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# The effect of nutrient-rich effluents from shrimp farming on mangrove soil carbon storage and geochemistry under semi-arid climate conditions in northern Brazil

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ABSTRACT

A semi-arid mangrove estuary system in the northeast Brazilian coast (Ceará state) was selected for this study to (i) evaluate the impact of shrimp farm nutrient-rich wastewater effluents on the soil geochemistry and organic carbon (OC) storage and (ii) estimate the total amount of OC stored in mangrove soils (0–40 cm). Wastewater-affected mangrove forests were referred to as WAM and undisturbed areas as Non-WAM. Redox conditions and OC content were statistically correlated ($P < 0.05$) with seasonality and type of land use (WAM vs. Non-WAM). Eh values were from anoxic to oxic conditions in the wet season (from −5 to 68 mV in WAM and from <40 to >400 mV in Non-WAM soils) and significantly higher (from 66 to 411 mV) in the dry season ($P < 0.01$). OC contents (0–40 cm soil depth) were significantly higher ($P < 0.01$) in the wet season than the dry season, and higher in Non-WAM soils than in WAM soils (values of 8.1 and 6.7 kg $m^{-2}$ in the wet and dry seasons, respectively, for Non-WAM, and values of 3.8 and 2.9 kg $m^{-2}$ in the wet and dry seasons, respectively, for WAM soils; $P < 0.01$). Iron partitioning was significantly dependent ($P < 0.05$) on type of land use, with a smaller degree of pyritization and lower Fe-pyrite presence in WAM soils compared to Non-WAM soils. Basal respiration of soil sediments was significantly influenced ($P < 0.01$) by type of land use with highest $CO_2$ flux rates measured in the WAM soils (mean values of 0.20 mg $CO_2$ $h^{-1}$–$g^{-1}$ C vs. 0.04 mg $CO_2$ $h^{-1}$–$g^{-1}$ C). The OC storage reduction in WAM soils was potentially caused (i) by an increase in microbial activity induced by loading of nutrient-rich effluents and (ii) by an increase of strong electron acceptors [e.g., $NO_3^-$] that promote a decrease in pyrite concentration and hence a reduction in soil OC burial. The current estimated OC stored in mangrove soils (0–40 cm) in the state of Ceará is approximately 1 million t.



## 1. Introduction

It is estimated that worldwide mangroves accumulate 1023 Mg carbon (C) $ha^{-1}$ and thus are considered potential sinks of "blue carbon", a term used to indicate organic carbon (OC) accumulated in sea-grass meadows, mangrove forests and tidal salt marshes (Bouillon et al., 2008; Chmura et al., 2003; Donato et al., 2011). Rates of OC burial in mangrove ecosystems range from 1.4 to 6.5 t C $ha^{-1}$ $yr^{-1}$ (Bouillon et al., 2008) while the total amount of OC stored in worldwide mangrove soils varies from 4 to 20 P g (Breithaupt et al., 2012; Donato et al., 2011; Twilley et al., 1992). This OC storage is significantly higher than the mean values in other forest including boreal, temperate and tropical upland forests (Donato et al., 2011). Overall, the top 30 cm layer of soil carbon in most forests is considered the most vulnerable to land use change (Donato et al., 2011). Although there are a number of studies assessing OC accumulation in mangroves in tropical and subtropical latitudes (e.g. Breithaupt et al., 2012), there is a lack of information from mangrove wetlands located in semi-arid coastal regions (Giani et al., 1996).

The global extent of mangrove surface area is approximately 137,760 $km^2$ and is distributed in 118 countries (Giri et al., 2011). The largest extension of mangrove forest in neotropical latitudes is in Brazil (9627 $km^2$) followed by Mexico (741,917 $km^2$) and Cuba (421,538 $km^2$). Despite the ecosystem services provided by these forested wetlands, such as carbon sequestration, mangrove forest area in Brazil has declined 46% since 1983 due to human settlements, the conversion of coastal areas to agriculture and silviculture, and the establishment of aquaculture shellfish farms in the intertidal zone (Guimaraes et al., 2010; IBAMA. Instituto Brasileiro de Meio Ambiente e dos

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Recursos Naturais Renováveis, 2005; Jablonski and Filet, 2008) among other causes. In particular, shrimp farming alone has caused a 26% mangrove area loss along the northeast Brazilian coast (e.g. state of Ceará; Queiroz et al., 2013).

Mangrove ecosystems have a critical role as a nutrient sink (e.g. denitrification) in the intertidal zone due to their efficient capacity to process excess nitrogen (N) and phosphorus (P) loading resulting from human impacts, including shrimp aquaculture and agriculture/urban development (Marchand et al., 2011; Páez-Osuna et al., 1998; Rivera-Monroy et al., 1999). Shrimp farming production on tropical coastal regions has increased significantly during the last 30 yr due to food demand and high economic value, particularly in Brazil (Queiroz et al., 2013). However, it is now recognized that the conversion of mangrove wetlands to shrimp ponds becomes unsustainable in the long term (Primavera et al., 2007; Rivera-Monroy et al., 1999) due to the environmental impacts (e.g., eutrophication) and strong disruption of local economies (Barbier and Cox, 2002, 2004; Koch et al., 2009). Current estimates indicate that total N and P loading rates into estuarine waters in northeastern Brazil, where 80% of the total shrimp pond area (7825 ha) is located, range from 9 to 485 t $yr^{-1}$ and from 0.7 to 27 t $yr^{-1}$, respectively (Lacerda, 2006). How this nutrient enrichment will affect mangrove forest productivity and carbon sequestration in the long term is unknown.

Tidal flooding and freshwater discharge in mangrove wetlands reduce $O_2$ diffusion into soils creating anoxic conditions. In the absence of $O_2$, other molecules (i.e. $NO_3^-$, $Fe^{3+}$, $Mn^{4+}$, $SO_4^{2-}$ and $CO_2$) are used as electron acceptors by anaerobic microorganisms (Berner, 1984; Froelich et al., 1979). Under anoxic conditions, the reduction of Fe(III) and $SO_4^{2-}$ in mangrove sediments are the main processes involved in the oxidation of OC to $CO_2$ (Luther and Church, 1988). Thus, Fe(II) and hydrogen sulfide ($H_2S$) are simultaneously formed; the former by $Fe^{+3}$ bacterial reduction (crystalline Fe-oxyhydroxides), and $H_2S$, by both $SO_4^{2-}$ reduction and sedimentary organic matter oxidation mediated by anaerobic bacteria (Luther, 1991). During this process, acid volatile sulfides (AVS, a metastable fraction) are formed and transformed into pyrite, which becomes stable under anoxic conditions (Berner, 1970; 1984). Further, the availability of dissolved OC, temperature, and sedimentation rates has an important role in the reduction of Fe(III) and $SO_4^2$ (Huerta-Díaz and Reimer, 2010). When changes in hydrology and hydroperiod, driven by either human activities or other natural disturbances, decrease the depth of the overlying water column, sub-superficial conditions in the soil might become suboxic, and even oxic. Under oxic conditions, the oxidation–reduction potential of Eh increases and pyrite is generally oxidized due to its thermodynamic instability under such conditions; although this reaction can be further catabolized by $SO_4^{2-}$ generating bacteria and acidity (Otero and Macias, 2002). Therefore, understanding the spatial variability controlling the Eh regime in mangrove soils as a result of human activities (e.g. nutrient enrichment, road and dam construction) is critical to evaluate spatial and temporal changes in C and nutrient cycling.

The objective of this research was to evaluate how soil C storage capacity is affected by shrimp farm nutrient-rich wastewater effluents in mangrove wetlands in a semi-arid coastal region of Brazil. It was hypothesized that the release of nutrient-rich waters increased microbial activity and modified soil redox conditions by increasing the concentration of strong electron acceptors [e.g. $NO_3^-$] thereby reducing pyritization rates in soils and negatively affecting the soil C storage capacity.

## 2. Materials and methods

### 2.1. Study area and soil sampling

The study was performed in two estuaries located in the northwest (Acarau) and southeast (Aracati) coastal regions of the state of Ceará,


**Fig. 1.** Location of the study area.