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EARTH SCIENCES

Phosphorus and suspended matter retention in mangroves affected by shrimp farm effluents in NE Brazil

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Abstract: This study compares two mangroves with different land uses in the Jaguaribe River estuary, harboring large shrimp farms, and in the more pristine Pacotí River estuary. Normalized Difference Vegetation Index (NDVI) was used to compare the overall health of the forests. Measures of suspended matter (TSS), total (TP), particulate (PartP) and soluble reactive phosphorus (SRP) in the inflow and outflow waters of tidal channels draining the mangroves were performed during tidal cycles. NDVI varied from 0.65 in the Jaguaribe estuary to 0.85 in the Pacotí, suggesting the impact of shrimp farm effluents on mangrove canopy cover. The shrimp farm influenced site showed 10 times larger absolute ΣP (TP + PartP + SRP) = 1.2-5.2 kg.hr-1) flux than the pristine site (ΣP = 0.22 kg.hr-1). Tidal balances showed smaller retentions of the total influx: 28-54%; 44-45%; 38-65% and 8-53% for TSS; TP; SRP; and PartP respectively, in the shrimp farm influenced site to over 93% of the total tidal input of TSS and all P fractions in the pristine mangrove. This suggests that mangrove phosphorus accumulation is decreased in the forest with lower NDVI and limits mangrove's potential as a natural barrier to the nutrient transport to adjacent estuarine and coastal waters.

Key words: Nutrients, shrimp farms, forest canopy, NDVI, hydrology, hydrochemistry.

INTRODUCTION

Population inhabiting the coastal region increased enormously in the last decades in Brazil, to a point that nearly 80% of the total country's inhabitants live within the first 100 km from the sea. Mangroves are the predominant vegetation in most of the coast from the North boarder with French Guiana to 28°30'S. Therefore, in most areas they presently suffer strong environmental pressures from the growing human population. In addition, rapid expanding intensive shrimp farming has increase enormously the environmental pressure on mangrove ecosystems (Lacerda et al. 2019).

Mangroves play a key role in the sediment balance and nutrient cycling in tropical estuaries and are key ecosystems to mitigate the impacts from global environmental changes, as well as from local anthropogenic drivers affecting estuaries (Valiela et al. 2018). Due to their root morphology and high densities, they act as traps to suspended particles coming in with the tides. It is relatively well established that mangroves not just opportunistically colonize existing mud flats but also actively create new mud deposits by efficiently trapping suspended matter, which renders increasing resistance to global and environmental changes (Godoy & Lacerda 2015). However, the effects of land uses neighboring mangrove areas on the capacity of these forests to filter the materials from tidal waters are still poorly understood. Improved knowledge of mangrove interactions over different stressing stages is essential for the conservation and sustainable management of this biome.

In the mangrove sediments, nutrients and organic matter undergo different chemical reactions mostly mediated by microorganisms and frequently under suboxic conditions. Whereas a fraction of these nutrients and of the organic matter is exported to coastal areas, where they sustain elevated rates of primary productivity, a significant portion is accumulated within the sedimentary environment (Alongi et al. 2005, Prasad & Ramanathan 2008). For some nutrients, such as phosphorus (P), the behavior of mangroves as exporters or importers seems to be site-specific (Adame & Lovelock 2011). Many authors, however, have actually measured a net import of P by mangroves by observing that only a fraction of the P input entering the forest is exported back to adjacent coastal areas (Sanchez-Carrillo et al. 2009, Silva et al. 1998). Others, by modeling P concentrations in waters as a function of dilution, came to the same conclusion, as observed in the Rio Coco Solo, in Panama (Bin & Dushof 2004). Both approaches suggest that mangroves actively immobilize this element. These studies suggest that the majority of the total P stock is accumulated in mangrove biomass and/or sediments. Some few studies on the other hand, e.g. in Malaysia (Gong & Ong 1990), reported a net export of P.

In general, however, a net P accumulation seems to be a characteristic property of mangroves, in particular those colonizing arid and semiarid coastlines. In these areas, although nutrient inputs may be limiting, mangroves may attain very high productivity rates, by inducing an efficient recycling of limiting nutrients (Holguin et al. 2001). Sediment fauna also influences this process, but seems very site-specific (Ferreira et al. 2019).

The response of mangroves as net sinks or sources of nutrients is a key parameter to proper coastal management, aiming to establish the support capacity of coastal areas to stand excess nutrient inputs from anthropogenic sources. The exporter or importer nature of mangroves will depend on the ecosystem "health" when the nutrient load is applied and the magnitude of the discharges. Removal efficiency of nutrients is dependent on the oxic conditions of surface and interstitial waters. Eutrophication, by reducing oxygen levels, reduces the efficiency of nutrient accumulation by mangroves (Agraz-Hernández et al. 2018). Also, the import/export nature of a given mangrove will depend on the specific response of functional groups of organisms to specific constituents (Feller et al. 2007).

The basis of vegetation indexes is the measurement of the amount of sun light reflected by leafs (Rebelo-Mochel & Ponzoni 2007). Leaf reflectance properties, controlled by properties of pigments, water and carbon, play a significant role in reflectance at the canopy level. Healthy vegetation strongly absorbs the sun light and reflects it back (Davaasuren & Meesters 2012). The NDVI (Normalized Difference Vegetation Index) can compare photosynthetic activity in different spatial or temporal scales to monitor structural, phenological and biophysical vegetation parameters (Wang et al. 2004). Thus, the NDVI is a qualitative environmental index applicable to determine decrease of green spectrum absorption that reflects in a lower NDVI (Alatorre et al. 2016, Meneses-Tovar 2011). The remote sensing and NDVI index were applied, for example, to estimate the loss of mangrove forest due to shrimp farming impacts (Alatorre et al. 2016, Omo-Irabor et al. 2011). However, to what extent a decrease in NDVI results in losses of ecological functions, such as nutrient accumulation capacity, of mangroves is still poorly documented.

To improve the understanding of the relationship between vegetation degradation, evaluated by NDVI, with phosphorus and suspended solids retention capacity of mangroves, this study compares two different estuaries, one pristine, taken as control site and another under strong environmental pressure from shrimp farming effluents. NDVI derived from Landsat TM5 images were calculate for both forests. Images were from the same period of the field work, which included measures of suspended matter (TSS) and of total (TP), particulate (PartP) and soluble reactive phosphorus (SRP) in the inflow and outflow waters of the mangrove channels during tidal cycles. Based on the results we discuss the role of mangroves as sinks or sources of P to adjacent coastal areas and the impact of shrimp farming effluents, since these ecosystems have been suggested as natural "treatment" for nutrient enriched waters in tropical areas.

MATERIALS AND METHODS

The two mangroves studied are located in the eastern portion of Ceará State, northeastern Brazil. A detailed map from the two areas is available in the Supplementary Material (Figure S1). The mangrove forest at the Jaguaribe estuary is located in a tidal creek that receives, at the time of the study, about 29 t yr^{-1} of P from nearly 1,600 ha of intensive shrimp farming located upstream, whereas at the Pacoti estuary, a nearly pristine environment, local mangroves receives about 0.16 t yr^{-1} of P from only 9 ha of shrimp farms. Other sources of P are from urban wastes and agriculture, but located in the higher basin of the rivers, with no direct inputs to the tidal creeks under study, to present (Lacerda et al. 2008, Ferreira et al. 2019). Both sites are under similar semi-diurnal tidal, wind and rainfall regime. Maximum tidal amplitude is 2.8 m; climate is tropical semi-arid and annual rainfall varies from 400 to 1,000 mm, with a short rain season from February to May and a long dry season from June to January (Dias et al. 2009, Marins et al. 2011). The sampled tidal creeks draining both sites harbor mangroves composed by *Rhizophora mangle* L., *Avicennia germinans* L., *A. schaueriana* Stapf & Leachman and *Laguncularia racemosa* R. Gaertn. The Jaguaribe creek extends through 600 m draining a mangrove area of about 12 ha. At the peak of high tide the creek is 20 m wide and 2.1 m deep. At the peak of low tide, creek width and depth are only 3 m and 0.1 m, respectively. The Pacotí creek extends through 300 m draining about 2 ha of mangroves. At the peak of high tide, creek width and depth are 22 m and 1.15 m, respectively. At the peak of low tide, the creek is only 3 m wide and 0.05 m deep. Both creeks discharge into major tributaries to the estuary.

For both forest canopies, NDVI was calculated based on Landsat TM5 images, acquired free from Instituto Nacional de Pesquisas Espaciais – INPE (www.dgi.inpe.br). Two images were from the July 2008, the month immediately previous to the sampling period for hydrochemical parameters in the two estuaries. An additional image from July 2003 (Figure S2) was also used for NDVI calculation in the shrimp farming influenced area, the Jaguaribe estuary. In 2003, pond area draining into the studied creek was 5 times smaller, about 340 ha.

The scenes of Landsat TM5 obtained in 2003 and 2008 were pre-processed to atmospheric correction through the 6s (Vermote et al. 1997, Xie et al. 2010) and the NDVI was calculated through SPRING 5.3 software (Camara et al. 1996), using equation 1 (Rouse et al. 1974), where IVP is the reflectance of the band in the near infrared (band 4), and V is the reflectance of the red band (band 3):

$$NDVI = IVP – V / IVP + V \text{ (equation 1)}$$

Two field campaigns, during the same year, were performed at the Jaguaribe site (August and November) and one in the Pacotí site (August), as a control, all during the dry season and under spring tide conditions, to avoid tidal range and rainfall variability between the two sites. Campaigns lasted for a semi-diurnal tidal cycle varying from 6 to 12 hours each and took place in tidal creeks inside the forests, fairly protected from wind disturbances.

Figure 1 shows satellite images of the two studied areas. A fixed monitoring station was established at the mouth of each creek in each site. It constituted of a cm-marked ruler fixed to the bottom at the central portion of the channel (See Figures S3 and S4 for details of station characteristics). At 30 min to 1 hr *intervals* water depth and channel width were taken and bathymetry and volume at each instant were determined with AutoCAD software. Simultaneously, we measured the *in situ* flow velocity (General Oceanics, Model 2030R flow meter, Figure S5), water temperature, salinity, electrical conductivity and dissolved oxygen (YSI 85 portable multiple probe) and pH (Orion portable pH meter). Integrated measurements were taken at 3 different depths (surface, middle and bottom) whenever depth was>0.5 m, in shallower depths triplicate measurements were performed about 10 cm below the water surface. All measurements were taken in duplicate, therefore for each sampling time we used the average of six measurements.

Three 500 mL water samples were taken at each sampling time with amber glass bottles for P and total suspended solids determinations and following the same strategy for hydrochemical measurements. Water samples were filtered through pre-weighted 0.45 µm Millipore cellulose filters, and frozen for transport. Filters were oven dried overnight (60 ^oC) and weighted for total suspended solids (TSS) determination, as the difference between filter weights before and after filtration. Phosphorus fractions analysis followed the speciation proposed by Hansen & Koroleff (1999), including SRP (Soluble Reactive Phosphorus), determined in filtered samples and consisting largely of the inorganic orthophosphate; TP (Total phosphorus), determined after sample digestion

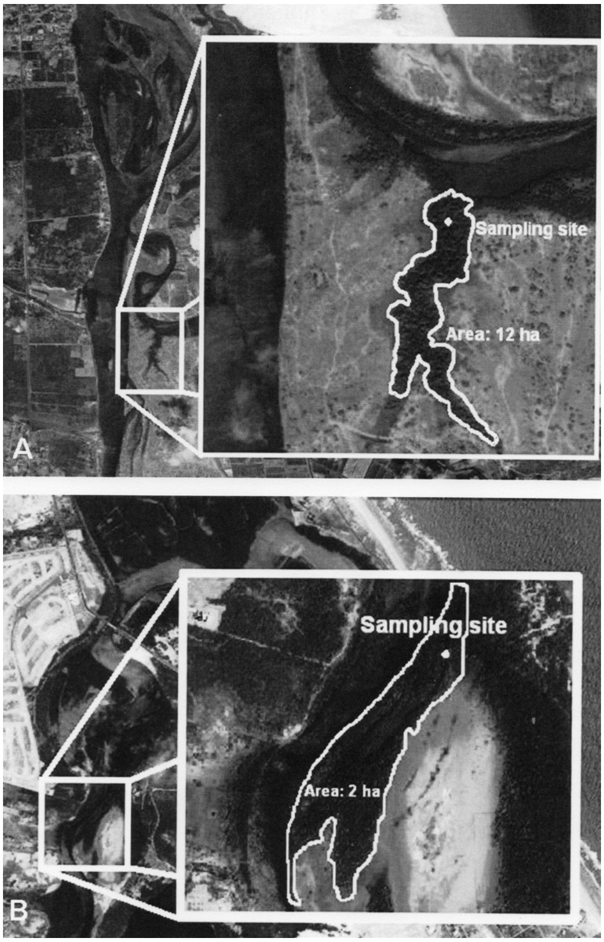

Figure 1. Map showing the location sampling sites of hydrochemistry and hydrology in the two studied areas. Forests limits are represented by the white lines. a - Pacotí Estuary at the Metropolitan Region of Fortaleza. b – Jaguaribe Estuary at Aracati, Municipality, both located in Ceará Sate, Northeastern Brazil.

and consisting of the sum of all filterable and particulate P forms; and PartP (Particulate phosphorus) obtained from the difference between TP and SRP.

Determinations of all P species were performed in an ultraviolet spectrophotometer by the phosphomolybdic acid method, as in Hansen & Koroleff (1999) and the average detection limit of the methods for all P species was 0.2 µM. Instantaneous fluxes, kg.hr^{-1} and g.hr^{-1} of TSS and P fractions (SRP, particulate and total), respectively, were obtained by multiplying concentrations by the instantaneous water discharges. Positive and negative fluxes considered importing and exporting fluxes respectively.

The Shapiro Wilk procedure was used to test the normality of the data. The Mann-Whitney test was used to compare variables between sites. The significance value used for the tests was 95% ($p<0.05$). Statistical tests were performed using RStudio software (version 1.1.423 – © 2009-2018 RStudio, Inc.) and Microsoft Office 365.

RESULTS

It is assumed that any difference in the P dynamics in the two sites will depend on the mangrove response to pressures from external factors, in this case shrimp farming. Since both sites presented similar tidal creek morphology (Table I) and mangrove species composition, both areas are in the same tidal regime with a peak tide delay of less than 15 minutes, and both lack direct inputs from tributary rivers and therefore display the same water residence time. Notwithstanding the stated similarities, the NDVI obtained for the areas suggests different forest biomass in the two sites. Figure 2 represents the absorption at blue and red region of the visible spectrum (light spectrum band 1 and 3, respectively) corresponding to chlorophyll and carotenes absorption, with a slight green peak and maximum of the absorption at the infrared region. Values for NDVI for the Jaguaribe and Pacotí mangroves were 0.65 and 0.85, respectively. The Pacotí area presented higher chlorophyll absorption showed by the higher NDVI value. This result infers that the Pacotí mangrove studied area had greater canopy biomass than the Jaguaribe one. The higher reflectance value in the IVP (band 4) in the Jaguaribe area can be related to lower shade of the canopy.

The decrease of NDVI value observed in the Jaguaribe area may result from the impact of the large effluents from shrimp farms released in the tributary, increasing environmental stress on the local mangroves and causing lower NDVI values. NDVI calculated based on the 2003 image (Figure S2), when shrimp pond was 5 times smaller, was 17% higher than in 2008 (0.78) strongly suggesting aquaculture as the major driver of environmental pressures on the Jaguaribe mangrove. The decrease in NDVI is not associate with direct deforestation because, but to tree mortality and thinning of canopy. However, when compared to the NDVI of our control site, this value obtained in 2003 is still 9% lower, in agreement with a total shrimp pond area at that time of about 340 ha (Marins et al. 2011).

Flooded area in the two sampling campaigns at the Jaguaribe creek varied from 0.2 to 28.7 m^2, and depth at the sampling stations from 0.1 to 2.1 m at the peak of ebb and flood tide, respectively. In the Pacotí creek, flooded area varied from 0.1 to 24.3 m^2, whereas depth at the sampling station was relatively shallower and varied from 0.1 to 1.6 m, at the extreme ebb and flood tide. Salinity and pH varied from 28.0 to 32.4 and 6.8 to 8.0, respectively, with no significant difference between the two sites or campaigns. Dissolved oxygen (DO) and TSS concentrations showed

Table I. **Hydrological and hydrochemical data during tidal cycles from the two sampled mangrove creeks in NE Brazil. First and last line of each campaign represents high tide, when creek depth was at the peak.**

Sampling	Creek depth (m)	Flooded area (m^2)	Temp. (°C)	Salinity	pH	Dissolved Oxygen ($mg.L^{-1}$)	Dissolved Oxygen (%) n (%)	TSS ($mg\ L^{-1}$)
1st Campaign: Jaguaribe estuary	2.10	28.7	26.9	29.9	7.3	3.30	49.8	61
	1.70	20.7	26.9	29.9	7.4	3.60	55.6	55
	0.95	7.0	26.8	29.8	7.3	3.48	52.3	88
	0.20	1.0	27.6	29.4	7.2	3.23	49.3	94
	0.10	0.2	27.6	30.3	6.9	1.52	24.5	86
	0.50	3.0	28.4	29.2	6.8	5.03	45.3	127
	0.90	5.9	28.1	28.0	7.2	4.44	70.1	173
2nd Campaign: Jaguaribe estuary	1.90	24.7	28.8	31.1	7.1	3.20	49.7	171
	1.40	14.7	27.7	32.1	7.3	3.10	46.7	138
	0.80	5.7	27.1	32.9	7.3	2.73	42.4	64
	0.35	1.7	27.6	33.9	7.2	3.47	53.0	49
	0.18	1.0	28.5	34.0	7.3	4.36	67.5	34
	0.15	0.5	29.3	34.8	7.2	5.07	80.0	34
	0.20	1.0	29.4	34.8	7.2	3.75	57.0	24
	0.35	1.7	30.5	33.5	7.2	4.12	60.6	34
	0.55	3.5	32.4	32.8	7.6	4.80	84.5	42
	0.75	5.0	31.4	32.5	7.9	7.49	125.0	55
	1.20	11.4	30.4	32.1	7.9	7.91	126.5	98
	1.90	24.7	29.8	31.9	7.8	4.80	76.2	53
	2.05	27.7	30.0	33.5	7.6	4.85	79.7	50
Campaign: Pacotí estuary	1.15	13.3	25.8	32.6	8.0	5.20	73.0	23
	1.00	10.1	25.9	33.3	7.9	5.57	82.2	69
	0.60	4.5	26.7	33.9	7.8	5.45	84.0	73
	0.30	1.5	29.3	34.1	7.7	6.17	97.5	90
	0.10	0.1	31.9	35.1	7.8	7.15	117.0	76
	0.20	0.7	28.4	32.0	7.3	4.38	67.0	65
	0.85	7.6	28.4	33.9	7.7	5.26	81.7	69
	1.60	24.3	27.6	34.9	7.8	5.35	80.1	102

significant spatial differences ($P<0.05$), DO being lower (1.52 to 7.91 mg.L^{-1}) in the Jaguaribe creek than in the Pacotí (4.38 a 7.15 mg.L^{-1}), whereas TSS was significantly higher ($P<0.05$) in the Jaguaribe creek (24 to 173 mg.L^{-1}), than in the Pacotí creek (23 to 102 mg.L^{-1}). In general, DO concentrations reach minimum values during the peak of low tide, in the Jaguaribe site. Whereas in the Pacotí, even during low tide, DO concentrations were relatively high (> 4.0 mg.L^{-1}). TSS concentrations were always higher during the changing of tides, just after peaks of faster flow velocity, in particular when tide starts flooding, resulting in the resuspension of sediments deposited in adjacent mud flats. Flow velocity varied from zero to 10.6 cm.s^{-1} at the Jaguaribe creek and from zero to 4.0 cm.s^{-1} in the Pacotí creek (Table II).

The concentrations and fluxes of phosphorus fractions are summarized in table II for the two areas and all campaigns. All P fractions were significant higher ($P < 0.05$) in the Jaguaribe compared to the Pacotí site. SRP varied between 2.1 to 6.5 µM, average 3.1 µM, in the two campaigns in the Jaguaribe site and from 0.1 to 0.9 µM, average 0.5 µM, in the Pacotí. Total phosphorus (TP) varied from 3.2 to 15.9 µM, average 8.8 µM, in the two campaigns in the Jaguaribe and from 2.9 to 7.3 µM, average 4.6 µM, in the Pacotí site. Particulate phosphorus (PartP) varied from 1.3 to 11.9 µM, average 5.6 µM, and from 2.8 to 7.7 µM, average 4.1 µM, in the Jaguaribe and Pacotí sites, respectively.

TSS fluxes were higher in the Jaguaribe creek (-39 to +663 kg.hr^{-1}), than in the Pacotí creek (-5 to +131 kg.hr^{-1}) and reflects the higher TSS concentrations in the Jaguaribe site, which is also probably derived from the larger shrimp farming area, of which effluents are enriched in TSS due to erosion of pond walls by aerators. Fluxes of SRP varied from -151 to + 2,552 g.hr^{-1} at the Jaguaribe creek, whereas at the Pacotí creek SRP fluxes were much lower and varied from -4 to +48 g.hr^{-1}. Fluxes of PartP varied from -208 to +1,941 g.hr^{-1} at the Jaguaribe creek, whereas at the Pacotí creek PartP fluxes were also lower and varied from a -46 to +1,012 g.hr^{-1}. Fluxes of TP varied from -360 to +4,493 g.hr^{-1} at the Jaguaribe

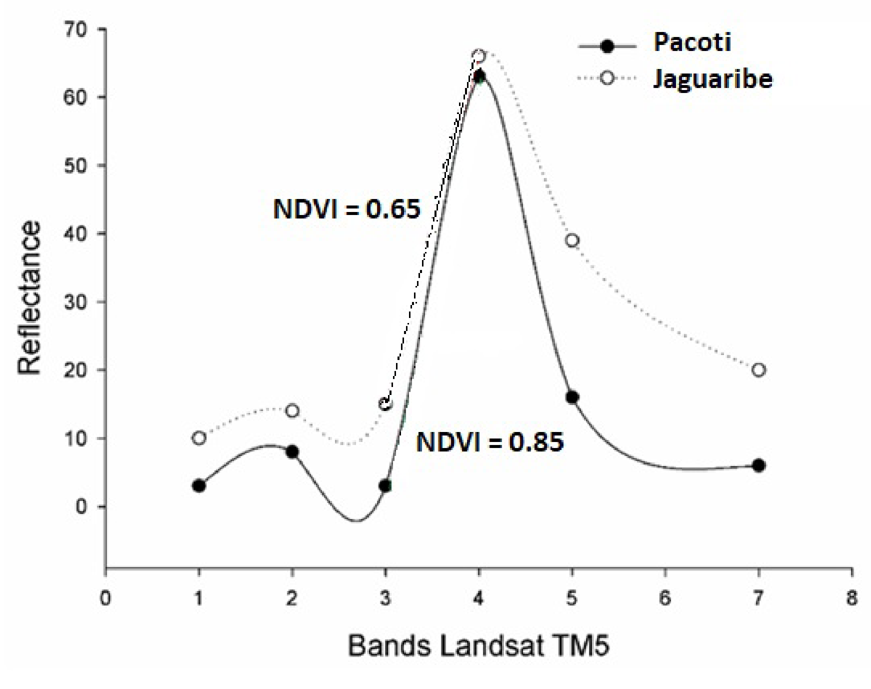

Figure 2. Reflectance and NDVIs values obtained from the images of the Landsat TM5 from the two mangrove areas evaluated.

creek, whereas at the Pacotí creek TP fluxes were lower and varied from -50 to +1,060 g.hr^{-1}. Overall, the shrimp farm influenced site showed 10 times larger fluxes of the sum of all P measured (ΣP (TP + PartP + SRP) = 1.2 - 5.2 kg.hr^{-1}) than the pristine site (ΣP = 0.22 kg.hr^{-1}).

DISCUSSION

The small number of tidal cycles sampled hampers a detailed discussion of controlling parameters of the hydrochemistry. However, floodwaters tend to present lower salinity, higher oxygen content and slightly higher pH. In contrast, ebb waters present higher salinity due to evaporation and salt concentration typical of semiarid mangroves, a decrease in oxygen content is also expected due to consumption by anoxic sediments. The presence of weak organic acids may explain the slightly lower pH in ebb waters. These differences between flood and ebb waters agree with previous results observed for other mangrove areas (Ovalle et al. 1990, Prasad and Ramanathan 2008, Sanchez-Carrillo et al. 2009). When comparing the two sites, the lower oxygen and higher TSS concentrations at the Jaguaribe site strongly suggest the effect of different inputs from anthropogenic sources. TSS concentrations in the same magnitude in mangrove sites influenced shrimp farms were reported in China under similar pond operations to those in the Jaguaribe estuary (Biao et al. 2004).

The range of concentrations of all P species is within the reported range for other mangroves occurring in semiarid littorals (Sanchez-Carrillo et al. 2009) but lower than values reported for mangroves in the high urbanized Sepetiba Bay in SE Brazil, for example (Ovalle et al. 1990). The relative importance of the different P fractions are in agreement with the estimated P loads for the two areas, in particular SRP with concentrations in the Jaguaribe site up to 6 times higher than in the Pacoti site. Differences were smaller for TP (~3 times) and PartP (~1.4 times). These results confirm the importance of anthropogenic P sources to the Jaguaribe site, particularly shrimp farming, which effluents released directly into mangrove creeks (Marins et al. 2007, 2011) are particularly enriched in SRP and organic PartP (Burford et al. 2003). Whereas SRP concentrations vary widely in anthropogenic affected mangroves, those measured at the Pacotí site are similar to SRP concentrations reported for other pristine mangrove areas in Brazil (Sanders et al. 2014).

Shrimp farm effluents are enriched in P used as fertilizer to induce phytoplankton growth in ponds (Lacerda et al. 2008), as a result effluents increase soil and water TP contents, as well as P fractionation and alter physicochemical conditions of mangrove waters and soils (Nobrega et al. 2004). In tidal creeks, SRP adsorbs onto suspended particles and both organic and inorganic particulate P deposit and accumulate in mangrove sediments (Ovalle et al. 1990). A fraction of the deposited P may be ressuspended, but most is believed to remain within the mangrove system (Sanchez-Carrillo et al. 2009).

When compared the two campaigns in the Jaguaribe estuary creek, higher P fluxes are associated with higher current velocity and P concentrations in both episodes. Slower current velocities would favor P retention within the mangrove system by facilitating finer, P-enriched particles deposition and augmenting of the interactions with sediment surfaces, including biofilms (Ovalle et al. 1990). The lower fluxes monitored in the Pacotí site relative to the Jaguaribe were also due to differences in TSS and P fractions concentrations, although slightly slower water flow velocities were recorded in

Table II. Hydrology and flow data for phosphorus and total suspended solids, measured during tidal cycles in the sampled mangrove creeks in NE Brazil. First and last line of each campaign represents high tide, when creek depth was the peak.

Sampling	Vel. (cm s^{-1})	SRP (μM)	TP (μM)	PartP (μM)	Flux SRP ($g.hr^{-1}$)	Flux PartP ($g.hr^{-1}$)	Flux TP ($g.hr^{-1}$)	Flux TSS ($kg.hr^{-1}$)
1st Campaign: Jaguaribe river	10.6	2.5	4.3	1.9	+2,552	+1,941	+4,493	+663
	7.3	2.9	4.7	1.8	-1,514	-902	-2,416	-298
	1.1	2.6	6.5	3.9	-66	-99	-165	-24
	0	2.5	7.5	5.0	0	0	0	0
	8.8	3.1	6.7	3.6	+23	+27	+50	+7
	0.5	4.5	9.4	4.9	+24	+25	+49	+7
	0.8	2.7	10.7	8.0	+43	+129	+173	+30
2nd Campaign: Jaguaribe river	2.4	2.7	3.2	1.3	+547	+117	+664	+50
	1.1	2.8	6.6	3.9	-151	-208	-360	-39
	0.3	2.5	9.9	7.4	-11	-34	-45	-4
	0.1	2.8	10.3	7.3	-1	-3	-4	-1
	4.9	3.7	8.7	5.0	-62	-85	-147	-13
	2.7	3.5	9.8	6.3	-15	-26	-40	-3
	0	4.8	11.6	6.8	0	0	0	0
	0	6.5	13.8	7.3	0	0	0	0
	0.1	4.0	15.9	11.9	+3	+8	+11	+1
	0.1	2.1	12.7	10.6	+2	+9	+11	+1
	0.4	2.1	8.7	6.6	+30	+94	+124	+10
	0.4	2.5	5.2	2.8	+84	+93	+177	+18
	0.1	2.1	9.3	7.2	+19	+65	+84	+3
Campaign: Pacotí river	0.3	0.3	3.3	3.0	-4	-46	-50	-5
	0.3	0.1	2.9	2.8	-2	-34	-35	-3
	0	0.6	4.6	4.0	0	0	0	0
	0	0.9	5.1	3.9	0	0	0	0
	4.0	0.8	7.3	7.7	+7	+61	+68	+9
	3.8	0.4	4.7	4.3	+44	+428	+473	+55
	3.0	0.2	4.2	4.1	+48	+1,012	+1,060	+131
	0.2	4.2	4.1	+48	+1,012	+1,060	+131	+131

the Pacotí site. Another important aspect is the lower oxygen concentrations in the Jaguaribe site. Sub-oxic conditions frequently develop in the region and this would result in SRP release from sediments, which diffusion would also be favored by faster flow velocities.

Figure 3 shows box diagrams of instantaneous P fluxes estimated for the three campaigns. In all campaigns, the mangrove acted as a sink for suspended particles, but the relative amount of TSS retained during the tidal cycle varied among campaigns and between sites. During the first campaign at the Jaguaribe site, from a total incoming TSS input of 706.1 kg, 384.6 kg (54%) were retained inside the mangrove, whereas during the second campaign, from a total input of 83 kg, 23.6 kg (28%) were retained. Considering the two cycles monitored, the Jaguaribe creek retained in average 41% of the total TSS tidal input. The eventual differences in flow rates between the two campaigns in the Jaguaribe creek, can be explained by the timing of the two samplings along the dry season, while August is the beginning of the dry period, November is in the end, accumulating nearly zero precipitation during the prior two months. In the Pacotí creek, TSS tidal inputs were smaller than those at the Jaguaribe. However, accumulation was stronger. From the incoming TSS input of 196.1 kg, 95% (186.4 kg) were retained inside the forest.

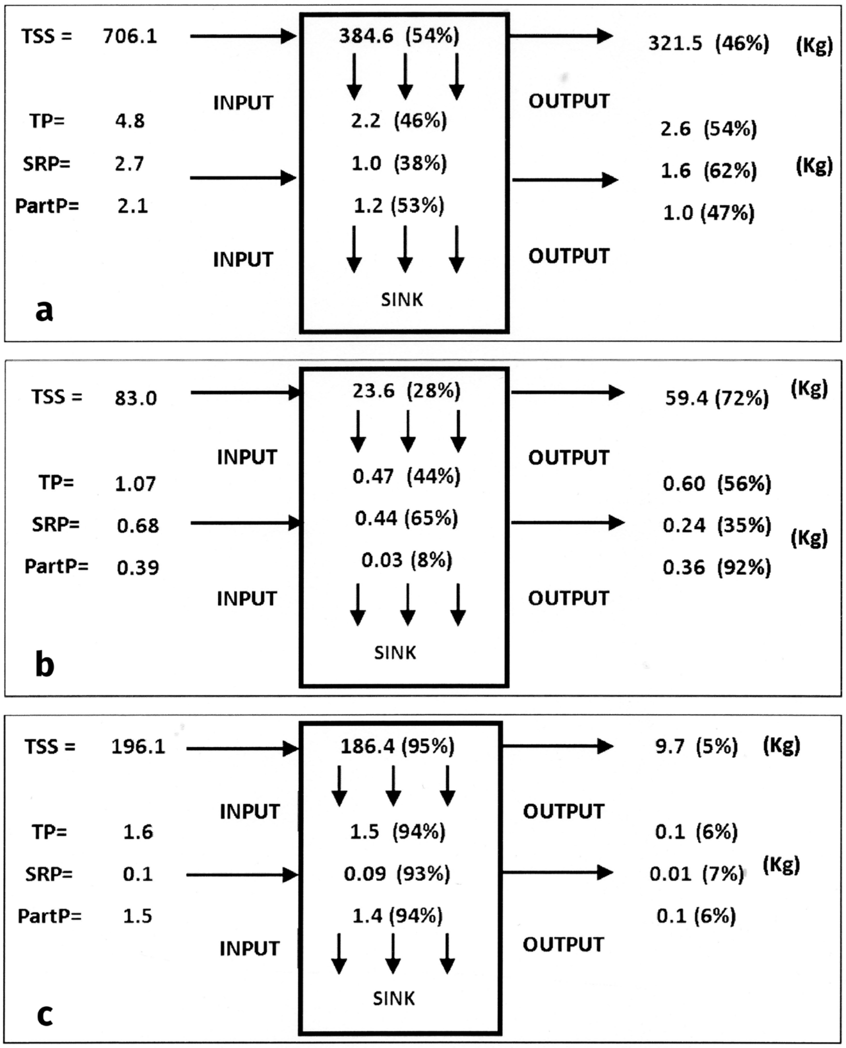

Figure 3. Box diagrams showing estimated instantaneous fluxes of total suspended solids (TSS) and P fractions. SRP: soluble reactive phosphorus, PartP: particulate phosphorus and TP: total phosphorus, all fluxes in fluxes in kg.h^{-1}. a and b represent the first and second campaign at the Jaguaribe estuary; c represents the single campaign at the Pacotí estuary.

The balance of P fractions displayed a similar behavior to that of the TSS. Fluxes estimated for the Jaguaribe creek were much larger than at the Pacotí creek, for all P fractions. However, P fractions presented both net export and net import depending on site and fraction. In the Jaguaribe creek, SRP fluxes showed that significant portions (38% and 65%) of the SRP entering the creek in the flood tide (2.7 and 0.68 kg) were exported back in the ebb tide (1.6 and 0.24 kg), in the first and second campaigns respectively. This is probably due to the higher solubility of phosphorus under de sub-oxic conditions observed in the Jaguaribe site, where oxygen levels can be as low as 25% saturation (Table I) (Nobrega et al. 2004) the Pacotí creek, SRP tidal input was much smaller (0.1 kg), but up to 93% were retained within the mangrove forest, in agreement with the oxidized conditions observed in this area, which would make difficult solubilization of deposited P (Marins et al. 2007). Redox conditions seem to be the major controlling parameter of SRP fluxes as noted by other authors (Ovalle et al. 1990, Silva et al. 1998, Barcellos et al. 2019). Significant proportions (47% and 92%) of the PartP flux entering the creek in the flood tide (2.1 and 0.39 kg) were exported back in the ebb tide (1.0 and 0.36 kg) in the first and second campaigns, respectively. In the Pacotí creek, PartP fluxes were smaller (1.5 kg), but with up to 94% being retained within the mangrove forest. Total P flux patterns were similar with most (46% and 44%) of the TP entering the creek in the flood tide (4.8 and 1.07 kg) being exported back in the ebb tide (2.6 and 0.6 kg) in the first and second campaigns in the Jaguaribe site, respectively. In the Pacotí creek, PartP fluxes were also smaller (1.5 kg), but also with up to 94% being retained within the mangrove forest.

Regarding TSS and P fractions balances, the Jaguaribe site behaves as a weaker importer, with average retention percentages varying from 41%; 45%, 52%; 31% for TSS, for TP; for SRP; and for PartP respectively, relative to the Pacotí site where over 93% of the total tidal input of TSS and all P fractions are retained within the mangrove. Agraz-Hernández et al. (2018) experimentally reached similar results. The estimated 97% retention of the total P input to an experimental greenhouse stand of *R. mangle* when excess nutrient loads were added for the first time. After the second treatment, however, retention efficiency was negligible. Barcellos et al. (2019) also reported increasing “leaking” of soluble P from mangroves subjected to eutrophication from anthropogenic effluents in northeastern Brazil.

Based on the instantaneous tidal balances presented, it is not possible to extrapolate the results to annual basis relative to the total forest area, due to the lack of data from the rainy season and from neap tides. This makes difficult comparisons with mostly published results, which are frequently expressed in terms of annual fluxes. Therefore, these instantaneous flux results should be viewed as site and season specific. However, when TP spring tide results are expresses as $kg.ha^{-1}.day^{-1}$ (1.4 and 0.23 for the Jaguaribe and the Pacotí sites, respectively), they compared well with other studies in semiarid coasts under relative pristine conditions (Sanchez-Carrillo et al. 2009). Moreover, these fluxes are lower than those reported for mangroves in areas closer to urbanized areas, such as in southeastern Brazil, for example (Ovalle et al. 1990, Silva et al. 1998). Notwithstanding, this comparison has to be viewed with care, since only one spring tide cycle was monitored in this study.

Phosphorus fluxes are usually low in mangroves (Holmer et al. 2001) but P balances are typically site specific, ranging from negative (exporter) to positive (importer) balances.

As P shows strong signs of anthropogenic contribution to the mangrove system of the Jaguaribe site, while being probably limiting in the Pacotí site, this could support the P-limitation response of mangroves as proposed by Feller et al. (2007), with higher retention rates when P availability is relatively low. Estimate of mangrove area expansion at the Pacotí estuary suggests a rapid increase in mangrove cover and biomass (Lacerda et al. 2007); whereas at the Jaguaribe creek site mangrove extension has changed little in the past 15 years and no change in forest structure or biomass have been reported (Godoy et al. 2018). Although most authors agree about the role of mangroves acting as P sinks (Tappin 2002), our results show that P import rates are higher than many values reported in other studies, which typically vary from 0.01 to 0.03 $kg.ha^{-1}.day^{-1}$, even though most of these studies were carried on in wet areas with significant P inputs from rivers (Wörsten 2003). On the other hand, when compared with dry climate areas with much lower P amounts reaching the estuary from fluvial inputs, our extrapolated daily balances are in agreement with those semiarid sites (Sanchez-Carrillo et al. 2009).

Some studies have suggested mangroves as useful sites for the disposal of nutrient-rich effluents from human activities, such as aquaculture, a most significant driver of environmental impacts on mangroves. On the other hand, studies suggested that nutrient enrichment reduces the resilience of mangroves to environmental stress, which may eventually results in increasing tree mortality (Lovelock et al. 2009). Eutrophication, from shrimp farm effluents, causes increases of foliar nitrogen and decreases of foliar base cations and a reduction of soil available P in *Rhizophora* spp. forests in Indonesia (Fauzi et al. 2014). Changes in nutrient availability and increasing tree mortality are important drivers to reduce NDVI of mangrove canopy, as clearly shown by the results but a direct relationship is still non-quantified, as well as ruling out other drivers such as changes in hydrology, also indirectly provoked by shrimp pond construction in the neighborhood of mangroves (Lacerda et al. 2019). In one of the very first paper on the use of mangroves to filter shrimp farm effluents, Robertson and Phillips (1995) estimated that from 2.8 to 21.7 ha of mangroves should be necessary to filter the amount of P present from 1 ha of shrimp pond. Considering the shrimp pond area in the Jaguaribe and Pacotí sites, and even considering the entire mangrove area in the studied estuaries, this capacity is already surpassed by a factor ranging from 6 to 48 in the Jaguaribe, whereas at our pristine site the accumulation capacity is still underutilized by a factor ranging from 0.1 to 0.6.

Our results supports latter findings that the higher P-input in the Jaguaribe site relative to the smaller P-input in the Pacotí site, strongly suggest that mangrove P accumulation capacity is significantly decreased with increasing P inputs. The P losses from the mangrove receiving large shrimp farm effluents, can therefore, limit mangrove`s potential as a natural barrier of nutrient transport through the continent-ocean interface and favor the eutrophication process and consequently altering marine productivity of adjacent coastal waters. Additionally, marine ecosystems tend to exhibit threshold response to increasing cumulative stress, such as shrimp farming effluents, although very difficult to predict (Crain et al. 2008, Hunsicker et al. 2016), this needs to be taken into consideration in managing mangrove areas already under stress by anthropogenic activities, such as the case of the Jaguaribe River estuary, reported here.

CONCLUSIONS

The results obtained in the mangrove sites at the northeastern Brazilian coast, clearly show the capacity of NDVI, even using a low resolution image such as Landsat, and at least for mangroves under semiarid climate, to respond to the stress resulting from shrimp farm effluents. This finding corroborates previous studies from mangroves in other semiarid coasts. Although a quantitative relationship between NDVI and phosphorus accumulation cannot be obtained based on the reported data, it is clear that lower NDVI, implying lower canopy integrity, occurred in the site where phosphorus inputs are highest and the relative accumulation is lowest, suggesting NDVI as a strong tool in assessing and monitoring environmental impacts from anthropogenic drivers. Mangrove phosphorus accumulation capacity is significantly decreased under high P inputs. The studied area under strong pressure from shrimp farm effluents has its support capacity overtaken by the dimension of the aquaculture activity. The decrease in P accumulation capacity is probably associated with low oxygen in tidal waters resulting from eutrophication caused by excess nutrients form shrimp farms. The results highlights the limitation, to a large extent, of mangrove's potential use as a natural barrier to the nutrient transport to adjacent estuarine and coastal areas hampering the use of mangrove as filters to nutrient enriched effluents.

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SUPPLEMENTARY MATERIAL

Figure S1. Map detailing the location of the two experimental sites in the Jaguaribe and Pacotí river estuaries in NE Brazil, including the position of shrimp farms and fixed sampling stations.

Figure S2. Comparison between images from 2003 and 2008 and respective NDVIs of the studied site in the Jaguaribe estuary mangrove.

Figure S3. Fixed sampling station at the Jaguaribe river site during high tide. A similar strategy was placed at the control site in the Pacotí estuary.

Figure S4. Fixed sampling station at the Jaguaribe river site during low tide. A similar strategy was placed at the control site in the Pacotí estuary.

Figure S5. Methodology for flux estimates used in the study.

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