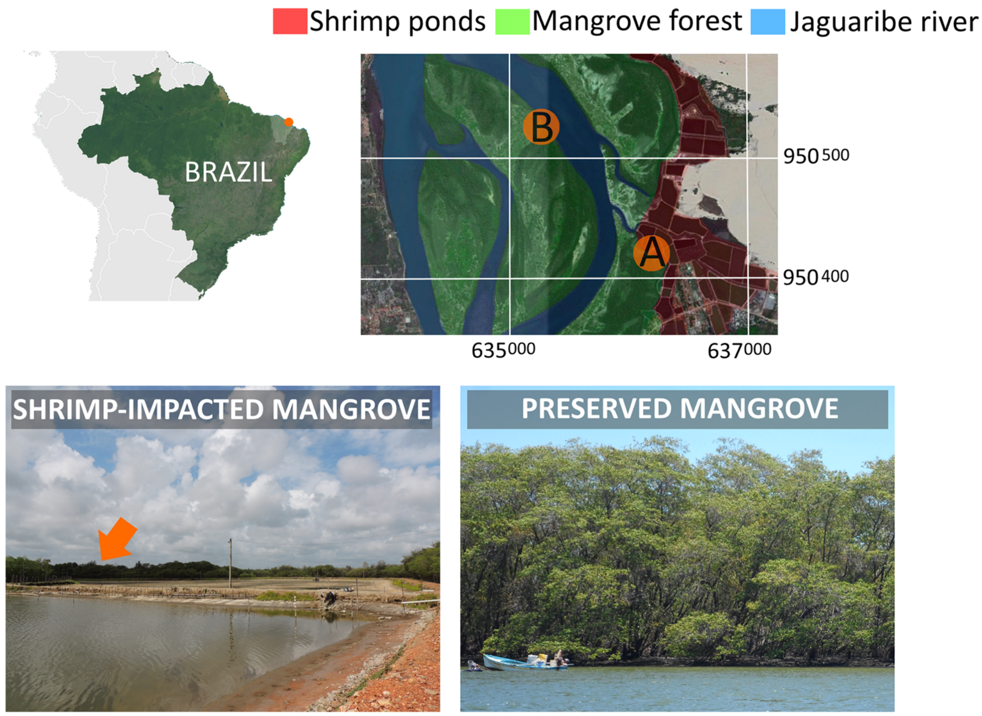



**Fig. 1** Location of Jaguaribe River in Ceará State, Northeastern Brazilian, illustrating shrimp-impacted mangroves (**A**) and preserved mangroves (**B**). The orange arrow shows the mangrove near a shrimp pond

May) and long dry (from June to December) seasons with annual mean temperature of 27 °C (Silva and Souza 2006; Queiroz et al. 2018). The study site is within a mesotidal system, with tidal oscillations from 0.7 m up to 3.3 m and 1.0 m between the spring and neap tides (Frota et al. 2016).

## Soil sampling and analysis

The soil samples were collected in two sites at the Jaguaribe River estuary: a mangrove near to the discharge of the shrimp farm effluents (shrimp-impacted site) and another mangrove free of shrimp farm effluents (preserved mangrove site). At both sites, the samples were collected at the same physiographic position in areas close to the dominant mangrove species (i.e., *Avicennia schaueriana* Stapf and Leechman and *Rhizophora mangle* L) to ensure no vegetation effect.

A total of 60 soil samples (30 disturbed and 30 undisturbed soil samples) were collected to the depth of 7.5 cm, using PVC cores (5 cm diameter). In the undisturbed cores, the bottom was protected with a Morim-type fabric and rubber band, to avoid soil losses and preserve them undisturbed. Both disturbed and undisturbed soil samples were then placed in plastic bags and transported refrigerated (approximately 4 °C) to the laboratory and then rapidly frozen to prevent extra microbial activities. The sampling was carried out in both seasons to embrace both dry and wet seasons, which are typical in this semi-arid region in Brazil (Moura et al. 2015).

Soil redox potential (Eh), pH, and salinity were measured in the field. Eh values were measured using a silver/silver chloride reference electrode, and pH values were obtained using a glass electrode previously calibrated with a pH of 4.0 and 7.0 standard solution. The river water salinity was measured using a portable refractometer (Model IPS-10T) in both seasons.

In the disturbed soil samples, we determined the particle size distribution by the method proposed by Gee and Bauder (1986), after the organic matter oxidation with $H_2O_2$, using a combination of physical (overnight shaking) and chemical (0.015 M $(NaPO_3)_6$ + 1.0 M NaOH) dispersing methods. Organic carbon content (Org-C) was determined by dry combustion at 680 °C after pretreating samples with 1.0 M HCl to remove inorganic C (Howard et al. 2014), using the C analyzer TOC–$V_{CPN}$ (Shimadzu Corp.) with purified air as carrier gas at a flow rate of 150 mL/min. The inorganic nitrogen forms ($NH_4^+$ and $NO_3^-$) were determined according to Keeney and Nelson (1982) and expressed as $NH_4^+$-N and $NO_3^-$-N forms, and the sum of both species is referred as inorganic N (inorganic-N), whereas the total nitrogen (total-N) was performed according to Bremner and Mulvaney (1982). Thus, the organic N (organic-N) was obtained as the difference between total-N and inorganic-N.

Additionally, the potentially mineralizable nitrogen (PMN) was determined through an anaerobic incubation using disturbed soil samples, according to Keeney and Bremner (1966). PMN indicates the soil organic-N that can be potentially mineralized by microorganisms, using organic substrates, such as microbial biomass, residues of plants, and humus (Campbell and Curtin 2007; Verhoeven et al. 2014).

### Nitrogen mineralization over simulated tidal fluctuations

An experiment was conducted to assess N-min over daily tidal variation in the studied sites using the undisturbed soil samples, as described in Lewis et al. (2014), by completely submerging and then draining the soils samples. Undisturbed soil cores ($n$ = 30) collected from both shrimp-impacted and preserved sites were placed in plastic containers containing artificial saline water (adapted from Bidwell and Spotte 1985) so that during 18 h the soil cores were completely submerged and during 6 h the soils were completely drained (the water was free to drain through the bottom of soil core) (Fig. 2), following a 24-h tidal variation during 30 days, to simulate the daily tidal frequency at the Jaguaribe River estuary. Throughout the experiment, the temperature was maintained at 27 °C, and the salinity was held at 27 PSU, the same value measured in the field, through the replacement of the evaporated water with deionized water.

At the beginning and end of the experiment, $NH_4^+$-N and $NO_3^-$-N contents in the undisturbed soil samples and saline water (tidal water) were determined, according to Keeney and Nelson (1982). The net N mineralization was calculated using the following equations:

$$\text{N}-\text{min} = \left(\text{N}_{\text{inorg soil final}} - \text{N}_{\text{inorg soil initial}}\right) + \text{N}_{\text{inorg saline water}}$$

where $N_{inorg\ soil\ final}$ is the soil inorganic-N obtained after 30 days of incubation and expressed in mg kg$^{-1}$ of dry soil; $N_{inorg\ soil\ initial}$ is the soil inorganic-N obtained before incubation and expressed in mg kg$^{-1}$ of dry soil; and

$N_{inorg\ saline\ water}$ is the inorganic-N in the saline water obtained after 30 days of incubation and expressed in mg kg$^{-1}$ of dry soil.

### Statistical analysis

The Kruskal-Wallis test (equivalent for the one-way ANOVA) at 5% minimum significance was performed in the software R (Dalgaard 2008) to assess differences between shrimp-impacted and preserved mangroves sites. Furthermore, a principal component analysis (PCA) (Reimann et al. 2008) was carried out for the variables that characterize the sampling sites (e.g., pH, Eh, Total-N, Org-N, Inorg-N, PMN, Org-C, C:N ratio) to assess the effluents disposal effect in soil and the N-min process, followed by varimax rotation which allows improving the data structure predominantly into two components, by using the software XLSTAT version 2014.5.03.

## Results and discussion

### Soil parameters and N dynamics

The Eh and pH measured in field indicate similar suboxic conditions in both studied sites (shrimp-impacted, Eh, 101 ± 110 mV and pH, 7.3 ± 0.5; and preserved mangrove, Eh, 149 ± 65 mV and 7.6 ± 0.3; Table 1). On another hand, the shrimp-impacted mangrove soil presented significantly higher amounts of total-N ($p$ value < 0.001), Org-N ($p$ value < 0.001), PMN ($p$ value = 0.013), and Org-C ($p$ value < 0.001) compared with the preserved mangrove, whereas, the contents of $NH_4^+$-N, $NO_3^-$-N, and inorganic-N, measured from fresh sampled soils were statistically similar for both sites (Table 1). The soil texture in the shrimp-impacted site was classified as clay loam, whereas in the preserved mangrove was silty clay. The C:N ratios were significantly different ($p$ value = 0.004), with the higher values observed in the shrimp-impacted mangrove soil (Table 1).

In fact, a higher organic matter content in shrimp-impacted mangrove soil was expected because the shrimp effluents contain large amounts of labile organic C and N, animal tissues, and shrimp feed (Boyd and Gautier 2000; Jackson et al. 2003; Jeronimo and Balbino 2012; Suárez-Abelenda et al. 2014). PMN represents an organic nitrogen pool potentially available for microbial mineralization and can be considered as a pool to be mineralized into inorganic-N (Verhoeven et al. 2014). Higher PMN was recorded in impacted mangrove soils as a result of the influence of shrimp farming effluents, resulting in greater $N_2O$ and $CO_2$ emissions (Queiroz et al. 2019).

Previous studies reported that N content is a limiting factor for eutrophication of coastal ecosystems so that mangrove forests receiving high loads of Org-C and total-N could lead the growth of phytoplankton and benthic algae, among other perils related to eutrophication (Howarth and Marino 2006; Sanders et al. 2014). In this sense, the N-min have a key role since the enhancement of inorganic-N compounds may trigger

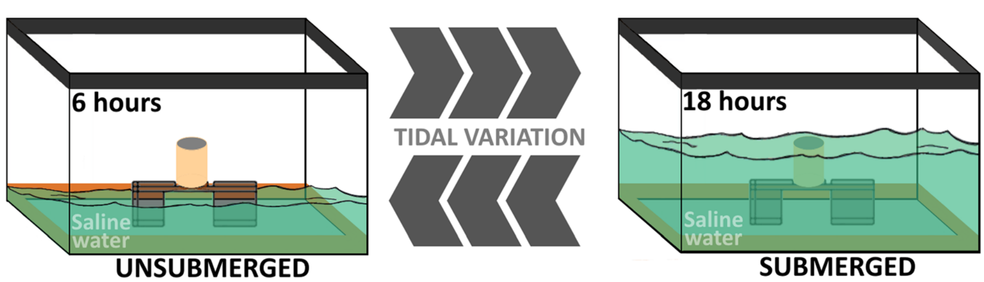



**Fig. 2** Experiment submerging (for 18 h) and draining (for 6 h) soils from both shrimp-impacted and preserved mangroves (over 30 days), simulating tidal daily variation at Jaguaribe River estuary, Brazil

**Table 1** Soil parameters: nitrogen forms, organic carbon, C:N-ratio, soil texture, Eh, and pH for the mangrove soils initially sampled

| Sites | Nitrogen forms in soil | | | | | | Org-C | C:N ratio | Sand | Silt | Clay | Eh | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | PMN | Total-N | $NO_3^-$-N | N-$NH_4^+$-N | Inorg-N | Org-N | | | | | | | |
| | mg kg$^{-1}$ | | | | | | g kg$^{-1}$ | | % | | | mV | |
| Shrimp-impacted | 410 ± 106a | 1998 ± 201a | 2.1 ± 3.4a | 9.8 ± 3.3a | 11.9 ± 6.2a | 1986 ± 202a | 21 ± 5a | 10.4 ± 1.4a | 10 | 56 | 34 | 101 ± 110 | 7.3 ± 0.5 |
| Preserved | 329 ± 77b | 1446 ± 295b | 3.7 ± 3.6a | 13.4 ± 4.8a | 17.1 ± 10.5a | 1429 ± 292b | 13 ± 2b | 9.3 ± 1.0b | 3 | 46 | 51 | 149 ± 65 | 7.6 ± 0.3 |

*PMN* potentially mineralizable nitrogen; *Total-N* total nitrogen; *$NO_3^-$-N* nitrate as nitrogen; *$NH_4^+$-N* ammonium as nitrogen; *Inorg-N* inorganic nitrogen; *Org-N* organic nitrogen; *Org-C* organic carbon; *C:N-ratio* ratio organic carbon and organic nitrogen; *Eh* redox potential. Lowercase letters (a and b) indicate significant differences between variables by Kruskal-Wallis test at the 5% probability level

shifts in the primary producers (i.e., microorganisms, algae, and plants) leading to environmental consequences such as eutrophication (Howarth and Paerl 2008; Naidoo 2009; Keuskamp et al. 2015; Queiroz et al. 2019).

## Shrimp effluents enhanced N content and N mineralization in mangroves

The tidal experiment indicated the N input from discharge of effluents in the shrimp-impacted site promoted shifts in the N-min in mangrove soils. At the end of the tidal experiment (Fig. 2), the N-min for shrimp-impacted soils was significantly higher (86.6 ± 37.6 N mg kg$^{-1}$; $p$ value < 0.017) than the preserved mangrove soils (56.5 ± 23.8 N mg kg$^{-1}$) (Fig. 3), indicating an increase of 53.3% in the N-min. This result echoes findings by Keuskamp et al. (2013), observing rapid organic matter mineralization in mangrove soils affecting nutrients cycling.

Ammoniacal-N dissolved in water, during the submerging/draining experiment, was the major product of N mineralization ($p$ value < 0.001), with higher amounts of $NH_4^+$-N recorded for the Shrimp-Impacted soil (61.4 ± 8.7 N mg kg$^{-1}$; $p$ value = 0.020), compared with the soil from the preserved site (41.5 ± 12.5 N mg kg$^{-1}$) (Fig. 4). Dissolved $NO_3^-$-N was absent in the tidal water in both shrimp-impacted and preserved treatments (Fig. 4). Thus, in our experiment, inorganic $NH_4^+$-N is the major N product from organic matter decomposition, since $NO_3^-$-N can be easily reduced under the Eh-pH conditions found in these mangrove ecosystems (i.e., denitrification) and can be lost by $N_2O$ emissions (Rahaman et al. 2013; Kaiser et al. 2015).

For both shrimp-impacted and preserved mangroves, remaining inorganic-N forms in the soil were smaller than inorganic-N forms in tidal water at the end of the experiment (Fig. 4). However, shrimp-impacted mangroves had higher contents of dissolved N in tidal water. These results indicate that only a small portion of the inorganic-N remained in the soil, so that large amounts of mineralized-N were drained into the saline water and may be available to plants, or drained to coastal areas, or available to anaerobic microorganisms to perform metabolic functions, such as denitrification (Muñoz-Hincapié et al. 2002; Campbell and Curtin 2007; Chen et al. 2012; Reis et al. 2017).

Other studies reported an increase in the dissolved $NH_4^+$-N derived from mangrove soils associated with shrimp ponds effluents (Trott et al. 2004; Molnar et al. 2013). However, these studied sites had different characteristics compared with our field sites, such as the climatic conditions, the area covered by the shrimp ponds, the effluent discharge fluxes, and the tidal amplitude which could control the biogeochemical processes

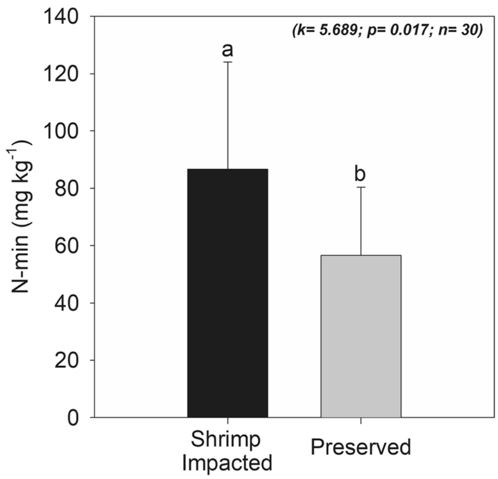



**Fig. 3** Net nitrogen mineralized from both soils and tidal waters at the end of the submerging/draining experiment, comparing shrimp-impacted and preserved mangrove soils. Means followed by the same lowercase letter do not differ by ANOVA and Kruskal-Wallis test at the 5% probability level

leading to distinct results regarding mineralization rates, nutrient fluxes, and phytoplankton uptake. In our study, N discharge fluxes from shrimp ponds into mangroves were higher than reported by Trott et al. (2004), which can be associated with by shrimp farming area (at least 200-fold bigger in the Jaguaribe River estuary) resulting in higher mineralization rates and fluxes of dissolved $NH_4^+$-N. Further, Molnar et al. (2013) also reported higher $NH_4^+$-N concentration in the water column in mangrove creeks receiving shrimp ponds effluents associated with effluent characteristics instead of soil biogeochemical processes as mineralization. Mangrove forests under semi-arid climate with suboxic condition in the soil tend to present an intense ammonification process from soil organic matter mineralization, and this process increases intensely in sites receiving shrimp pond effluents compared with sites free of effluent impacts (Queiroz et al. 2019).

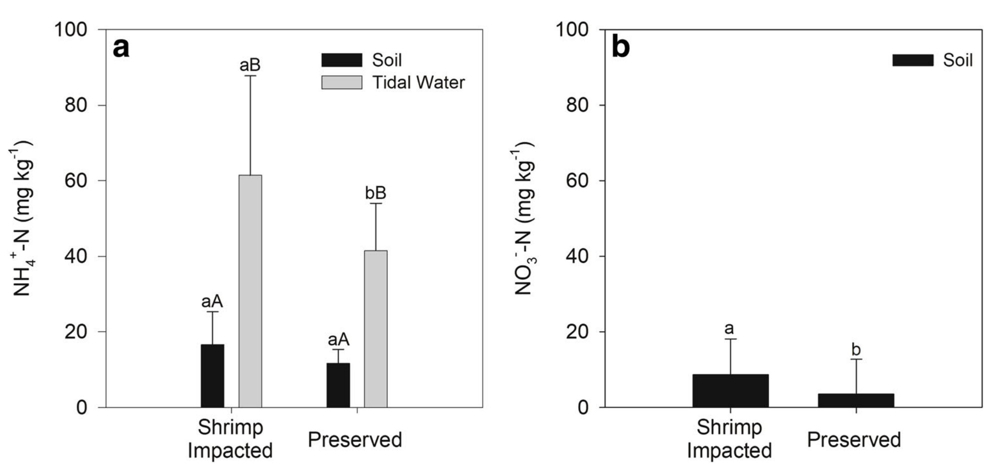
Considering the results of PCA, the first component (D1) is composed of PMN, Total-N, Org-N, and Org-C explains 39.21% of the data variation, whereas the second component (D2) is composed of Inorg-N, N-min, C:N ratio, Eh, and pH, representing 30.89% of the data variance (Fig. 5). The first component could represent an N enrichment mainly in the shrimp-impacted mangrove soil as a result of effluent discharge. On another hand, the component 2 which is composed of Inorg-N, N-min, C:N ratio, Eh, and pH could be attributed to mineralization processes. Consequently, the discharge of effluent directly affects the N mineralization since the shrimp-impacted site has a greater N-min (Fig. 5).

Furthermore, the discharge of shrimp farming effluents may trigger a priming effect because of a higher N-min in these mangrove soils under semi-arid conditions, which received these effluents. Thus, the elevated N-min found in our submerging/draining soil's experiment indicates a priming effect for N cycling in mangrove ecosystems. We further postulated that the priming effect may result from the competition for energy and nutrients among microorganisms either specialized in the decomposition of fresh organic matter (discharged from shrimp ponds) or in depolymerization of soil organic matter compounds (Fontaine et al. 2003).

The priming effect is a process oftentimes ignored in coastal wetlands ecosystems, but previous studies reported that the input of organic matter labile (e.g., shrimp ponds effluent) in these ecosystems may promote a great increase in organic matter degradation (from 10 up to 500%), which led to eutrophication and an increase in bioavailability of previously limiting nutrients, such as N (Guenet et al. 2010).

Regarding the eutrophication, N and P bioavailability regulates which nutrients are limiting in an ecosystem; then, the N:P ratio often is an indicator of nutrient's bioavailability for primary producers (Howarth et al. 2011). However, the N:P ratio as an indicator might be limited since the N and P biogeochemical mechanisms rapidly change that could affect the

**Fig. 4** Contents of $NH^{4+}$-N (**A**) and $NO_3^-$-N (**B**) in the soil and the tidal water after 30 days of daily submerging/draining the soils. Lowercase letters (**a** and **b**) indicate significant differences between sites ($n = 30$), and uppercase letters (**A** and **B**) indicate significant differences between variables for soil and tidal water, by Kruskal-Wallis test at the 5% probability level



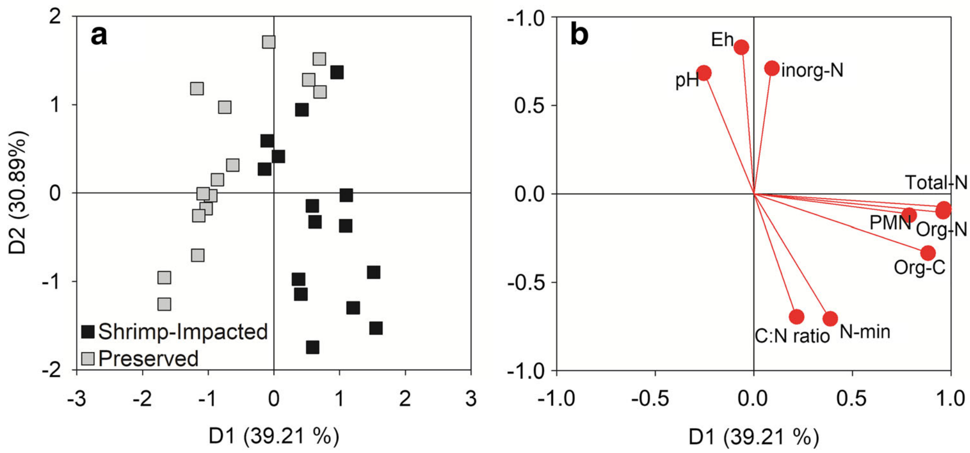



**Fig. 5** Principal components analysis (PCA) for the main soil patterns and sampled sites. Total-N, total nitrogen; Inorg-N, initial soil inorganic nitrogen ($NH_4^+$-N and $NO_3^-$-N); PMN, potentially mineralizable nitrogen; N-min, mineralized nitrogen; Eh, soil redox potential; Org-C, organic carbon; C:N ratio, organic carbon and organic nitrogen ratio

content of bioavailable nutrients promptly, for instance, the nitrogen mineralization rate (Cleveland and Liptzin 2007; Howarth et al. 2011).

In the Jaguaribe River estuary, despite previous studies reported the increase of P content in soil and water as results of effluents discharged from shrimp ponds which leads an imminent eutrophication risk by P (Lacerda 2008; Barcellos et al. 2019), few studies reported the concentrations of N inputs, which may lead to eutrophication (Lacerda 2008), and so far there are no studies pointing out the mineralization process as a trigger for eutrophication. Thus, our results indicate an imminent eutrophication risk by N in the Jaguaribe River estuary, which coincides with findings from eutrophicated estuaries worldwide (Table 2).

## Conclusions

Our results demonstrated that disposal of shrimp farming effluents into mangroves promotes enrichment of N content in soil/water systems, resulting in latent environmental risks revealing the need to decrease the N-rich-effluent discharge from shrimp ponds into mangrove soil in the Ceará State. Although mangrove soils are capable of storing large amounts of nutrients because of low mineralization rates, the higher N content from anthropogenic effluents can be readily available to microorganisms, inducing an increase in N mineralization.

This observed increment in N mineralization, aligned to the daily tidal height variations in our experiment, indicates a priming effect in mangrove soils that received nutrient-rich effluents, resulting in potential risks for eutrophication in estuarine and coastal systems.

Considering that shrimp farming nutrient disposal into mangroves is a worldwide problem and that the Jaguaribe River estuary is the largest shrimp producer in the semi-arid region of Brazil, our study brings an approach that few studies have demonstrated so far, emphasizing the potential for N-min enhancement in soils, and to predict nutrient responses in human-impacted marine systems. Additionally, since mangrove forests are within the confluence of marine, terrestrial, and freshwater, results from our study can be of important use for the ecosystem and biogeochemical nutrient cycling models.

**Table 2** Total-N content in soil and trophic condition in other coastal wetlands worldwide

| Sites | Location | Total-N (mg $kg^{-1}$) | N source | Trophic state* | Reference |
|---|---|---|---|---|---|
| *Jaguaribe River estuary* | *Mangrove* | *1998 ± 201* | *Shrimp farming* | - | *This study* |
| Mahakam delta, Indonesia | Mangrove | 3400 ± 829 | Shrimp farming | Eutrophicated | Fauzi et al. (2014) |
| Futian National Nature Reserve, China | Mangrove | 1960 ± 314 | Municipal sewage | High eutrophication risk | Wong et al. (1995) |
| Guanabara bay, Brazil | Mangrove | 2240 ± 261 | Urban sewage | Eutrophicated | Pérez et al. (2018) |
| Gulf of Riga, Russia | Coastal wetland | 3175 ± 1464 | Urban and Industrial waste | Eutrophicated | Voss et al. (2000) |
| Shenzhen, China | Mangrove | 1730 ± 110 | Agriculture and aquaculture | High eutrophication risk | Tam and Wong (1996) |
| Mexican Central Plateau | Cointzio reservoir | 983 ± 75 | Agricultura and urban runoff | Eutrophicated | Némery et al. (2016) |

*According to authors

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