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ESTRUTURA DA COMUNIDADE FITOPLANCTÔNICA E CARACTERÍSTICAS AMBIENTAIS DO ESTUÁRIO E PLUMA DO RIO JABOATÃO (REGIÃO NORDESTE DO BRASIL)

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Tese apresentada ao Programa de Pós-Graduação em Oceanografia da Universidade Federal de Pernambuco, como requisito parcial para obtenção do título de Doutor em Oceanografia.

Área de concentração: Oceanografia Biológica.

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RESUMO

O presente trabalho foi desenvolvido no estuário do rio Jaboatão e sua pluma, com o objetivo principal de descrever a estrutura da comunidade fitoplanctônica e suas características ambientais. As amostras foram coletadas em oito estações, quatro em cada local, nas estofas de baixa-mares de sizígia. Foram aferidos dados dos parâmetros abióticos *in situ*: temperatura superficial da água, profundidade local e transparência da água; e coletadas amostras de água com garrafas Van Dorn para determinação do pH e oxigênio dissolvido, amônia, nitrito, nitrato, fosfato e silicato. As amostras para o estudo quantitativo do fitoplâncton foram coletadas com garrafas oceanográficas de Ninskin e posteriormente fixadas com solução de lugol, sendo analisadas através do método de sedimentação de Utermöhl. Para a análise qualitativa, realizada no estuário, as amostras foram coletadas com redes de plâncton com abertura de malha de 45 µm e imediatamente fixadas com formol neutro a 4%, sendo posteriormente analisadas em em câmaras de Sedgwick-Rafter Nas amostras de garrafa foram registrados 80 táxons, havendo um maior número de espécies ocorrendo na pluma do que no estuário, com 65 e 38 táxons, respectivamente. Na análise qualitativa foram registrados 123 táxons. As diatomáceas, em ambas as análises, foram o grupo mais representativo em termos de riqueza de espécies; já em termos de densidade as cianobactérias foram mais representativas. A diversidade e a equitabilidade foram em geral baixas no estuário devido à dominância da cianobactéria *Microcystis aeruginosa*, espécie oportunista e potencialmente tóxica. O estuário do rio Jaboatão é fortemente impactado, conseqüência dos menores valores de salinidade, oxigênio dissolvido e altas concentração de nutrientes, principalmente os componentes nitrogenados e o fosfato, indicativos do recebimento de altas cargas poluidoras. Valores positivos de AOU (média: +2.7 e +2.1 ml/L, para ambos os períodos sazonais) indicam altas taxas respiratórias e a modelagem do sistema indica altas taxas de respiração de matéria orgânica (produção-respiração) e uma permanente desnitrificação estuarina. A eutrofização do ambiente propiciou o surgimento de *blooms* significativos de *M. aeruginosa.* A pluma apresentou águas bem oxigenadas, salinas e de baixa concentração de nutrientes, indicando a influência do fluxo marinho na área e permitindo a dominância de outras espécies, contribuindo para o aumento da diversidade e melhorando a qualidade local. *M. aeruginosa,* considerando suas altas densidade, dominância e freqüência de ocorrência, foi considerada a espécie chave na área.

Palavras-chave: Ambiente costeiro. Biodiversidade. Variáves fisico-quimicas. Nutrientes. Densidade celular. Bloom.

ABSTRACT

The present work was carred out in the estuary of the Jaboatão River and its plume, with the main objective of describing the phytoplankton community structure and its environmental characteristics. The samples were collected at eight stations, four at each site, at low tide. Abiotic parameters were measured in situ: surface water temperature, local depth and water transparency. Water samples were collected with Van Dorn bottles for determination of pH and dissolved oxygen, ammonia, nitrite, nitrate, phosphate and silicate. Samples for the quantitative study of phytoplankton were collected with Ninskin oceanographic bottles and later fixed with lugol solution and analyzed using the Utermöhl sedimentation method. For the qualitative analysis, the samples were collected with 45 µm mesh sizeplankton nets and immediately fixed with 4% neutral formalin and analyzed in Sedgwick-Rafter chambers. In the bottle samples were recorded 80 taxa, with a greater number of species occurring in the plume than in the estuary, with 65 and 38 taxa, respectively. In the qualitative analysis, 123 taxa were registered. Diatoms, in both analyzes, were the most representative group in terms of species richness; in terms of density the cyanobacteria were more representative. Diversity and equitability were generally low in the estuary due to the dominance of the opportunistic and potentially toxic cyanobacteria *Microcystis aeruginosa*. The estuary of the Jaboatão River is strongly impacted, due to the lower values of salinity, dissolved oxygen and high concentration of nutrients, mainly nitrogenous components and phosphate, indicative of high pollutant loads. Positive values of AOU (mean: +2.7 and +2.1 ml / L, for both seasonal periods) indicate high respiratory rates and the modeling of the system indicates high rates of respiration of organic matter (production-respiration) and a permanent estuarine denitrification. Eutrophication of the environment led to the appearance of significant *M. aeruginosa* blooms. The plume presented well oxygenated, saline and low concentration of nutrients, indicating the influence of the marine flow in the area and allowing the dominance of other species, contributing to the increase of diversity and improving local quality. *M. aeruginosa*, considering its high density, dominance and frequency of occurrence, was considered the key species in the area.

Keywords: Coastal environment. Biodiversity. Physico-chemical variables. Nutrients. Cell density. Bloom.

SUMÁRIO

1 INTRODUÇÃO

A zona costeira é certamente uma das parcelas de território mais complexas e ricas em termos ambientais. É uma área com grande concentração de habitats e com uma importante diversidade biológica, sendo composta por ambientes com marés, manguezais, recifes, praias, ondas, baías, entre outros. Possui um equilíbrio dinâmico, que resulta da interferência de inúmeros fatores, naturais ou antrópicos (GIZC, 2007).

Segundo Teal (1962), os ecossistemas estuarinos e baías costeiras produzem uma quantidade de matéria orgânica maior do que são capazes de utilizar e o excesso deste material seria exportado para as áreas adjacentes (pluma).

Causas naturais que levam os ecossistemas aquáticos a incorporarem diferentes substâncias ao longo do tempo podem alterar a qualidade da água, afetando a sua constituição e as finalidades de seu uso. No entanto, lançamentos nos corpos hídricos pelas atividades humanas comprometem seriamente a qualidade das águas (PIMENTA et al., 2009).

O efeito conjunto dos principais fatores físico-químicos do ambiente pelágico tais como intensidade luminosa, concentração de nutrientes, temperatura e salinidade determinam a distribuição geográfica, a composição específica e a variabilidade das taxas de produção do fitoplâncton (PELIZZARI, 1996).

Devido à resposta rápida do fitoplâncton às mudanças nas condições ambientais, esta comunidade pode ser utilizada como indicador no monitoramento de recursos hídricos, cujas características biológicas, químicas e físicas determinam a ocorrência, distribuição e composição destes organismos, podendo influenciar na riqueza de espécies, bem como levar à substituição ou desaparecimento destas (CARVALHO, 2003; SANTIAGO et al., 2010).

Estudos sobre o fitoplâncton e suas respostas às variáveis ambientais representam importantes ferramentas para a compreensão e diagnóstico dos impactos, naturais e/ou antropogênicos, que ocorrem nos ecossistemas aquáticos no nível dos produtores primários (Honorato da Silva et. al. 2009). O conhecimento da composição taxonômica do fitoplâncton é fundamental para o estudo da dinâmica espacial e temporal da comunidade (Cloern 1994 apud Gameiro et al. 2007).

Registrar a estrutura da comunidade fitoplanctônica objetiva, mais do que simplesmente conhecer, correlacionando sua composição com as variáveis ambientais, aplicar esses dados a fim de instituir políticas de conservação e manutenção da qualidade do sistema em toda sua abrangência.

Padrões de distribuição espaço-temporal são abordados nos estudos quantitativos do fitoplâncton, configurando uma ferramenta importante na avaliação da qualidade da água. Estas flutuações espaço-temporais em suas composições e biomassa são indicadores eficientes destas alterações, sejam elas naturais ou não. A composição dos organismos pode variar de acordo com as mudanças na condições físicas, químicas e ambientais do corpo hídrico (BRANDINI et al., 1997).

Fatores limitantes (nitrogênio e fósforo) e controladores influenciam o crescimento do fitoplâncton. Considerando a essencialidade do nutriente limitante, ele limita o crescimento da população, ou seja, em baixas concentrações do nutriente limitante o crescimento populacional é baixo. Com a elevação da concentração do nutriente limitante o crescimento populacional também aumenta (VON SPERLING, 1996).

Ao longo dos últimos séculos, o enriquecimento de nutrientes por fontes antropogênicas (particularmente nitrogênio e fósforo) associados aos desenvolvimentos urbano, agrícola e industrial, tem promovido taxas aceleradas de produção primária, ou eutrofização (PAERL e PAUL, 2012). A eutrofização produz mudanças na qualidade da água, podendo ocorrer à redução de oxigênio dissolvido, morte extensiva de peixes, perda da qualidade cênica do ambiente e aumento da incidência de florações de microalgas e cianobactérias (ARRUDA, 1997).

O aumento no número de registros de florações pode ser atribuído a fatores como os mecanismos de dispersão das algas; aumento na concentração de nutrientes devido à atividade humana, que favorece a seleção e proliferação de algas nocivas; aumento das operações de aquicultura, favorecendo a presença de espécies desconhecidas; dispersão de algas através de água de lastro; e mudanças climáticas (GEOHAB, 2001).

Dentre os efeitos nocivos causados por microalgas, podemos destacar os gerados por espécies não tóxicas, cujas florações ocasionam anoxia na coluna d’água, causando a mortandade de peixes e invertebrados; os gerados por espécies que produzem toxinas, que podem chegar ao homem através da cadeia trófica; e aqueles gerados por espécies que não são tóxicas ao homem, mas prejudicam peixes ou invertebrados por obstrução de brânquias ou sistemas de filtração. Dentre as espécies produtoras de toxinas, destacam-se diferentes grupos, principalmente as cianobactérias, dinoflagelados e diatomáceas (HALLEGRAEFF et al., 1995).

Das mais de 5000 espécies do fitoplâncton, somente cerca de 6% podem ser nocivas e menos de 2% produtoras de toxinas (GRANÉLI e TURNER, 2006). Na categoria de microalgas potencialmente nocivas estão incluídas várias classes de protistas (dinoflagelados, primnesiofíceas, crisofíceas, diatomáceas, rafidofíceas) predominantemente espécies fotossintetizantes, assim como as cianobactérias (SOURNIA, 1995). Temperaturas acima de 20°C; pouca luminosidade; baixas razões Ntotal/Ptotal; baixa concentração de CO2; elevada capacidade de armazenar fósforo intracelular; presença de aerótopos que auxiliam na flutuação e deslocamento na coluna d'água; e baixa taxa de herbivoria pelo zooplâncton favorecem o desenvolvimento de cianobactérias. Estas características conferem a este grupo uma grande vantagem competitiva (OLIVER e GANF, 2000).

Mesmo sendo um fenômeno de ordem natural, a ocorrência de florações em regiões costeiras tem sido cada vez mais frequente e se tem registrado espécies cada vez mais tóxicas (PROENÇA et al., 2004) e, muitas vezes, a presença destas toxinas não estão necessariamente associadas a densidades de alerta destas espécies. Portanto, o estudo da composição e ecologia do fitoplâncton são métodos eficazes para avaliação do ambiente pela resposta às variações nas condições ambientais, bem como sua riqueza e abundância associadas aos parâmetros abióticos, que fornecem subsídios para a definição das abordagens no local (CERVETTO et al. 2002).

Estrutura da tese

Este documento foi organizado em artigos, buscando a melhor abordagem dos resultados do trabalho. Apresenta conhecimentos sobre o fitoplâncton, com ênfase na dominância de cianobactérias na região estuarina e sua resposta às diversas variações do ambiente. As partes desta tese são: uma contextualização dos temas abordados (introdução, revisão bibliográfica e objetivos); Artigo 1, que aborda a estrutura da comunidade fitoplanctônica no estuário do rio Jaboatão e cujo objetivo é meramente descritivo; o Artigo 2, publicado na revista Open Journal of Ecology, que correlaciona a ocorrência das espécies com as variáveis ambientais; e o Artigo 3, que aborda a ocorrência dos blooms da espécie mais representativa da área.

2 OBJETIVOS

Os objetivos geral e específicos deste trabalho são conforme segue:

2.1 OBJETIVO GERAL

Caracterizar a estrutura da comunidade fitoplanctônica do estuário e pluma do Rio Jaboatão, entender a dinâmica da comunidade e as respostas desta às alterações naturais e/ou antrópicas.

2.2 OBJETIVOS ESPECÍFICOS

- Evidenciar a estrutura ecológica da comunidade fitoplanctônica;
- Evidenciar os fatores que influenciam na estrutura da comunidade fitoplanctônica na área de estudo;
- Avaliar a dinâmica da comunidade em resposta äs variações do ambiente;
- Determinar espécies bioindicadoras da qualidade ambiental;
- Avaliar a ocorrência de blooms de espécies.

3 REVISÃO BIBLIOGRÁFICA

Trabalhos sobre fitoplâncton em ecossistemas estuarinos na região nordeste e principalmente em Pernambuco são bastante conhecidos, tratando principalmente da estrutura e dinâmica da comunidade fitoplanctônica (SANTOS-FERNANDES et al., 1998; KOENING et al., 2002; FEITOSA et al., 2004; LACERDA et al., 2004; BRANCO et al., 2006; GREGO et al., 2009; HONORATO DA SILVA et al., 2009; SANTIAGO et al., 2010; TIBURCIO, 2011; BORGES, 2016).

Nos estuários e em seus ambientes associados, os estudos realizados destacam uma maior representatividade das diatomáceas, seguidas de espécies de dinoflagelados e cianobactérias. A dominância das diatomáceas como a entidade taxonômica mais representativa, é um fato já comumente registrado para as águas costeiras do Nordeste do Brasil (FEITOSA et al. 1999, no sistema estuarino do rio Goiana; ESKINAZI-LEÇA et al. 2000 e 2004; CAMPELO et al., 2001, na praia de Carne de Vaca, Goiana; LEÃO, 2004, no estuário do rio Igarassu; SANTIAGO et al., 2004, no estuário do rio Pisa Sal, RN; MACEDO et al., 2005, no sistema estuarino de Barra das Jangadas, registrando blooms de diatomáceas e cianobactérias; ROSEVEL DA SILVA et al., 2005, na baía de Tamandaré; BRANCO, 2007, em Barra das Jangadas; HONORATO DA SILVA et al. 2009, no estuário do rio Formoso; FERREIRA et al., 2010, em praias urbanas do litoral sul de Pernambuco; SANTIAGO et al. 2010, na bacia do Pina; JALES, 2011, nos recifes de Serrambi; e AQUINO et al., 2015, no estuário do rio dos Passos). Na região Norte são conhecidos os trabalhos de Cardoso (2009), no estuário do rio Guajará-Mirim (Pará) e SOUSA et al., 2009, na zona de arrebentação da Ilha Canela (Pará).

No que se refere às áreas costeiras, ainda são poucos os trabalhos relacionados com a comunidade fitoplanctônica (ESKINAZI-LEÇA et al., 1997; ESKINAZI-LEÇA et al., 2004; KOENING et al. 2009 e MELO et al. 2014).

Especificamente para as áreas costeiras adjacentes ao estuário do rio Jaboatão estes trabalhos são inexistentes sendo este, portanto, pioneiro para a área. Melo et al. (2014) destacam a maior representatividade das diatomáceas na pluma do rio Capibaribe, seguida dos dinoflagelados, mesmo padrão encontrado para a pluma do rio Jaboatão.

Estudos anteriores realizados no ecossistema estuarino do rio Jaboatão por Lacerda et al. (2004), Branco et.al. (2004) e Branco (2007) consideram as diatomáceas Bellerochea mallleus (Brightwell) van Heurck, Coscinodiscus centralis Ehrenberg e Cyclotella meneghiniana Kützing as espécies chave da área, sendo dominantes e muito frequentes. Branco et al. (2004) registraram uma diversidade específica variando de média a alta; já Lacerda et al. (2004) e Branco (2008) registraram a ocorrência de uma redução bastante acentuada desta diversidade.

Nas últimas décadas, as áreas costeiras de Pernambuco vêm sofrendo mudanças temporais na distribuição e abundância da comunidade fitoplanctônica, causadas principalmente pela eutrofização, descarga dos rios, ciclo de marés e precipitação (ESKINAZI-LEÇA et al. 1997; FERREIRA et al. 2010). Devido a essas características, nos ecossistemas aquáticos tropicais os eventos de florações fitoplanctônicas vêm sendo comumente relatados, trazendo consequências no odore na coloração da água, variações no teor de oxigênio dissolvido, além do aparecimento de espécies potencialmente tóxicas e nocivas ao homem e meio ambiente (HAYS et al., 2005).

Na plataforma brasileira, espécies de cianobactérias do gênero *Trichodesmium* são frequentes (SATÔ et al. 1963; BRANDINI, 1988; GIANESELLA-GALVÃO et al., 1995, MONTEIRO et al., 2010 e 2012), formando florações associadas a condições hidrográficas ainda pouco compreendidas.

Melo et al. (2014) registram no período chuvoso algumas espécies dominantes de cianobactérias na pluma do rio Capibaribe como *Planktothrix agardhii* (Gomont) Anagnostidis & Komárek (80%) e *Trichodesmium thiebautii* Gomont ex Gomont (70%). Estas espécies caracterizam a existência de problemas locais de eutrofização e condicionaram a uma baixa diversidade específica.

Já no estuário do rio Jaboatão e sua pluma, a espécie *Microcystis aeruginosa*, pela sua elevada densidade, dominância e frequencia de ocorrência, foi considerada a espécie chave, principalmente na região estuarina, com valores mais elevados no período chuvoso. Deve ser ressaltado que Melo et al. (2014) não registraram a presença de florações *de Microcystis aeruginosa* na pluma do Capibaribe.

As cianobactérias encontram nos ambientes de água doce condições mais propícias ao seu desenvolvimento, pois a maioria das espécies apresenta melhor crescimento em águas neutro alcalinas (pH entre 6 e 9), temperatura entre 15ºC e 30ºC e com alta concentração de nutrientes, principalmente nitrogênio e fósforo (FOGG E THAKE, 1987). No Brasil são registradas ocorrências de florações de cianobactérias, incluindo espécies potencialmente tóxicas, principalmente em reservatórios de abastecimento público, lagoas salobras e rios de vários estados (AZEVEDO, 1998; SÁ et al., 2010; SILVA et al., 2011).

Florações de *Microcystis aeruginosa* são frequentes e as de *Cylindrospermopsis* estão se tornando cada vez mais comuns (LAGOS et al. 1999, FERRÃO-FILHO et al. 2010). Ferrão Filho et al. (2002a) mostram como o desenvolvimento de florações de *M. aeruginosa* na lagoa de Jacarepaguá são potencialmente nocivas para a população de cladóceras na região.

A ocorrência de microalgas produtoras de toxinas, especialmente em florações, representa uma ameaça potencial à saúde pública. Intoxicações de populações humanas pelo consumo de água contaminada por espécies tóxicas de cianobactérias já foram descritas em países como Austrália, Inglaterra, China e África do Sul (FALCONER, 1994). O primeiro e mais repercutido caso no Brasil de mortes humanas ocasionadas por cianotoxinas ocorreu em 1996, em Caruaru (PE), quando 130 pacientes renais crônicos, após sessões de hemodiálise passaram a apresentar sintomas compatíveis com uma grave hepatotoxicose. Destes, 52 vieram a falecer (CARMICHAEL, 1996; JOCHIMSEN et al., 1998; POURIA et al., 1998, AZEVEDO et al. 2002, YUAN et al. 2006). Azevedo et al. (1994) apontaram a presença de microcistinas e cilindrospermopsinas no sistema de purificação de água da clínica e de microcistinas em amostras de sangue e fígado dos pacientes intoxicados.

São mais frequentemente registradas ocorrências de florações de cianobactérias em reservatórios de abastecimento do Norte, Nordeste, Sudeste e Sul do país (FERNANDES et al., 2005). Em Minas Gerais, cianobactérias potencialmente tóxicas foram registradas em vários reservatório por Jardim et al. (2000).

A eutrofização favorece o desenvolvimento e dominância de blooms de cianobactérias potencialmente tóxicas em ambientes planctônicos (STEINBERG e HARTMANN, 1988; HUISMAN et al., 2005; PAERL e FULTON, 2006). Eskinazi-Santana et al. (2005) observaram florações mistas em reservatório eutrofizados no RN. Azevedo (1998) descreveu a ocorrência de florações em reservatórios dos Estados de São Paulo, Rio de Janeiro, Minas Gerais, Pará, Paraná, Bahia, Pernambuco e Distrito Federal. Carmichaeal (1992), Vasconcelos et al. (2001), Trabeau et al. (2004), observaram a bioacumulação de toxinas em moluscos bivalves; Falconer (1991), Falconer et al. (1994), Amorim e Vasconcelos (1999), Magalhães et al. (2001) e Magalhães et al. (2003) abordaram a capacidade de bioacumulação da toxina microcistina nestes organismos.

Ramírez (1996) e Nogueira (1997) registraram florações de *M. aeruginosa* para o Lago das Garças (SP), ambos nos períodos de primavera e verão. Takenaka (2007) avaliou a toxicidade de *Microcystis aeruginosa* e de florações naturais de cianobactérias de reservatórios do rio Tietê por meio de testes com *Ceriodaphnia dubia* e *C. silvestrii*, cujos resultados indicam o aumento da concentração da microcistina com o aumento populacional de *M. aeruginosa*.

Deve-se considerar, no entanto, que as florações são um fenômeno tipicamente costeiro, observando-se que possam ser dependentes ou influenciadas por processos produtivos característicos de águas próximas à costa. Existem evidências razoáveis de que as florações estão associadas a um condicionamento biológico das águas costeiras devido à introdução de compostos orgânicos de origem terrígena (CETESB, 1983), portanto, essas florações são mais intensas em áreas que recebem cargas advindas de esgotos domésticos ou efluentes industriais, com elevadas concentrações de nutrientes (FLORES-MONTES, 1996).

Feitosa et al. (1999), em estudo feito no estuário do rio Goiana, registraram florações das diatomáceas *Coscinodiscus centralis*, *Biddulphia regia*, *Gyrosigma balticum* e *Bellerochea malleus*, espécies generalistas que provocaram o aumento da biomassa e queda na diversidade fitoplanctônica. No estuário do rio Igarassu, Macedo e Costa (1990) registraram a diversidade específica do fitoplâncton variando de muito baixa a alta, relacionada às florações das espécies neríticas e oceânicas dominantes do microfitoplâncton.

Flores-Montes (1996), estudando a variação nictemeral do fitoplâncton e parâmetros hidrológicos no Canal de Santa Cruz, registrando uma diversidade específica variando de média a baixa e blooms de *Thalassiosira* sp. e fitoflagelados. Cardoso (2009), estudando a dinâmica do microfitoplâncton e sua correlação com os fatores ambientais no estuário do rio Guajará-Mirim (PA), registrou uma densidade média mensal do microfitoplâncton variando de 9.999 org.L-1 a 535.411 org.L-1, assim como a floração da diatomácea *Skeletonema costatum*, com densidade de 1.996.613 org.L-1.

Passavante et al. (2007), em estudo do microfitoplâncton do estuário do rio Igarassu, registraram a ocorrência de *Microcystis aeruginosa* tendo ocorrido um florescimento expressivo no fim do período chuvoso e inicio do período de estiagem. Este padrão de densidade mais elevada no período chuvoso tem sido reportado para outros estuários no estado de Pernambuco (SANTOS-FERNANDES, 1997; FLORES

MONTES et al., 1998; LACERDA et al., 2004, SILVA et al., 2017).

Experimentos em laboratório foram também realizados utilizando cepas tóxicas de *Microcystis aeruginosa*, isolada do estuário da Lagoa dos Patos, onde mariscos foram expostos a células vivas desta cianobactéria durante 12 dias, apresentando valores de retenção significativos no hepatopâncreas destes animais. Considerando que várias ocorrências de florações de *M. aeruginosa* no estuário da Lagoa dos Patos e áreas costeiras são observadas, os resultados indicam que essas toxinas, comuns nessas florações, podem ser acumuladas por esse animal, tornando-o um potencial vetor para a teia trófica local (LEÃO et al., 2010).

Matthiensen et al. (1999) abordam a ocorrência, distribuição e toxicidade de cianobactérias no estuário da Lagoa dos Patos, RS. Neste estudo foram feitas análises quali-quantitativas das cianobactérias, particularmente *M. aeruginosa*, que apresentou florações, com densidade máxima de 1.3 x 106 cél.L–1. As florações registradas foram altamente tóxicas. Florações de *Microcystis aeruginosa*, segundo Yunes et al. (1996), têm sido registradas na Lagoa dos Patos desde 1987, com maiores densidades principalmente no verão e outono, com sua toxicidade determinada.

No caso das florações de espécies de microalgas nocivas planctônicas, a associação entre o aumento da ocorrência de eventos de floração e o processo de eutrofização das regiões costeiras do mundo é considerado hoje um consenso científico (HEISLER et al., 2008). Em resposta a este processo de eutrofização, a comunidade fitoplanctônica apresenta redução da diversidade especifica e um aumento considerável da biomassa de espécies dominantes e consequente desenvolvimento de florações.

É notável que os ecossistemas estuarinos tropicais vêm sofrendo grandes impactos ambientais por pressões urbana e o aumento da produção agrícola e industrial, necessitando medidas de controle e implementação de programas de monitoramento.

4 ARTIGO 1 - A ESTRUTURA DA COMUNIDADE FITOPLANCTÔNICA NO ESTUÁRIO DO RIO JABOATÃO (NORDESTE-BRASIL).

Resumo

O presente trabalho foi desenvolvido no estuário do rio Jaboatão, com o objetivo de descrever a estrutura da comunidade fitoplanctônica. As amostras foram coletadas em quatro estações, nas estofas de baixa-mares de sizígia. As amostras para o estudo fitoplanctônico foram coletadas com redes de plâncton com abertura de malha de 45 µm e analisadas em microscópio utilizando câmaras de contagem de Sedgwick-Rafter. Foram registrados 123 táxons, com as diatomáceas como o grupo mais representativo em termos de riqueza de espécies. Em termos de densidade, as cianobactérias foram mais representativas. A diversidade e a equitabilidade foram em geral baixas, variando de muito baixa a média. A baixa diversidade no estuário deve-se à dominância da cianobactéria *Microcystis aeruginosa*, espécie oportunista e potencialmente tóxica. O rio Jaboatão PE foi considerado fortemente impactado, conseqüência dos menores valores de salinidade, oxigênio dissolvido e altas concentração de nutrientes, indicativos do recebimento de altas cargas poluidoras. *Microcystis aeruginosa,* considerando suas altas densidade, dominância e frequência de ocorrência, foi considerada a espécie chave na área

Palavras-chave: cianobactéria, diatomáceas, estuário, ecologia.

Introdução

Os estuários são ecossistemas aquáticos muito dinâmicos, onde os mecanismos das marés, as correntes e as modificações de densidade, juntamente com os fatores climatológicos, refletem grandes variações dos parâmetros físico-químicos, influenciando na distribuição e flutuação da abundância das comunidades aquáticas (TUNDISI, 1970; ODUM, 1988; MCLUSKY, 1989; UNDERWOOD e KROMKAMP, 1999).

Segundo Noriega et al. (2014) alguns fatores podem influenciar na mudança da dinâmica de um ambiente estuarino, como circulação, evaporação, precipitação, ventos e correntes, determinando as variações sazonais de alguns parâmetros hidrológicos de regiões tropicais. Essa dinâmica influencia diretamente a comunidade fitoplanctônica, que responde rapidamente a essas flutuações.

As condições hidrodinâmicas de uma região favorecem os organismos mais adaptados e influenciam na estrutura da comunidade e na sua distribuição vertical e horizontal (BRANDINI et al., 2000). Entendendo as adaptações do fitoplâncton torna-se possível descrever os padrões de distribuição de sua abundância em função dos processos hidrológicos e da distribuição de nutrientes, além do impacto da pressão de predadores sobre as comunidades (HALLEGRAEFF, 2010).

As microalgas marinhas estão distribuídas por todo o planeta, porém, são em geral mais abundantes nas regiões costeiras que nas regiões oceânicas e mais abundantes nas altas latitudes que nos trópicos e equador. Eventualmente, em função de alterações de luminosidade, disponibilidade de nutrientes, temperatura, salinidade, predadores, entre outros fatores, a abundância desses organismos pode aumentar significativamente (GEOHAB, 2001).

Por possuírem um curto ciclo de vida e responderem rapidamente às alterações ambientais, as microalgas podem ser utilizadas como bioindicadores (ROUND et al., 1990), uma vez que são a base da teia trófica em sistemas aquáticos, deles dependendo os organismos dos demais níveis tróficos (DE LEÓN e CHALAR, 2003). A relevância dessas algas como indicadoras é ainda mais importante quando se verificam processos de eutrofização através de florescimentos maciços e mudanças quantitativas em suas populações (VALIELA, 1995; ESTEVES, 1998).

Grande parte dos trabalhos desenvolvidos nos ambientes estuarinos de Pernambuco abordam a composição florística de comunidades fitoplanctônicas, com destaque para os de Santos-Fernandes et al. (1997); Feitosa et al. (1999); Koening et al. (2002); Feitosa et al. (2004); Lacerda et al. (2004); Leão (2004); Macedo et al., (2005); Branco et al. (2003); Grego et al. (2009); Honorato da Silva et al. (2009); Santiago et al. (2010); Tiburcio (2011); Aquino et al. (2014); Borges (2016). No ecossistema estuarino do rio Jaboatão, registram-se os trabalhos de Lacerda et al. (2004), Branco et.al. (2006) e Branco (2007).

A Bacia Hidrográfica do Rio Jaboatão, localizada em sua maior parte na Região Metropolitana do Recife (RMR), logo, com características de uma Bacia urbana, apresenta todos os problemas comuns às bacias hídricas urbanas brasileiras: degradação dos recursos naturais, através da ocupação e uso inadequados do solo; poluição dos recursos hídricos, provocada por lançamentos de dejetos domésticos e efluentes industriais; ausência de manejo conservacionista, em contraponto ao discurso e a prática da sustentabilidade, com impactos diretos na saúde da população (GALINDO, 2008).

O município de Jaboatão dos Guararapes situa-se numa região de transição entre os climas Ams' e As', segundo a classificação de Köppen (quente e úmido, com a taxa de precipitação superando a de evaporação). O período das chuvas desenvolve-se entre os meses de março a agosto (outono-inverno), com precipitação máxima nos meses de inverno. Dentro deste período a precipitação pluviométrica oscila entre 140 mm e 270 mm mensais, com média anual superior a 1500 mm. A temperatura média anual está em torno de 26ºC, com temperaturas mínimas e máximas em torno de 18ºC e 32ºC, respectivamente (PFALTZGRAFF, 1996).

Segundo a CPRH (2010), observa-se o comprometimento da qualidade da água, com valores de oxigênio dissolvido abaixo do limite para as águas doces; o Índice do estado Trófico variando de mesotrófico a supereutrófico; e os altos valores de coliformes termotolerantes e fósforo total indicando contaminação por efluente doméstico. Evidencia-se, então, a necessidade de controle e fiscalização das fontes responsáveis pelo estado das águas da bacia.

Este trabalho tem como objetivo descrever a estrutura da comunidade fitoplanctônica encontrada no estuário do rio Jaboatao.

Material e métodos

As amostragens foram realizadas em quatro estações num perfil longitudinal no estuário do rio Jaboatão, e quatro estações na plataforma adjacente (Figura 1), nas baixa-mares de sizígia, nos meses de maio, julho e novembro de 2010, e fevereiro, maio, julho e setembro de 2011.

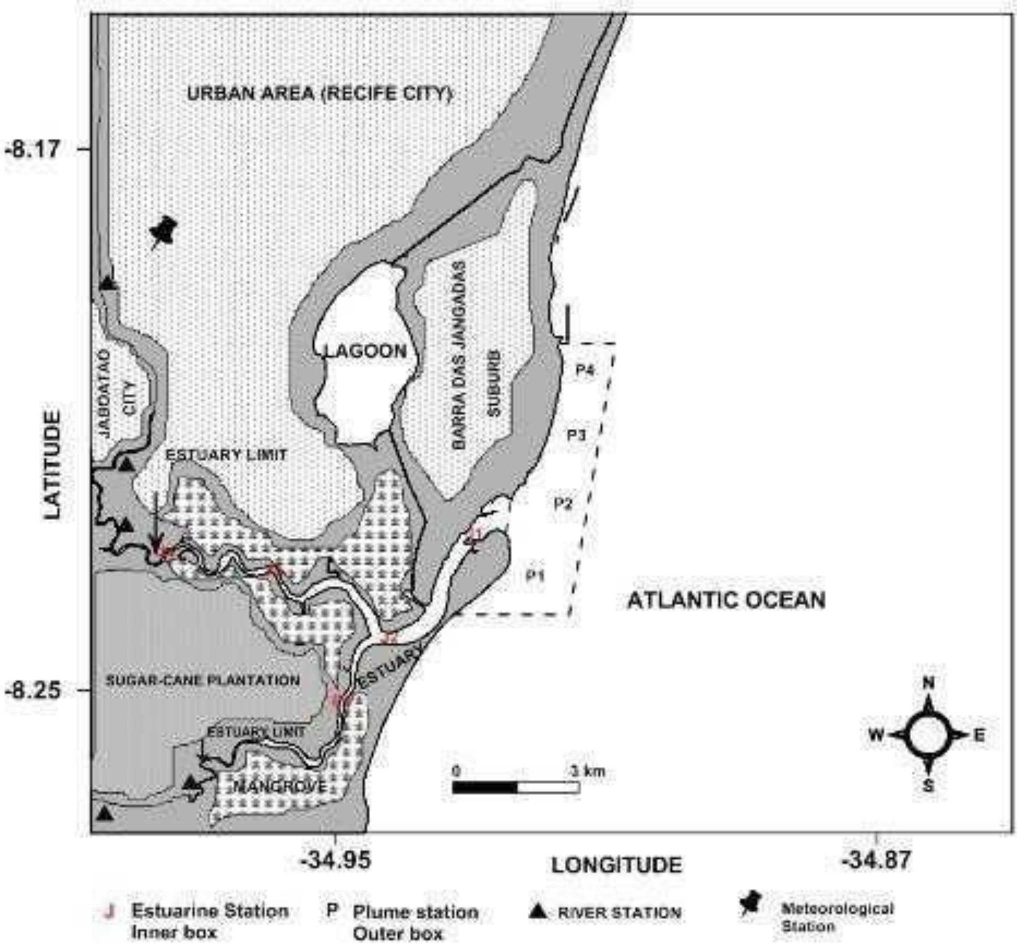
As amostras foram coletadas com redes de plâncton com abertura de malha de 45 µm e imediatamente fixadas com formol neutro a 4%, sendo posteriormente analisadas em microscópio utilizando câmaras de contagem de Sedgwick-Rafter, com capacidade de 1mL, apresentando 20mm de largura, 50mm de comprimento e 1mm de profundidade. A contagem dos organismos foi realizada pela técnica de transecção, sendo padronizada a leitura de um transecto por amostra. Para o cálculo do número de indivíduos por mL, utilizou-se a fórmula definida pelo *Standard Methods:*

$$Ind./mL = (N \times C)/ (Ct \times P \times Lt \times T)$$

Onde:

- N = número de indivíduos na contagem;
- C = Capacidade da câmara de S-R (1000 mm^3);
- Ct = Comprimento do transecto (= comprimento da S-R), mm;
- P = Profundidade do transecto (= profundidade da S-R), mm;
- Lt = Largura do transecto (= largura do retículo de Whipple), mm;
- T = Número de transecto s contados.

Figura 1 – Estações de coleta no estuário e pluma do rio Jaboatão



A identificação das espécies foi baseada bibliografia especializada. Os táxons encontrados foram organizados de acordo com os sistemas de classificação de Round et al. (1990) para Bacillariophyta; Fensome et al. (1993) para Dinoflagellata; Anagnostidis e Komárek (1990) para Cyanobacteria; e para a atualização taxonômica foi utilizado o banco de dados internacional ALGAEBASE (http://ww.algaebase.org).

Os dados obtidos com a análise das amostras foram trabalhados numericamente quanto à abundância relativa (LOBO e LEIGHTON, 1986), freqüência de ocorrência (MATEUCCI e COLMA, 1982), diversidade específica (SHANNON,1948) e equitabilidade (PIELOU,1977).

Para a abundância relativa, foi levado em consideração o número total de organismos de cada táxon, em relação ao número total de organismos na amostra. As seguintes categorias foram consideradas: dominante (≥ 50%), abundante (50% |— 30%), pouco abundante (30% |— 10 %) e raras (≤ 10%).

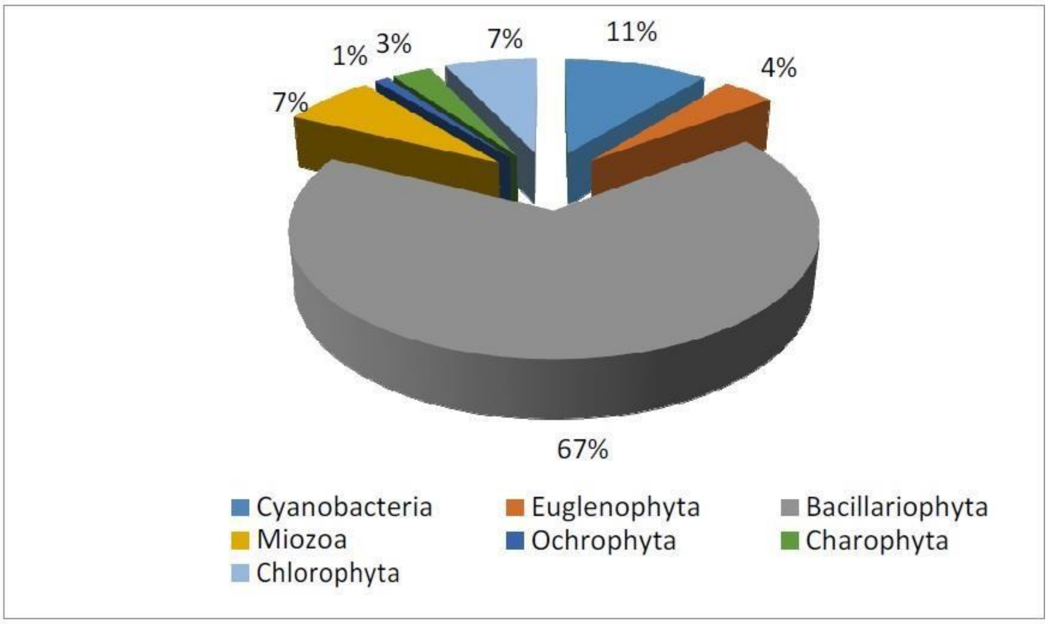
Para a frequência de ocorrência, foi levado em consideração o número de amostras nas quais cada táxon ocorreu e o número total de amostras analisadas, sendo adotadas as seguintes categorias: muito freqüente (≥ 70%), freqüente (70% |— 40%), pouco freqüente (40% |— 10%) e esporádica (≤ 10%). A diversidade específica foi considerada alta quando os resultados obtidos foram ≥ 3,0 bits.cel^{-1}; média, com resultados entre 2 e 3 bits.cel^{-1}; baixa, entre 1 e 2 bits.cel^{-1}; e muito baixa, com resultado ≤ 1 bit.cel^{-1}. Uma baixa eqüitabilidade é representada por resultados próximos a zero e uma alta eqüitabilidade, por valores próximos a um.

Resultados

Composição Florística

A comunidade fitoplanctônica no estuário estudado esteve representada por 123 táxons, distribuidos entre os filos Bacillariophyta (68%), Cyanobacteria (11%), Miozoa (7%), Chlorophyta (7%), Euglenophyta (4%), Charophyta (3%) e Ochrophyta (1%). As diatomáceas foram o grupo com maior representatividade no local, tanto no período chuvoso quanto no de estiagem (Figura 2).

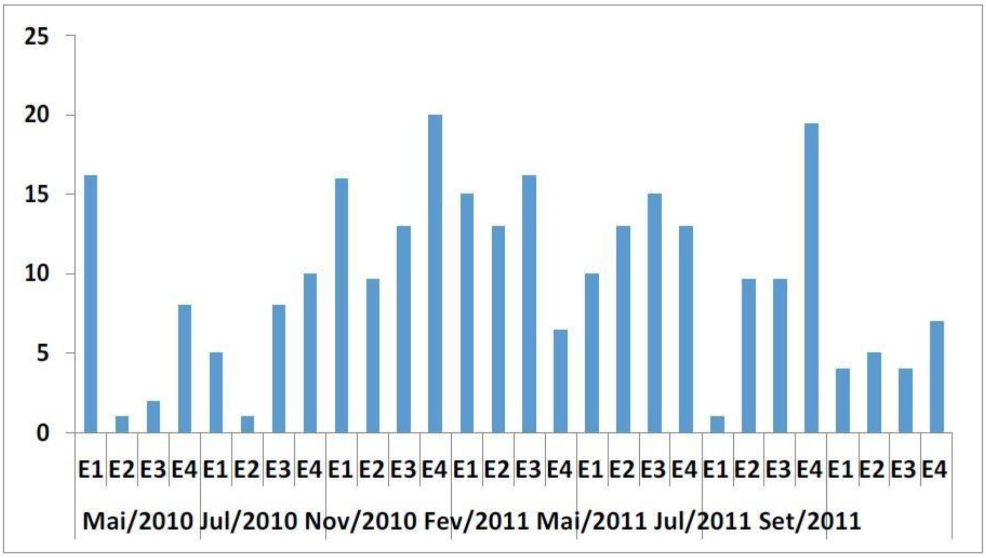
Figura 2 - Percentual dos grupos fitoplanctônicos ocorrentes no estuário estudado



Riqueza de espécies

A riqueza taxonômica na área estudada apresentou pequenas diferenças entre os ciclos sazonais. No período chuvoso, foram identificados 99 táxons e no período seco, 103. Quanto à riqueza de espécies por estação, foi observado um número menor de espécies nos meses chuvosos, influenciado diretamente pela dominância de *Microcystis aeruginosa* (Kutzing) Kutzing.

Figura 3 - Variação da riqueza, nas estações de coleta, dos táxons ocorrentes no estuário estudado

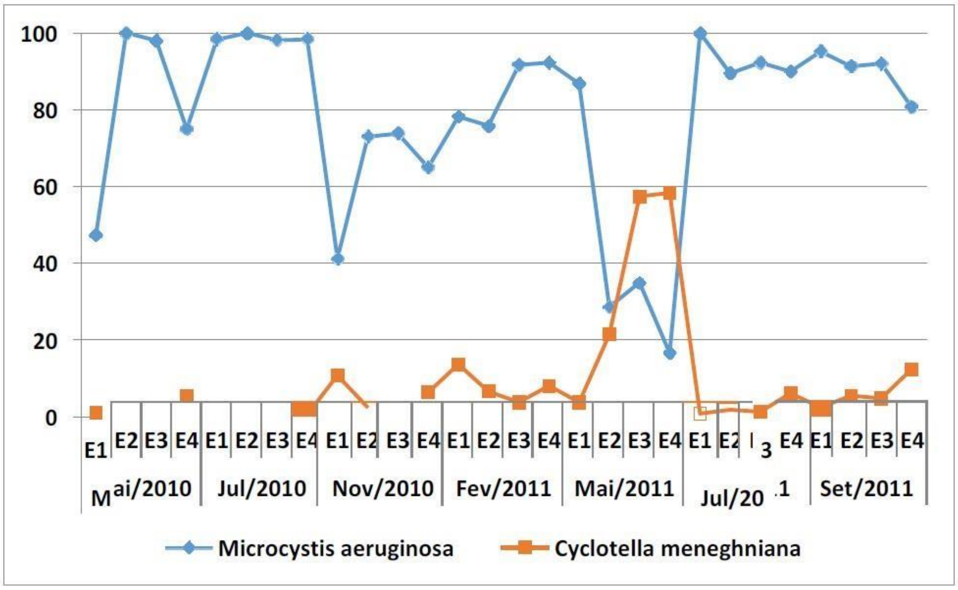


Abundância relativa

As espécies mais representativas no estuário estudado foram a cianobactéria *Microcystis aeruginosa* e a diatomácea *Cyclotella meneghiniana* Kutzing. Os táxons *Coscinodiscus centralis* Ehrenberg, *Cylindrospermopsis raciborskii* (Woloszynska) Seenayya & Subba Rajuand e *Oscillatoria tenuis* foram considerados abundantes.

Pode-se observar no mês de maio/11 a dominância de *C. meneghiniana* e uma diminuição na abundância de *M. aeruginosa,* espécie que se manteve dominante em quase todo o período estudado. Isto evidencia a competição entre as duas espécies (Figura 4).

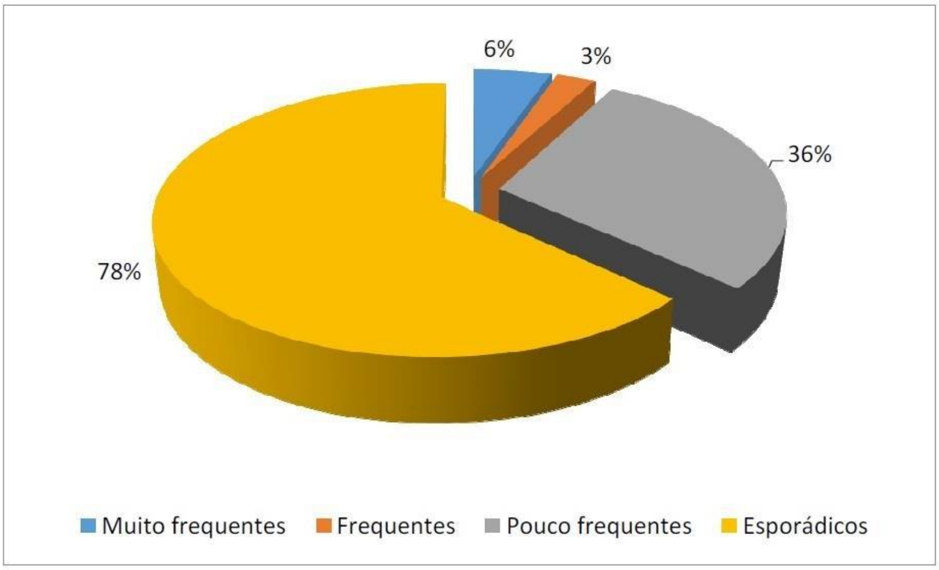
Figura 4 - Variação da abundância relativa das espécies características nas estações de coleta do estuário estudado



Frequencia de ocorrência

No estuário do rio Jaboatão, dos 123 táxons identificados, 6% foram considerandos muito frequentes, 3% foram considerados frequentes, 36% foram pouco frequentes e 78% foram esporádicos (Figura 5).

Figura 5 – Distribuição percentual da freqüência de ocorrência dos táxons identificados no estuário estudado

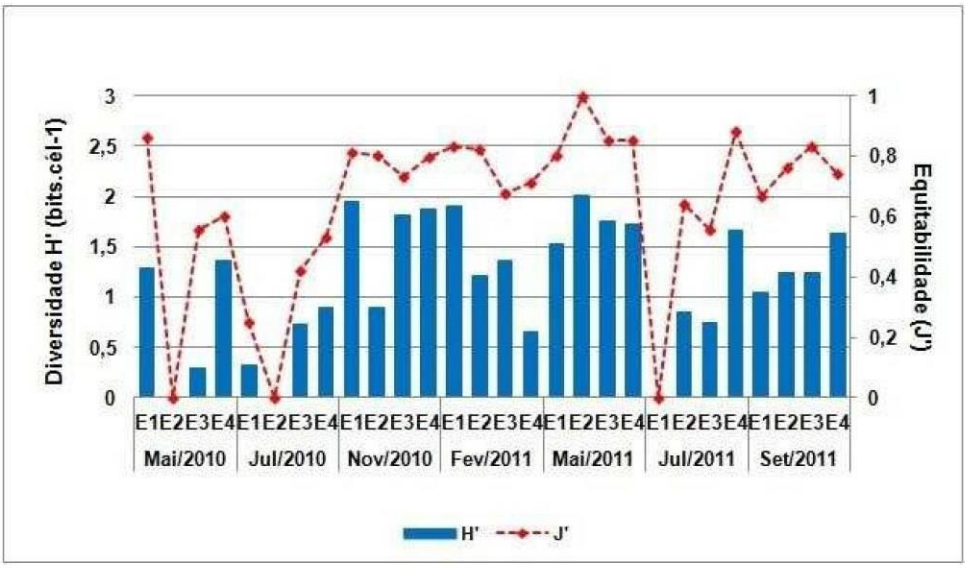


Os táxons considerados muito frequentes foram *Microcystis aeruginosa, Oscillatoria tenuis*, *Cyclotella meneghiniana*, *Coscinodiscus centralis e Cerataulus turgidus. Os táxons frequentes foram Navicula sp., Cylindrospermopsis raciborskii e Bellerochea malleus.*

Diversidade específica e Eqüitabilidade

Na área estudada, os índices de diversidade específica indicaram que a comunidade está caracterizada por uma diversidade variando de muito baixa a média. Da mesma forma, a eqüitabilidade apresentou valores variando de baixa a alta (Figura 6).

Figura 6 - Diversidade e equitabilidade na área estudada



Caracterização Ecológica

A flora do estuário do rio Jaboatão esteve representada principalmente por táxons infragenéricos classificados na categoria de ticoplanctônicos, com percentual de 32%, seguidos pelos dulciaquícolas com 26%, marinhos planctônicos neríticos e oceânicos, com percentuais de 20% e 18%, respectivamente. A categoria estuarina foi pouco representativa, com porcentagem de 4 % (Figura 7). Na tabela 1 é apresentada uma sinopse dos táxons registrado no estuário do rio Jaboatão, bem como a ecologia de cada um.

Figura 7 - Ecologia das espécies encontradas no estuário do rio Jaboatão

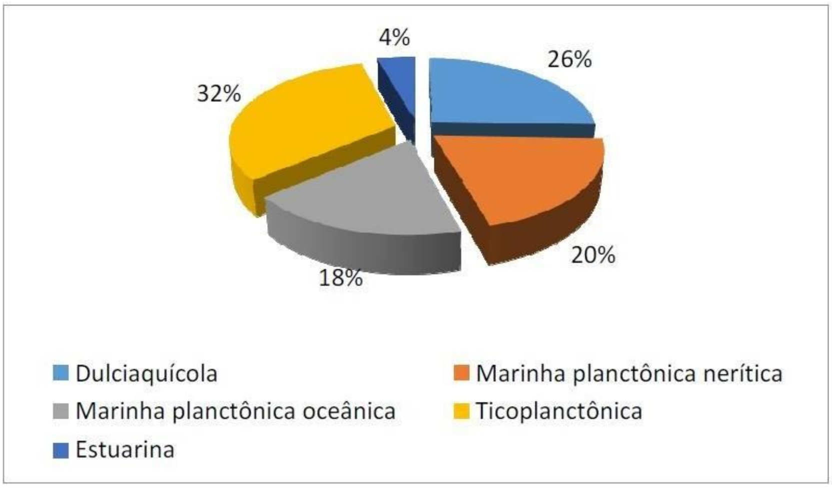


Tabela 1 – Sinopse e ecologia dos táxons registrado no estuário do rio Jaboatão

TÁXON	**ECOLOGIA**
CYANOBACTERIA	
CYANOPHYCEAE	
NOSTOCALES	
APHANIZOMENACEAE	
Dolichospermum spiroides (Klebhan) Wacklin, L.Hoffmann & Komárek	D D
Anabaena sp.	
Cylindrospermopsis raciborskii (Woloszynska) Seenayya & Subba	
Raju CHROOCOCCALES	
CHROOCOCCACEAE	D
Chroococcus sp.	
Nägeli	D D
MICROSCYSTAC	
EAE	
Microcystis aeruginosa (Kützing)	
Kützing OSCILLATORIALES	D MPO
OSCILLATORIACEAE	
Oscillatoria limosa C.Agardh ex	
Gomont *Oscilllatoria tenuis*	
C.Agardh ex Gomont *Phormidium*	
sp. Kützing ex Gomont *Oscillatoria*	D
sp.	
MICROCOLEACEAE	
Planktothrix agardhii (Gomont) Anagnostidis &	
Komárek *Trichodesmium thiebautii* Gomont ex	
Gomont SPIRULINALES	D
SPIRULINACEAE	
Spirulina sp. Turpin ex.	D
Gomont	
SYNECHOCOCCALES	
MERISMOPEDIACEAE	
Merismopedia elegans A.Braun ex	
Kützing EUGLENOPHYTA	
EUGLENOPHYCEA	
E EUGLENALES	
PHACACEAE	
Lepocinclis acus (O.F.Müller) Marin & Melkonian	
Phacus sp.	
Dujardin	
EUGLENACEA	
E	
Euglena proxima P.A.Dangeard	
Euglena sp. Ehrenberg	
Trachelomonas sp. Ehrenberg	

Continua

MIOZOA	
DINOPHYCEAE	
GONYAULACALES	
CERATIACEAE	
Tripos furca (Ehrenberg) F.Gómez	MPN
Tripos teres (Kofoid) F.Gómez	MPO
GYMNODINIALES	
GYMNODINIACEAE	
Gymnodinium sp. F.Stein	
PROTOPERIDINIACEAE	
Protoperidinium bispinum (Schiller) Balech	MPO
Protoperidinium sp. R.S.Bergh	
PROROCENTRALES	
PROROCENTRACEAE	
Prorocentum lima (Ehrenberg) F.Stein	MPO
Prorocentrum micans Ehrenberg	MPO
Prorocentrum sp.	
BACILLARIOPHYTA	
BACILLARIOPHYCEAE	
AULACOSEIRALES	
AULACOSEIRACEAE	
Aulacoseira granulata (Ehrenberg) Simonsen	MPN
SURIRELLALES	
SURIRELLACEAE	
Campylodiscus clypeus (Ehrenberg) Ehrenberg ex Kützing	TC
Campylodiscus fastuosus Ehrenberg	TC
Campylodiscus sp.	
Surirella fastuosa (Ehrenberg) Ehrenberg	TC
Surirella febigerii F.W.Lewis	TC
COCCONEIDALES	
COCCONEIDACEAE	
Campyloneis grevillei (W.Smith) Grunow & Eulenstein	TC
Cocconeis scutellum Ehrenberg	TC
RHOPALODIALES	
ENTOMONEIDACEAE	
Entomoneis alata (Ehrenberg) Ehrenberg	E
RHAPHONEIDALES	
RHAPHONEIDACEAE	
Asterionellopsis glacialis (Castracane) Round in Round, R.M.Crawford & D.G.Mann	MPN
NAVICULALES	
DIPLONEIDACEAE	
Diploneis bombus (Ehrenberg) Ehrenberg	TC

Continua

NAVICULACEAE	
Gyrosigma balticum (Ehrenberg) Rabenhorst	E
Gyrosigma fasciola (Ehrenberg) J.W.Griffith & Henfrey	TC
Navicula marina Ralfs	MPN
Navicula sp. Bory	
Navicula sp.2	
Petroneis humerosa Brébisson ex W.Smith	MPN
Pleuro/Gyrosigma sp.	
PLEUROSIGMATACEAE	
Pleurosigma elongatum W.Smith	MPN
Pleurosigma sp.	
LYRELLALES	
LYRELLACEAE	
Lyrella lyra (Ehrenberg) Karajeva	TC
BACILLARIALES	
BACILLARIACEAE	
Bacillaria paxillifera (O.F.Müller) T.Marsson	MPO
Nitzschia longissima (Brébisson) Ralfs	TC
Nitzschia lorenziana Grunow	D
Nitzschia sigma (Kützing) W.Smith	TC
Nitzschia tryblionella Hantzsch	D
Nitzschia sp.	
Pseudo-nitzschia pungens (Grunow ex Cleve) Hasle	MPN
CHAETOCEROTALES	
CHAETOCEROTACEAE	
Chaetoceros affinis Lauder	MPO
Chaetoceros curvisetus Cleve	MPN
Chaetoceros sp.	
PLAGIOGRAMMALES	
PLAGIOGRAMMACEAE	
Dimeregramma dubium Grunow	MPO
FRAGILARIALES	
FRAGILARIACEAE	
Fragilaria capucina Desmazières	D
Synedra gailonii (Bory) Ehrenberg	E
Synedra ulna (Nitzsch) Ehrenberg	D
COSCINODISCOPHYCEAE	
COSCINODISCALES	
AULACODISCACEAE	
Aulacodiscus sp. Ehrenberg	
COSCINODISCACEAE	
Coscinodiscus centralis Ehrenberg	MPO
Coscinodiscus oculus-iridis (Ehrenberg) Ehrenberg	MPN

Continua

HELIOPELTACEAE	
Actinoptychus vulgaris Schumann	MPN
RHIZOSOLENIALES	
RHIZOSOLENIACEAE	
Guinardia delicatula (Cleve) Hasle	MPN
Guinardia striata (Stolterfoth) Hasle in Hasle & Syvertsen	MPO
Pseudosolenia calcar-avis (Schultze) B.G.Sundström	MPO
MELOSIRALES	
MELOSIRACEAE	
Melosira dubia C.G.Kützing	TC
Melosira granulata (Ehrenberg) Ralfs	D
Melosira moniliformis (O.F.Müller) C.Agardh	TC
Melosira sp.	
PARALIACEAE	
Paralia sulcata (Ehrenberg) Cleve	TC
STEPHANOPYXALES	
HYDROSERACEAE	
Hydrosera triquetra Wallich	D
TRICERATIALES	
TRICERATIACEAE	
Triceratium alternans Bailey	TC
Triceratium favus var. *quadratum* Grunow	TC
Triceratium sp.	
MEDIOPHYCEAE	
ANAULALES	
ANAULACEAE	
Terpsinoë musica Ehrenberg	TC
EUPODISCALES	
EUPODISCACEAE	
Cerataulus turgidus (Ehrenberg) Ehrenberg	TC
Odontella aurita (Lyngbye) C.Agardh	MPN
Odontella mobiliensis (J.W.Bailey) Grunow	MPN
Odontella regia (Schultze) Simonsen	MPN
Pleurosira laevis (Ehrenberg) Compère	MPN
LITHODESMIALES	
LITHODESMIACEAE	
Tropidoneis lepidoptera (Gregory) Cleve	TC
TOXARIALES	
CLIMACOSPHENIACEAE	
Climacosphaenia moniligera Ehrenberg	TC
THALASSIOPHYSALES	
CATENULACEAE	
Amphora angusta W.Gregory	TC
Amphora arenaria	TC

Continua

AMPHIPRORACEAE	
Amphiprora paludosa	E
Amphiprora pulchra var. *pulchella* Peragallo	MPN
Amphiprora sulcata	MPN
THALASSIOSIRALES	
STHEPHANODISCACEAE	
Cyclotella styllorum Brightwell	D
Cyclotella meneghiniana Kützing	D
THALASSIOSIRACEAE	
Thalassiosira leptopus (Grunow ex Van Heurck) Hasle & G.Fryxell	MPO
Thalassiosira subtilis (Ostenfeld) Gran	MPO
BIDDULPHIALES	
BIDDULPHIACEAE	
Bellerochea malleus (Brightwell) Van Heurck	MPN
Biddulphia biddulphiana (J.E.Smith) Boyer	TC
Isthmia enervis Ehrenberg	TC
BRIGGERALES	
STREPTOTHECACEAE	
Helicotheca tamesis (Shrubsole) M.Ricard	MPO
LEPTOCYLINDRALES	
LEPTOCYLINDRACEAE	
Leptocylindrus danicus Cleve	MPN
FRAGILARIOPHYCEAE	
RHABDONEMATALES	
GRAMMATOPHORACEAE	
Grammatophora marina (Lyngbye) Kützing	TC
Grammatophora oceanica Ehrenberg	MPO
RHABDONEMATACEAE	
Rhabdonema adriaticum Kützing	TC
Rhabdonema punctatum (Harvey & Bailey) Stodder	TC
LICMOPHORALES	
LICMOPHORACEAE	
Licmophora abbreviata C.Agardh	TC
Licmoplora remulus Grunow	TC
FLAGIRALIALES	
FLAGILARIACEAE	
Podocystis adriatica (Kützing) Ralfs	TC
THALASSIONEMATALES	
THALASSIONEMATACEAE	
Thalassionema nitzschioides (Grunow) Mereschkowsky	MPO
Thalassionema sp.	

Continua

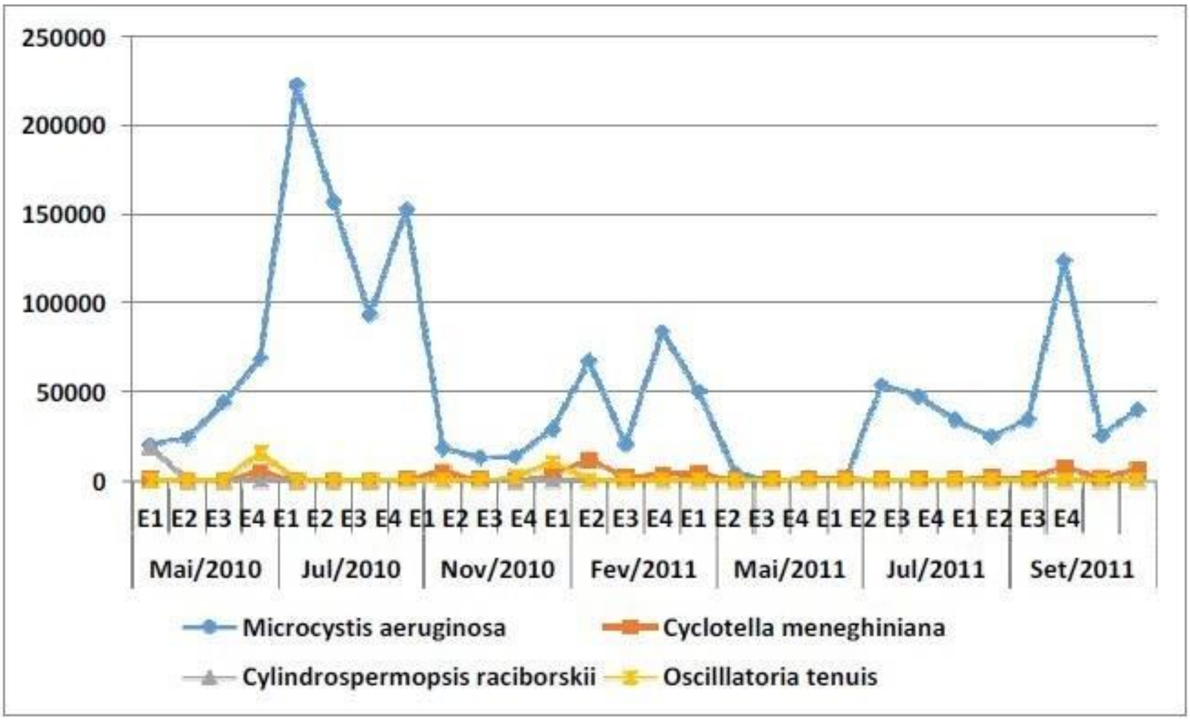
OCHROPHYTA	
DICTYOCHOPHYCEAE	
DICTIOCHALES	
DICTYOCHACEAE	
Dictyocha fíbula Ehrenberg	MPO
STHEPHANODISCACEAE	
CHLOROPHYTA	
CHLOROPHYCEAE	
CHLAMYDOMONADALES	
VOLVOCACEAE	
Eudorina elegans Ehrenberg	D
SPHAEROPLEALES	
SCENEDESMACEAE	
Scenedesmus bijuga (Turpin) Lagerheim	D
Scenedesmus quadricauda (Turpin) Brébisson	D
Scenedesmus sp	
HYDRODICTYACEAE	
Pediastrum duplex Meyen	D
Pediastrum sp.	
TREBOUXIOPHYCEAE	
TREBOUXIOPHYCEAE (ordo ircertae sedis)	
TREBOUXIOPHYCEAE (incertae sedis)	
Crucigenia fenestrata (Schmidle) Schmidle	D
ZYGNEMATOPHYCEAE	
ZYGNEMATALES	
ZYGNEMATACEAE	
Spirogyra sp.	
CHAROPHYTA	
CONJUGATOPHYCEAE	
DESMIDIALES	
CLOSTERIACEAE	
Closterium gracile Brébisson ex Ralfs	D
Closterium setaceum Ehrenberg ex Ralfs	D
Closterium sp. Nitzsch ex Ralfs	
DESMIDIACEAE	
Staurastrum sp. Meyen ex Ralfs	

Nota: D = dulciaquícola; TC = ticoplanctônica; MPN = marinha planctônica nerítica; MPO = marinha planctônica oceânica; E = estuarina.

Densidade (Ind.mL^{-1})

A densidade das espécies variou de 87 Ind.mL^{-1} a 222609 Ind.mL^{-1}, com o período chuvoso apresentando valores um pouco mais elevados. As espécies dominantes destacaram-se com as densidades mais elevadas. *Microcystis aeruginosa* teve a densidade elevada em todos os meses estudados, variando de 348 a 222609 Ind.mL^{-1}. *Cyclotella meneghniana* apresentou um pico de densidade de 11739 Ind.mL^{-1} no mês de fev/2011. *Cylidrospermopsis raciborskii* e *Oscillatoria tenuis* apresentaram picos 19130 Ind.mL^{-1} e 15652 Ind.mL^{-1}, respectivamente, em maio/2010 (Figura 8).

Figura 8 - Densidade das espécies mais representativa no local estudado



Discussão

Os estuários, devido à sua elevada potencialidade e riqueza de recursos naturais renováveis, constituem uma constante preocupação devido aos altos níveis de degradação causados pelos efluentes industriais e domésticos (MACÊDO et.al., 2004).

No estuário do rio Jaboatão, as diatomáceas foram o grupo fitoplanctônico mais representativo, perfazendo quase 70% da composição florística total. Segundo Procopiak et al. (2006), as diatomáceas constituem o grupo mais representativo em regiões estuarinas e são aos principais produtores nesses ecossistemas, cuja abundância está condicionada às suas características de eurialinidade, associadas às condições eutróficas. Isto é um fato nos ambientes marinhos neríticos e estuarinos do Estado de Pernambuco (ESKINAZI-LEÇA et al., 2000). Apesar da maior representatividade das diatomáceas em termos de riqueza de espécies, o ambiente foi dominado pela cianobactéria *Microcystis aeruginosa,* que ocorreu em todas as estações e todos os meses estudados, apresentanto elevada abundância e densidade.

A dominância de uma espécie sobre as demais é algo comum em regiões estuarinas, em decorrência de uma melhor adaptação às condições do ambiente (RILEY, 1967). O desenvolvimento desta espécie é conseqüência do enriquecimento do estuário, que possibilitou o aumento desta população, as quais requerem e se adaptam bem às condições eutróficas.

As águas da bacia hidrográfica do rio Jaboatão apresentam um alto comprometimento de sua qualidade, apresentando valores elevados de DBO, concentrações de oxigênio dissolvido abaixo do limite estabelecido pela legislação e altos valores de coliformes termotolerantes e fósforo total, que indicam o recebimento de elevadas cargas poluidoras, com o estado trófico do ambiente variando de mesotrófico a supereutrófico (CPRH, 2010)

Na área estudada, constatou-se o predomínio das espécies marinhas ticoplanctônicas, o que pode ser justificado pela pouca profundidade do estuário e hidrodinamismo local, com processos de mistura vertical e de ressuspensão. O segundo grupo ecológico com maior representatividade foi o das espécies dulciaquícolas, correspondendo a 26% das espécies, o que é indicativo da importância do aporte de águas doces no local, considerando a dominância da cianobactéria dulciaquícola *Microcystis aeruginosa* e abundância de *Cylindrospermopsis raciborskii* e *Oscillatoria tenuis.*

Pode-se observar no local, em maio/2011, a competição entre duas espécies dominantes na área, onde *C. meneghiniana* dominou e ocasionou a diminuição da abundância de *M. aeruginosa.* Silva et al. (2017) relataram a alternância na dominância destas duas espécies para o mesmo local, em amostras de garrafa analisadas, influenciada pela alta concentração de nitrato e diminuição do fósforo e amônia quando da dominância de *C. meneghiniana.*

Ainda, a dominância desta cianobactéria influenciou diretamente a diversidade local, que variou de muito baixa a média. Omori e Ikeda (1984) relatam que a diversidade específica indica o grau de complexidade da estrutura da comunidade, decrescendo quando a comunidade torna-se dominada por uma ou algumas espécies, quando indivíduos de espécies raras são substituídos por indivíduos de espécies mais comuns, ou quando algumas espécies se reproduzem mais rapidamente.

A elevada densidade de *M.aeruginosa* alterou a diversidade específica local. O constante aumento da eutrofização, com a consequente queda da qualidade da água, tem sido a causa mais comum da dominância de cianobactérias em recursos naturais. As atividades humanas aumentam a probabilidade de multiplicação das cianobactérias devido à presença de nutrientes, principalmente fósforo e nitrogênio (CARMICHAEL, 1992). Borges (1991) observou uma correspondência entre a contaminação de águas nas zonas costeiras ou de estuários de circulação restrita e a ocorrência de florescimentos excepcionais.

Segundo Silva et al. (2017), os altos valores de compostos nitrogenados e fosfato a alta degradação e a forte influência da ação antrópica naquele local, além dos baixos valores de salinidade e oxigênio dissolvido.

O rio Jaboatão sofre *inputs* urbanos e industriais que produzem significantes variações na qualidade do ecossistema e podem causar alterações nas populações de espécies fitoplanctônicas, muitas vezes ocasionando *blooms* algais, como observado neste trabalho, sendo possível determinar que *M. aeruginosa* constitui a espécie chave na área e é bioindicadora da qualidade local.

Conclusão

Podemos concluir que o estuário do rio Jaboatão PE é fortemente impactado, conseqüência dos menores valores de salinidade, oxigênio dissolvido e altas concentração de nutrientes, principalmente os componentes nitrogenados e o fosfato (SILVA et al., 2017), indicativos do recebimento de altas cargas poluidoras. A cianobactéria *Microcystis aeruginosa*, espécie oportunista e potencialmente tóxica, constitui a espécie dominante e responsável pela baixa diversidade de espécies no local.

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5 ARTIGO 2 - DISTRIBUTION OF NUTRIENTS AND CHANGES IN PHYTOPLANKTON COMPOSITION IN A TROPICAL MESOTIDAL ESTUARY, NORTHEASTERN BRAZIL.

Situação

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Abstract

Abiotic parameters and phytoplankton were collected during 2010 and 2011 with the purpose of describing the phytoplankton distribution and the environmental characteristics. The diatoms were the most representative group in terms of species richness; in terms of density, the Cyanobacteria were more representative. Diversity and equitability were generally low in the estuary due to the dominance of *Microcystis aeruginosa*, an opportunistic and potentially toxic species of Cyanobacteria. The estuarine region is strongly impacted by high pollutant loads, especially nitrogen and phosphate compounds. Historical series of Apparent Oxygen Utilization (AOU) showed negative trends associated with changes in the estuarine system. The main biological components changed through 1999-2011 period. The dominance of the species changed from the Bacillariophyta in previous studies to the Cyanobacteria in our study. The species *Microcystis aeruginosa*, through its high density, dominance and frequency of occurrence, was the key species in the area.

Keywords: Coastal Environment, Nutrients, Biodiversity, Phytoplankton, Tropical Estuary

Introduction

Estuaries are dynamic systems characterized by gradients of salinity, turbidity, temperature, nutrient concentration and organic matter (MEIRE et al., 2005).

Approximately 60% of the large cities distributed around the Earth are located near estuarine regions, making these environments of great importance for the planet. These regions are the main suppliers of nutrients to the coastal regions, since they receive and concentrate the material originating from their drainage basin and can receive significant contributions from anthropic action (MIRANDA et al., 2002). The spatial connection with this region is the continental shelf, which acts as a final recipient of water and materials from the continent that are transported by the discharge of rivers and estuaries. The meeting of low-salinity continental waters with coastal waters defines regions where there are high gradients of properties, the so- called front zones (MARQUES, 2006).

Currently, the coastal zones, due to population and urban growth, are the areas most impacted by anthropic action and consequently are the areas most subject to algal blooms due to eutrophication processes resulting from domestic effluents and increases in organic matter (GRAHAM et al., 2000). The ability to respond quickly to spatial and temporal fluctuations of environmental conditions makes the phytoplankton community a good bioindicator of changes in environments arising from natural causes or as a result of human actions (LIVINGSTON, 2001).

The contamination of an aquatic ecosystem is manifested in phytoplankton populations by the development of two inverse and simultaneous phenomena: on the one hand, the emergence and proliferation of selective species and on the other hand, the disappearance of part or all of the original population of the environment. To determine the biological quality of water, the populations can be used as a reference frame in which the presence or absence of organisms is fundamental or to verify the existence of organisms that are indicative or characteristic of some type of contamination (ORTEGA, 2000). In estuarine ecosystems, planktonic populations are known to be influenced by spatio-temporal variations in physico-chemical parameters and tidal dynamics (UNESCO, 1981).

Phytoplankton is the main primary producer of the coastal environments, being responsible for the beginning of the flow of matter and energy of the trophic network of these environments; contributing to their fertilization; and directly supporting the herbivores and indirectly the animals of the higher trophic levels, including economically important species (SOUSA et al., 2009).

Works about phytoplankton in estuarine ecosystems in the northeastern region of Brazil, and especially in the state of Pernambuco, are well known (ESKINAZI and

SATO, 1966; FLORES MONTES et al., 1998; KOENING et al., 2002; FEITOSA et al., 2002; LACERDA et al., 2004; BRANCO et al., 2006; BRANCO, 2007; BRANCO, 2008; GREGO et al., 2009; HONORATO DA SILVA et al., 2009; NORIEGA e ARAUJO, 2009, RODRIGUES and CUTRIM, 2010; SANTIAGO et al., 2010; AQUINO et al., 2014). Work in coastal areas is still insufficient (ESKINAZI-LEÇA et al., 1997; ESKINAZI-LEÇA et al., 2004; KOENING et al., 2004; MELO et al., 2014) and, specifically for the coastal areas adjacent to the estuary of the Jaboatao River, are non-existent.

The Jaboatao River Basin, located mostly in the Metropolitan Region of Recife (RMR), presents problems common to Brazilian urban water basins: the degradation of natural resources through inadequate land occupation and use; pollution caused by the release of domestic wastes and industrial effluents; and high population density. This estuary represents one of the most vulnerable areas in the RMR to the degradation provoked by the increase of urban pressure and real estate (1100 inhabitants/km^2) (NORIEGA and ARAUJO, 2009). These factors constitute a high degree of risk to the continuity of the existence of this environment. The present work aimed to identify the phytoplankton community, correlating its density and environmental characteristics (nutrients, DO) in the estuary of the Jaboatao River as well as in its adjacent platform in the area under the influence of the estuarine plume.

Materials and Methods

Study Area

The Jaboatao watershed, located in northeastern Brazilin Pernambuco State (8˚00'S - 8˚14'S and 34˚50'W - 35˚15'W), is 413 km^2 in area and 75 km in length. The river crosses the RMR, and the mouth is on the Atlantic Ocean (Figure 1).

The climate is typically tropical, hot and humid. The air temperature is 26˚C ± 2.8˚C, and the mean annual precipitation and evaporation are approximately 1.5 and 1.2 $m.yr^{-1}$, respectively (ARAÚJO et al., 2009). The rainfall regime is subdivided into two welldefined periods: the dry season (September-February), when precipitation is exceeded by evaporation; and the rainy season (March-August), when rainfall dominates evaporation (Figure 2). The estuary extends for approximately 13 km^2, with an average depth of 2.6 m (NORIEGA and ARAUJO, 2009; NORIEGA and ARAÚJO, 2009; BRANCO et al., 2002; NORIEGA and ARAÚJO, 2011) (Figure 1).

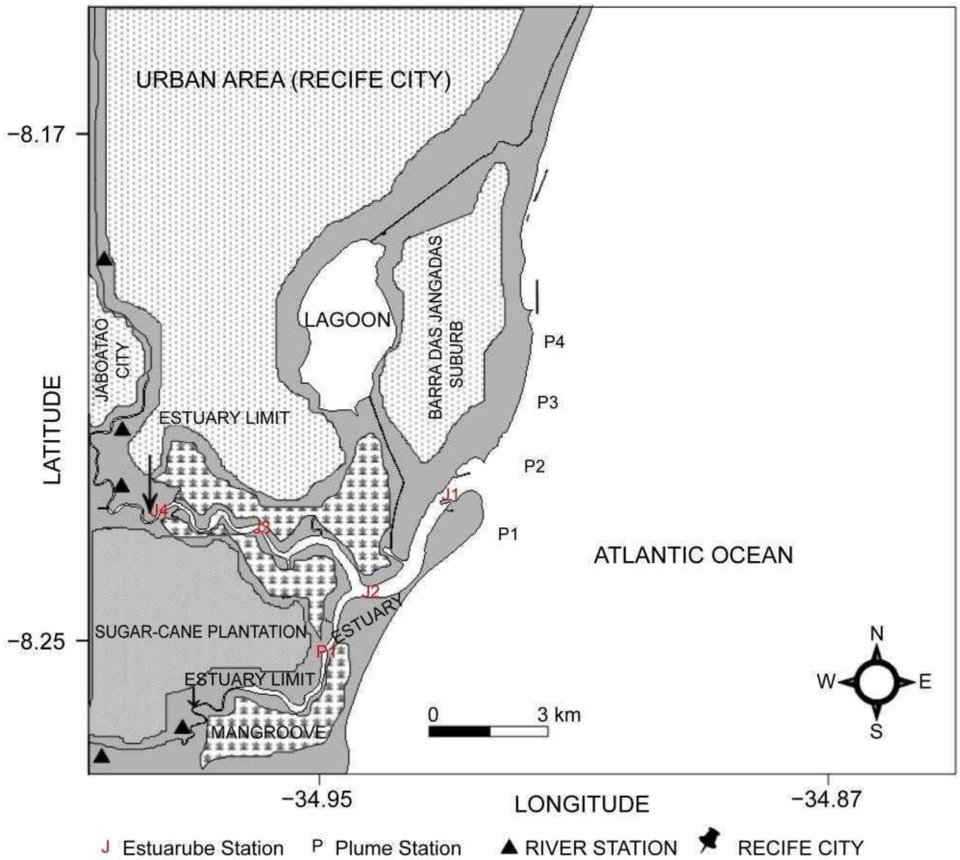

Figure 1. Sampling stations located in the estuary and plume of the Jaboatao River (northeastern Brazil).

The drainage basin includes areas originally covered by the Atlantic Rain Forest and is presently occupied by sugar cane and high-density populated areas (1100 inhabitants/km^2) (NORIEGA and ARAÚJO, 2009; IBGE, 2010). Despite the deforestation of the margins and the large volume of industrial and domestic effluents it receives, the estuary itself is surrounded by relatively well-preserved and highly productive mangrove forests. Organic matter pollution by the sugar-cane agro industry increases substantially during the harvest and milling season, which is from September to February.

Environmental state agency reported a high BOD of 69.6 mg.L^{-1} in the harvest periods (NORIEGA and ARAÚJO, 2011). The polluting organic load sources are represented mainly by domestic sewage in the Jaboatao River (14.46 t BOD.d^{-1}) (CPRH, 2003). Algal blooms are now more frequente during the year and consist of several species of Cyanophyceae, *Oscillatoria* sp. and *Euglena* sp. (Euglenophyta), suggesting some degree of permanent impact on the environment (BRANCO et al., 2002). The river runoff is strongly controlled by rainfall (Figure 2), with an average discharge of 2 - 10 $m^3.s^{-1}$ (annual average) (NORIEGA and ARAÚJO, 2011; SECTMA, 1999; SOUZA e TUNDISI, 2003). The tidal regime is semidiurnal, with mean amplitude of 1.3 m (neap tides) and 1.8 m (spring tides) (ARAÚJO et al., 2009). The estuary is well mixed, being classified as type 1 with an absence of vertical stratification (ARAÚJO et al., 2009; NORIEGA and ARAÚJO, 2011).

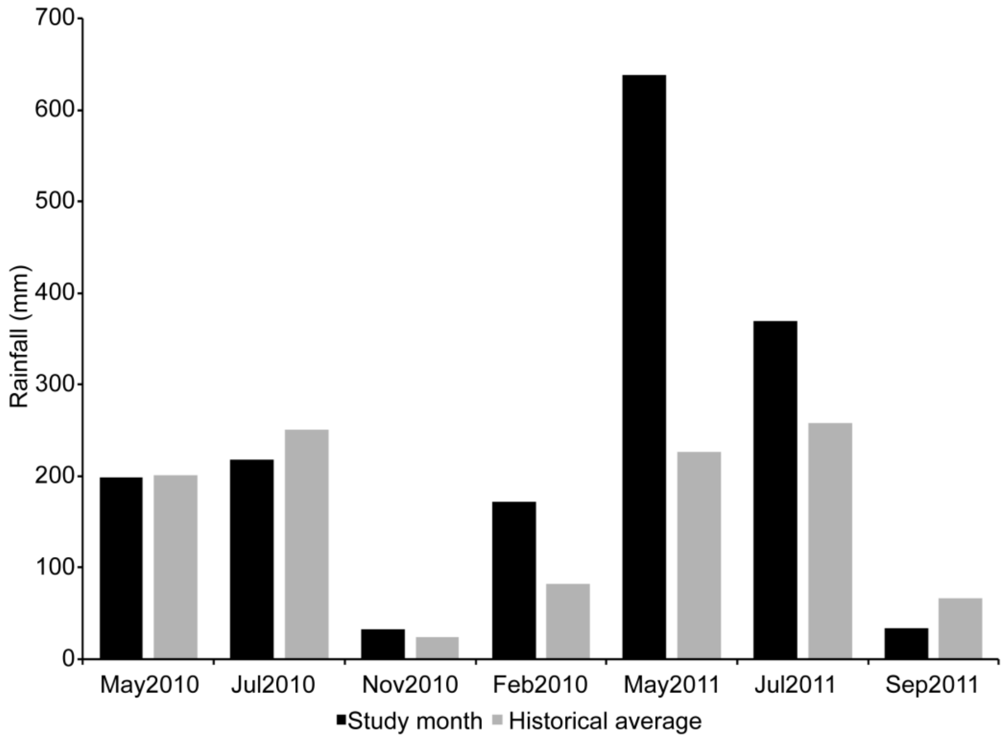

Figure 2. Climatological series of precipitation (1981-2011) for the study area (source: INMET).

Sampling and Analysis

The samples were collected in a longitudinal profile in the Jaboatao River estuary, covering the marine area (estuarine plume) through four stations in the estuary and four in the plume (Figure 1). Samples were taken during the dry (November 2010, February 2011 and September 2011) and the rainy seasons (May 2010, July 2010, May 2011 and July 2011), comprising a total of seven campaigns.

For this study, we divided the estuarine region into 8 segments (every 5 units of salinity) based on the longitudinal saline gradient classification proposed by McLusky (1993). The estuarine limit with the plume region was calculated based on the average saline in the plume samplings.

The temperature and salinity (conductivity) were measured using a CTD (Sea-

Bird Electronics SBE911plus; Sea-Bird Scientific Inc.R). The salinity was also verified against the chlorinity, which was determined using AgNO3 titration (STRICKLAND and PARSONS, 1972). The local depth was determined by digital echo sounder, mark LCD-resolution: 0.1 m) and depth of visual disappearance of the Secchi disk (water transparency).

Water samples were collected with Van Dorn bottles for further analysis of dissolved oxygen (DO) and nutrients. The pH was measured on the NBS scaleon board after sample collection using a pH/ion analyser 350 and a Ross combination electrode (OrionR). The precision and the accuracy of the pH measurements were ±0.005 units and 0.1%, respectively. DO was analysed by the Winkler method (GRASSHOFF et al., 1983), with a precision of ±1.3 µM. The relative oxygen saturation (%) in the water was calculated using the following equation for temperatures between 0˚C and 40˚C and salinities between 0 and 40:

$$\% = (DO / DO^*) \times 100$$

where DO is the oxygen concentration in the sample and DO* is the oxygen solubility in the water at the same temperature and salinity using the UNESCO tables (UNESCO, 1986). Apparent oxygen utilization (AOU) was calculated according to Garcia and Gordon (1992).

The dissolved inorganic nutrients, ammonia + nitrite + nitrate (DIN), phosphate (DIP), were analysed according to Grasshoff et al. (1983) after filtration of the samples using Whatman® GF/C 0.47-mm glass fibre filters. The precision was ±0.02 µmol for nitrate, ±0.02 µmol for nitrite, ±0.02 µmol for ammonia, and 0.01 µmol for phosphate. The accuracy was ±2% for DIP, ±3% for nitrate and nitrite, and ±5% for ammonia.

The samples for the phytoplankton study were collected with Niskin oceanographic bottles and later fixed with Lugol solution. The analyses were performed according to the sedimentation method of Utermohl (HASLE, 1978; EDLER, 1979; FERRARIO et al., 1995), and counts were performed under a ZEISS Axiovert inverted microscope. Additional information on the phytoplankton identification methodology can be seen in the supplementary material.

Meteorological Data

The rainfall data were obtained through the website of the Pernambuco State Agency for Water and Climate (APAC) and the National Institute of Meteorology (INMET).

Statistical Analyses

The similarity between the biological samples was evaluated based on the Bray-Curtis coefficient, using the data based on the relative abundance, transformed into the fourth root, with amalgamation method by the group mean. The similarity between the abiotic samples was also evaluated with the relative abundance data transformed into the fourth root, by the mean of the group but based on the Euclidean distance.

The Principal Components analysis (PCA) was based on the hydrological parameters and the phytoplankton cell density, applying the Pearson's moment-to-product correlation coefficient, with the self-value of the main components and the auto-vector being extracted. The trend of the time series was obtained through the Mann-Kendall test and Linear Regression. For the two tests, the programs PRIMER 6® (Plymouth Routines in Multivariate Ecological Research) and XLSt at 2010® were used, respectively.

Results

Climatology and Physical Factors

The total monthly rainfall ranged from 32.4 mm in November 2010 to 638.6 mm in May 2011. The typical dry season months had the lowest indexes, according to the historical values of the study region (Figure 3(a)). The study period did not show significant differences with the values recorded historically for the same months (*t* -test; *p*: 0.38; *α*: 0.05).

The salinity in the estuary ranged from 0.04 to 27.54, from freshwater to polyhaline, presenting the highest values mainly in the dry period (Figure 3(b)). In the dry period, the variability was lower in relation to the rainy season, showing significant differences between the two periods (*t* -test, *p*: 0.05, *α*: 0.05).

In the estuary, the thermal amplitude and its average value were 2.5˚C and 28.0˚C ± 1.0˚C, respectively, while in the plume region, the amplitude was 3˚C and the average 28.5˚C ± 0.8˚C. The studied area showed significant diferences (*t* -test, *p*: 0.04; *α*: 0.05), which can also be observed in Figure 3(c) and Figure 3(d) through the salt gradient. Seasonal analyses also showed statistically significant differences between the dry and the rainy season (*t* -test; *p*: 0.0001; *α*: 0.05).

As shown in Figure 3(c) and Figure 3(d), the estuarine gradient also showed thermal variations throughout the year, which are characteristic in tropical coastal areas. The mean amplitude between the climatic periods was 1˚C (Figure 3(c): 28.8˚C; Figure 3(d): 27.8˚C).

The local depth in the estuary presented an average value of 3.0 ± 2.0 m, while in the plume region, the mean depth was 11.5 ± 2.0 m. The water transparency was also lower in the estuary (0.53 ± 0.2 m) than in the plume region, where the Secchi disc recorded an average value of 2.23 ± 1.4 m (Figure 3(e) and Figure 3(f)). In the estuary, the highest values of transparency occurred in the dry period (September to February), a season of lower fluvial contribution and lower values of rainfall. The values observed between the dry and rainy periods did not show significant differences (*t* -test; *p*: 0.37; *α*: 0.05).

Chemical Factors: pH and Oxygen

The pH values recorded in the estuarine area showed a range of 6.41 to 8.36, while in the plume region, the values ranged from 7.76 to 8.92. Statistical analysis showed significant differences between the two regions (t -test; *p*: 0.0001; *α*: 0.05). The pH values were always lower in regions near the river and did not show significant differences (*t* -test; *p*: 0.82; *α*: 0.05) between the dry and the wet period (Figure 4(a) and Figure 4(d)).

DO in the estuary presented low levels, with a minimum of anoxia and a maximum of 4.1 $mL.L^{-1}$; the mean value in the estuarine area was 1.6 $mL.L^{-1}$, while in the plume region, the mean value was 4.4 $mL.L^{-1}$. DO concentrations showed significant differences between the estuarine area and the plume region (*t* -test; *p*: 0.0001; *α*: 0.05). During climatic periods in the study region, 50% of the samples showed concentrations below the limit indicated by CONAMA (3.5 $mL.L^{-1}$; law decree

357, 2005) (CONAMA, 2005) (Figure 4(c), Figure 4(d); red line).

The oxygen saturation (%) followed the same pattern as DO, with a minimum of 0%, a maximum of 85.65%, and an average of 30%. In the plume region, the oxygen saturation showed an average of 95.45%, with a minimum of 78.46% and a maximum of 110.5%.

Chemical Factors: Nutrients

Ammonia showed a mean of 2.70 $\mu mol.L^{-1}$, with a minimum of 0.05 $\mu mol.L^{-1}$, presenting a peak of 14.29 $\mu mol.L^{-1}$ in May of 2010 and the lowest concentrations in November. Spatial variations showed significant differences between estuarine and plume regions (*t* -test; *p*: 0.0001; *α*: 0.05) (Figure 5(a), Figure 5(b)).

Nitrate concentrations varied between 0.58 $\mu mol.L^{-1}$ and 32.0 $\mu mol.L^{-1}$, with higher values in February and September (dry period), but ~90% of the observations occurred below 9 $\mu mol.L^{-1}$. The spatial gradient showed significant diferences between the two regions (*t* -test; *p*: 0.0001; *α*: 0.05) (Figure 5(c), Figure 5(d)).

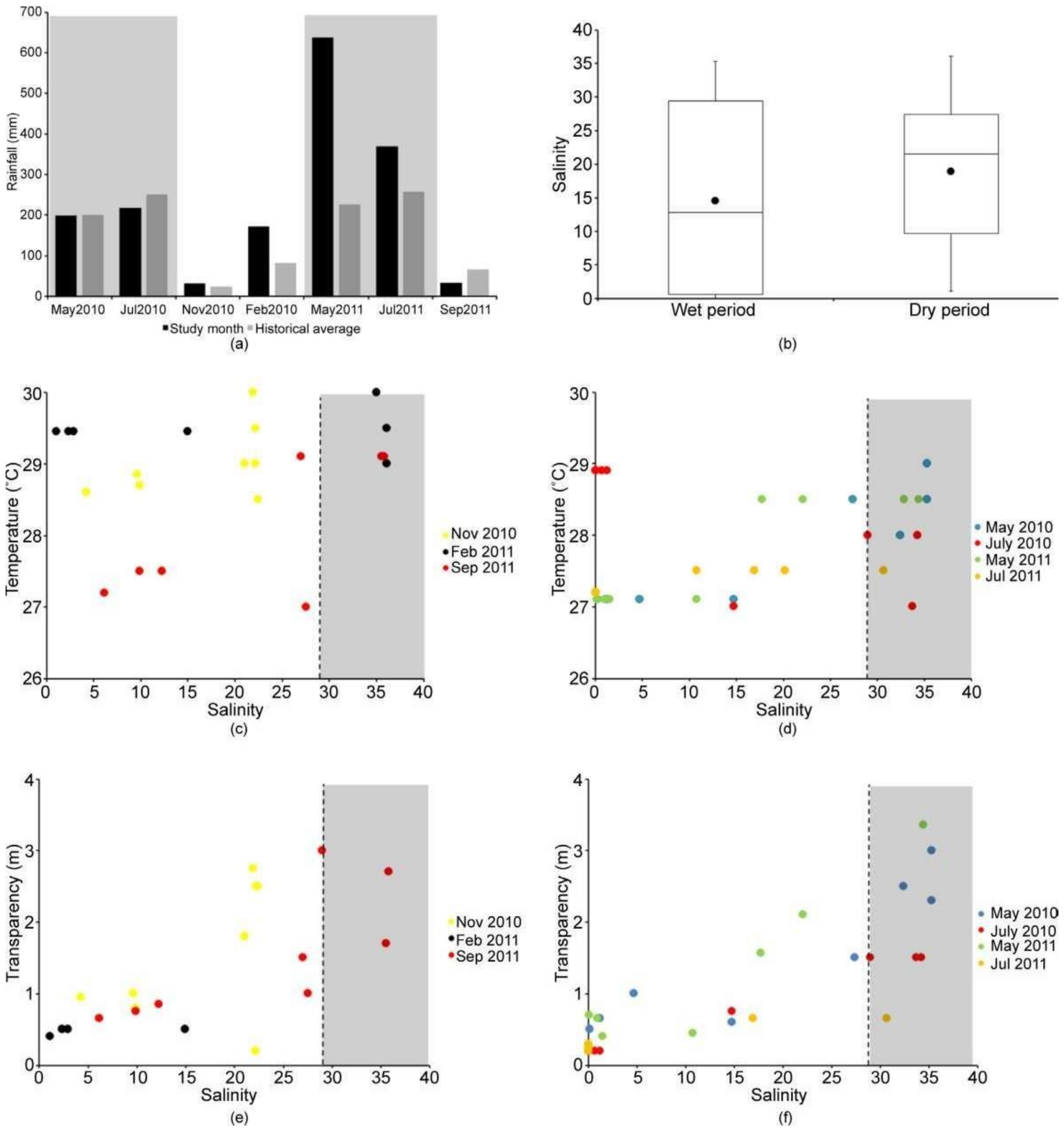

Figure 3. Rainfall (study period and historical average). Grey region indicate wet period (a); salinity (b); surface temperature (˚C) of the water through the salt gradient (c)-(d) and transparency (m) in the estuary and plume of the Jaboatao River (e)-(f). The dotted line indicates the mean salinity value for the plume region. In Figure 3(b), black circles indicate the mean and the horizontal line indicates the median.

The nitrite varied from 0.05 μmol.L^{-1} to 3.82 μmol.L^{-1}, with the highest concentrations in November, and showed an increasing downstream-upstream gradiente (Figure 5(e), Figure 5(f)). Spatial variations were observed between the estuarine and plume regions (*t* -test; *p*: 0.0001; *α*: 0.05).

The phosphate showed a minimum concentration of 0.27 μmol.L^{-1} and a maximum of 9.46 μmol.L^{-1}, with an increasing downstream-upstream gradient. In the plume region, the concentrations were <1 μmol.L^{-1} (Figure 5(g), Figure 5(h)).
The spatial variations showed significant differences between the estuary and the

plume (*t* -test; *p*: 0.0001; *α*: 0.05).

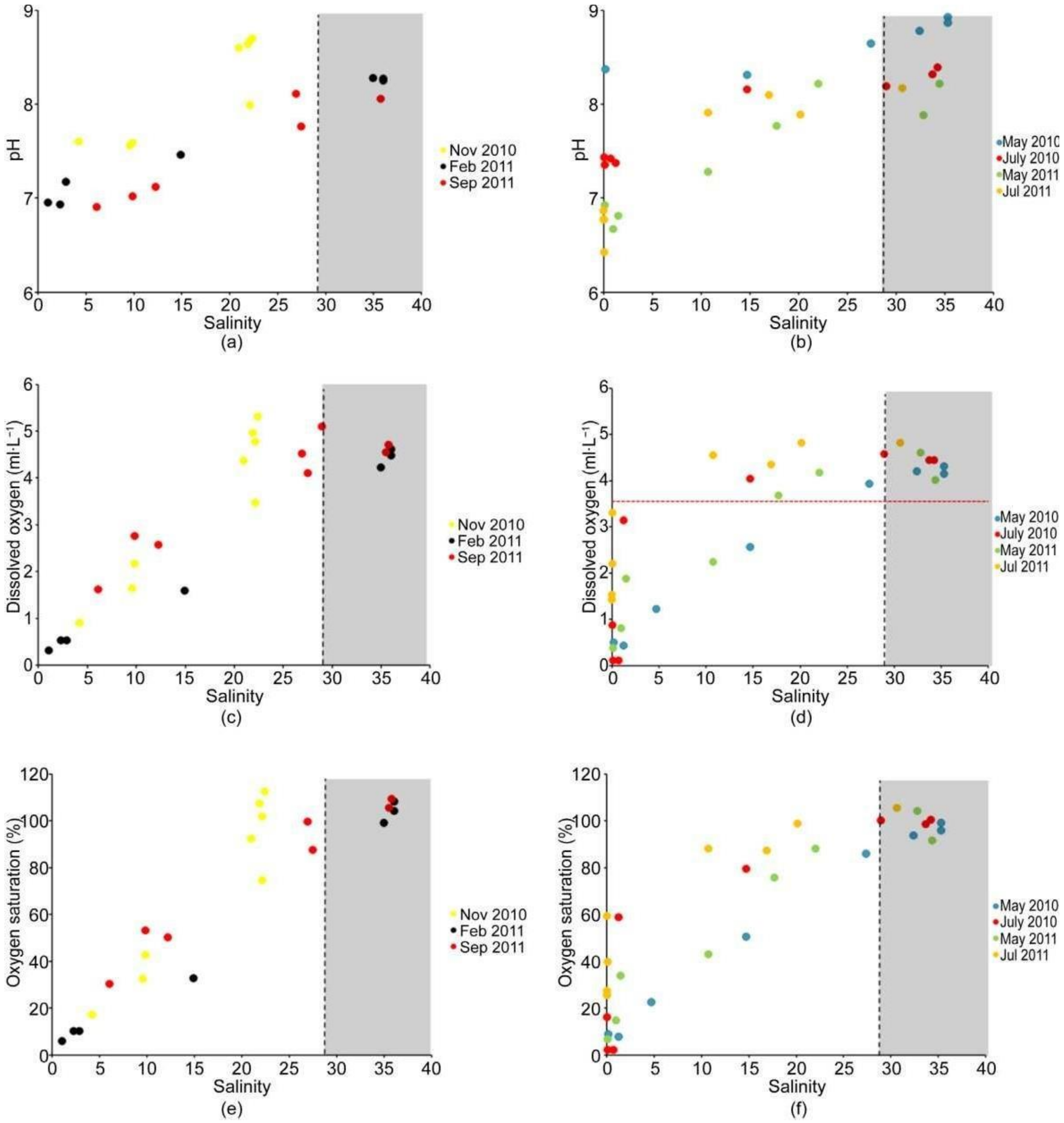

Figure 4. Surface pH of the water through the salt gradient (a)-(b), dissolved oxygen (c)-(d) and oxygen saturation rate (e)-(f) in the estuary and plume of the Jaboatao River. The red line indicates the limit established by the CONAMA 357 legislation. The dotted line indicates the mean value of salinity in the pen region. Grey area corresponds to plume region. Average and standard deviation for the dry and wet period are also shown.

Silicate showed higher concentrations principally in the estuarine region. The higher concentrations were registered in May (wet period), whereas the lower values were observed in February. The estuary and plume showed significant differences (*t* -test; *p*: 0.0001; *α*: 0.05).

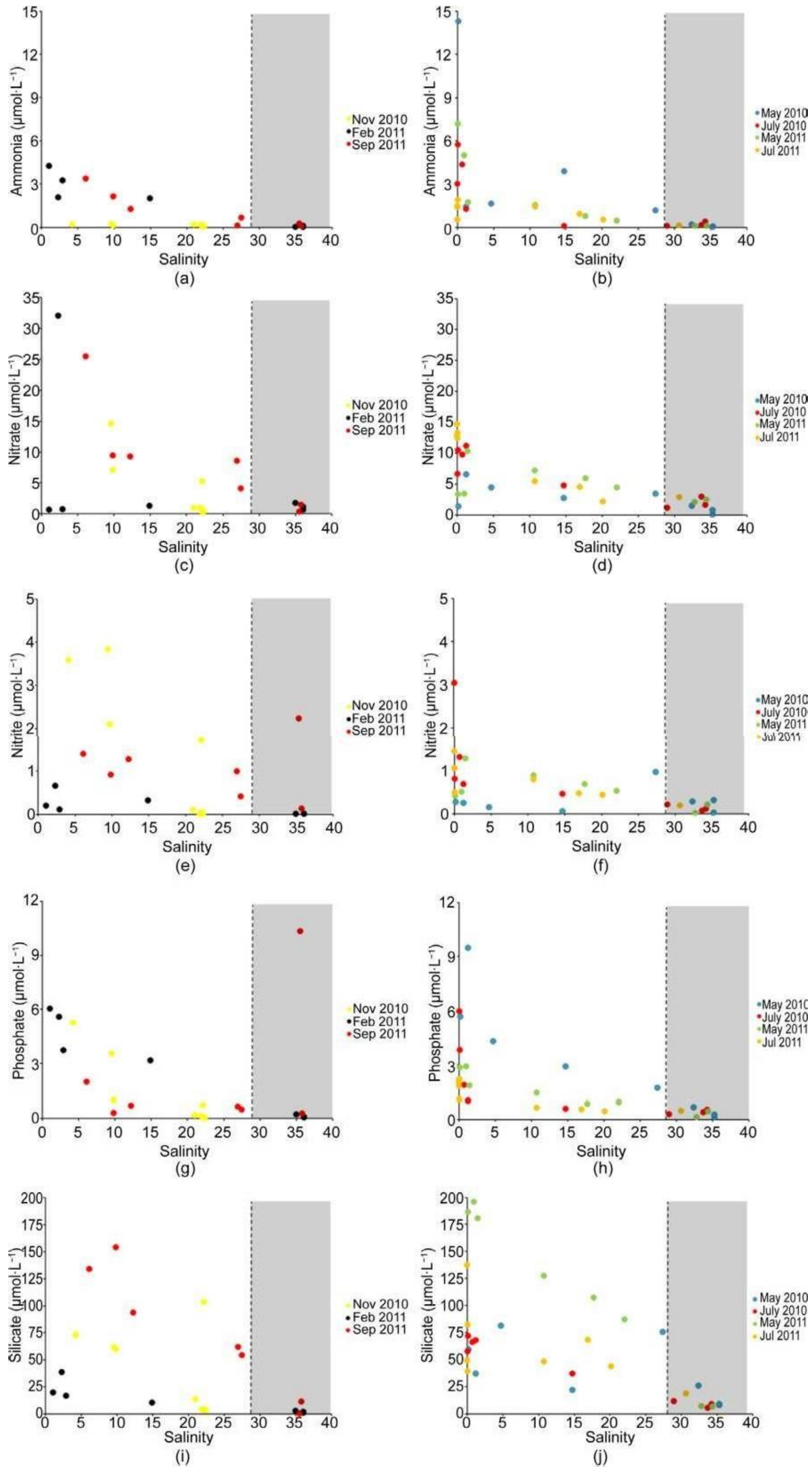

Figure 5. Concentrations of the dissolved nutrients in the two studied areas: (a)-(b) = ammonia, (c)-(d) = nitrate, (e)-(f) = nitrite, (g)-(h) = phosphate, (i)-(j) = silicate, during dry and rainy periods. Grey area corresponds to plume region. Average and standard deviation for the dry and wet period are also shown.

Biological Factors: Phytoplankton and Apparent Oxygen Utilization (AOU)

The phytoplankton community in the studied areas consisted of 80 taxa, represented by seven phyla: Bacillariophyta (55%), Miozoa (21%), Cyanobacteria (11%), Euglenophyta (5%), Chlorophyta (4%), Charophyta (3%) and Ochrophyta (1%).

The phyla Bacillariophyta and Miozoa characterized the planktonic flora in 76% of the floristic diversity. The diatoms were more representative, presenting 4 classes, 22 orders and 26 families. Dinoflagellates had the secondhighest representation, with 1 class, 5 orders and 8 families, with emphasis on the genera Protoperidinium and Prorocentrum, with five taxa each. Cyanobacteria were represented by 1 class, 3 orders and 5 families (Table S1; Supplementarymaterial).

The Bacillariophyta and Cyanobacteria groups showed different spatial distributions. Bacillariophyta did not show significant differences between the estuarine and plume regions (*t* -test; *p*: 0.24; *α*: 0.05), while Cyanobacteria showed significant differences between these regions (*t* -test; *p*: 0.0001; *α*: 0.05). Higher values were observed principally in the estuarine region (Figures 6(a)-(d)).

The calculated AOU showed positive values in both climatic periods. The wet period showed higher values that the dry period (average: +2.7 and +2.1 $mL.L^{-1}$, respectively). Additionally, 2 samples were negatives and were recorded in the dry period, corresponding to <9% of the total samples of the period (Figure 6(e), Figure 6(f)).

In the estuary, 38 taxa were identified, and 15 occurred only in that location, with the majority represented by Bacillariophyta (47%), Cyanobacteria (18%) and Miozoa (11%). In the plume region, 65 taxa were recorded, and 39 occurred exclusively in this region, following the general pattern of a majority of Bacillariophyta (62%), Miozoa (23%) and Cyanobacteria (8%) (Figure 7).

The specific richness showed little difference in the estuary, ranging from seven taxa in July of 2011 to 15 in November of 2010. In the plume region, the difference was quite pronounced, with a minimum of seven taxa in July of 2010 and a maximum of 35 taxa in May of 2010. However, in both sites, no seasonal pattern was evident (*t* -test; *p*: 0.0001; *α*: 0.05). Only two species were considered to be dominant in the estuary: *Microcystis aeruginosa* (Kutzing) Kutzing and *Cyclotella meneghiniana*

Kutzing. *Microcystis aeruginosa* occurred in all seasons and months in the estuary, being dominant in 23 of 28 analysed samples and abundant in the others. *Cyclotella meneghiniana* was dominant only in station 4 (upstream) in May of 2011. Most taxa were considered rare except *Cylindrospermopsis raciborskii* (Woloszynska) Seenayya & Subba Rajuand and *Oscillatoria tenuis* C. Agardh ex Gomont, which were abundant.

The plume region was dominated by *Microcystis aeruginosa*, *Planktothrix agardhii* (Gomont) Anagnostidis & Komarek, *Lepocinclis acus* (O. F. Muller) Marin & Melkonian, *Protoperidinium bispinum* (Schiller) Balech, *Coscinodiscus centralis* Ehrenberg, *Cyclotella meneghiniana* and *Paralia sulcata* (Ehrenberg) Cleve. *Climacosphenia moniligera* Ehrenberg, *Diploneis bombus* (Ehrenberg) Ehrenberg, *Grammatophora marina* (Lyngbye) Kutzing, *Licmophora abbreviate* C. Agardh, *Melosira dubia* C. G. Kutzing, *Navicula humerosa* Brebisson ex W. Smith, *Navicula* sp., *Pleuro/Gyrosigma* sp. and *Thalassiosira leptopus* (Grunow ex Van Heurck) Hasle & G. Fryxell were abundant (Figure 8).

We identified 38 taxa in the estuary, of which 63% were sporadic, 29% were uncommon, 3% were considered frequent and 5% were very frequent. The dominant *Microcystis aeruginosa* and *Cyclotella meneghiniana* were the very frequente species on the site. In the plume, no taxon was considered very frequent; 68% were sporadic, 26% were uncommon and 6% were frequent. Among the frequent were *Microcystis aeruginosa*, *Coscinodiscus centralis*, *Navicula* sp. and *Paralia sulcata.*

In the estuary, the values of specific diversity were between the minimum of 0 bits.cell^{-1} and the maximum of 1.99 bits.cell^{-1}, with 60% of the samples presenting low diversity and 40%, very low, while the equitability ranged from 0 to 0.99, with 90% of the samples showing high equitability. In the plume region, the diversity was higher, ranging from very low to medium, with 0 bits.cell^{-1} and 2.98 bits.cell^{-1}, respectively. The equitability presented minimum and maximum values of 0 and 0.99, with 32% of the samples presenting medium diversity and 82% being highly equitable (Figure 9).

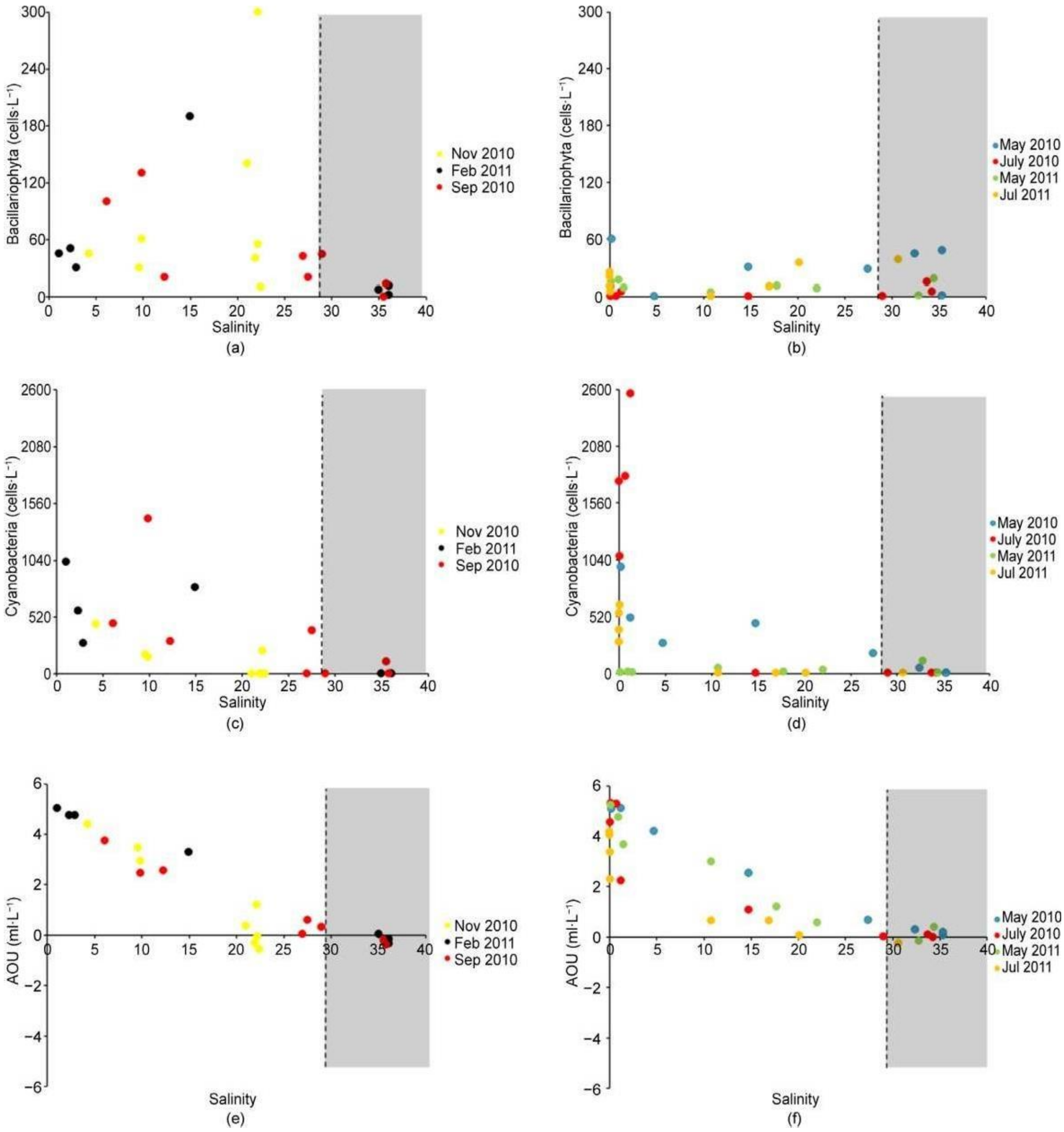

Figure 6. Bacillariophyta through the salt gradient (a)-(b), Cyanobacteria (c)-(d) and AOU (e)-(f) in the estuary and plume of the Jaboatao River. The dotted line indicates the mean value of salinity in the pen region. Grey area corresponds to plume region. Average and standard deviation for the dry and wet period are also shown.

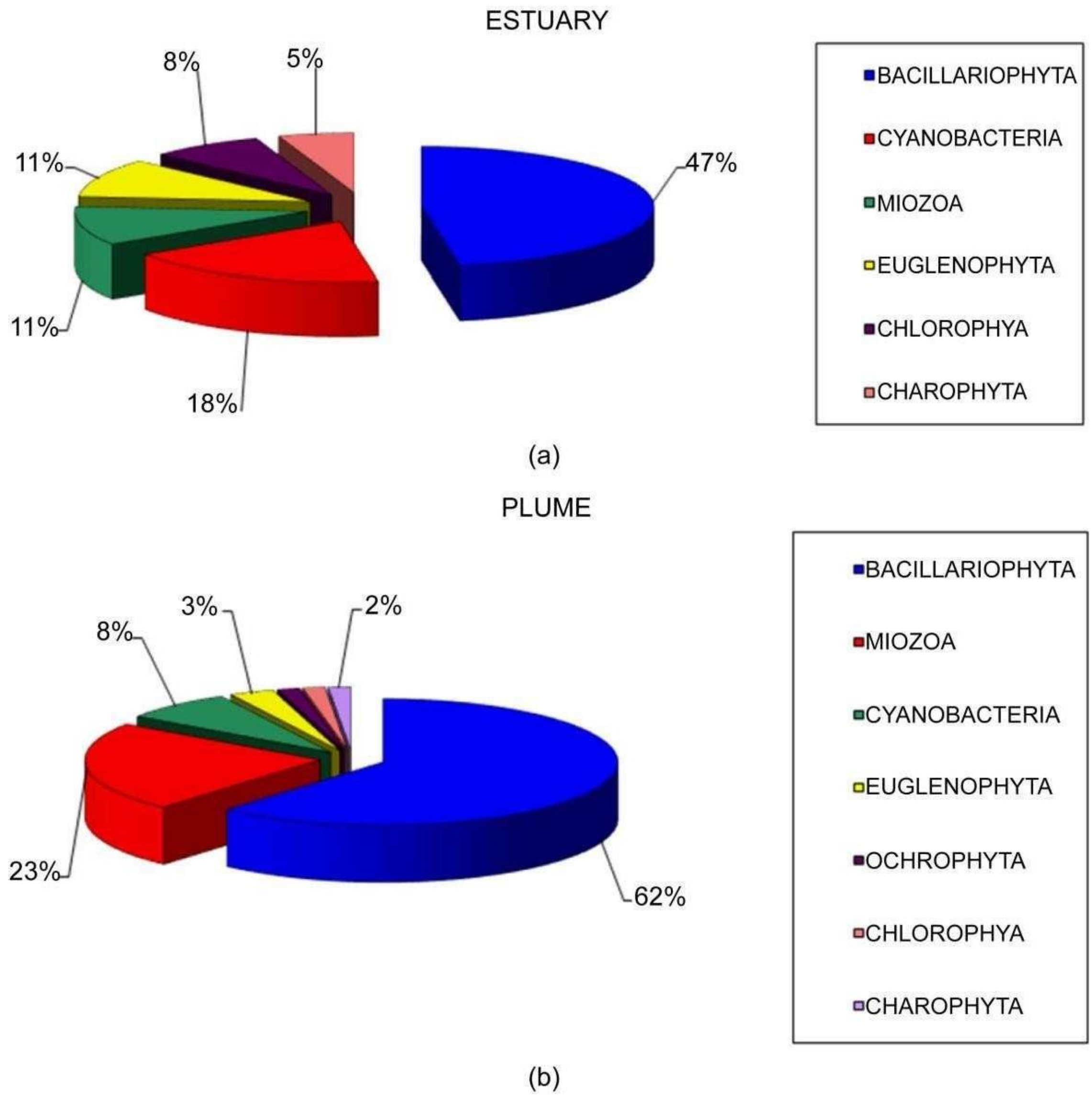

Figure 7. Percentage of occurrence of phyla in each area studied.

In cell density, the most representative group in the estuary was the cyanobacteria, with 17548 cell.$L^{-1}10^3$, constituting 92.6%, followed by diatoms, with 1230 cell.$L^{-1}.10^3$, constituting 6.5%. The rest of the groups found (Euglenaceae, Dinoflagellates, Chlorophyceae and Carophyceae) totalled 0.9% in 167 cell.$L^{-1}.10^3$. In the plume as well as in the estuary, cyanobacteria constituted 97% of the cells counted, with 13879 cell.$L^{-1}.10^3$, followed by diatoms, with 740 cell.$L^{-1}.10^3$, representing 2%; The remaining groups (Euglenophytes, Dinoflagellates, Chlorophyceae, Carophytes and Octylites) were 0.9%, adding 290 cell.$L^{-1}.10^3$ (Figure S1; Supplementary material).

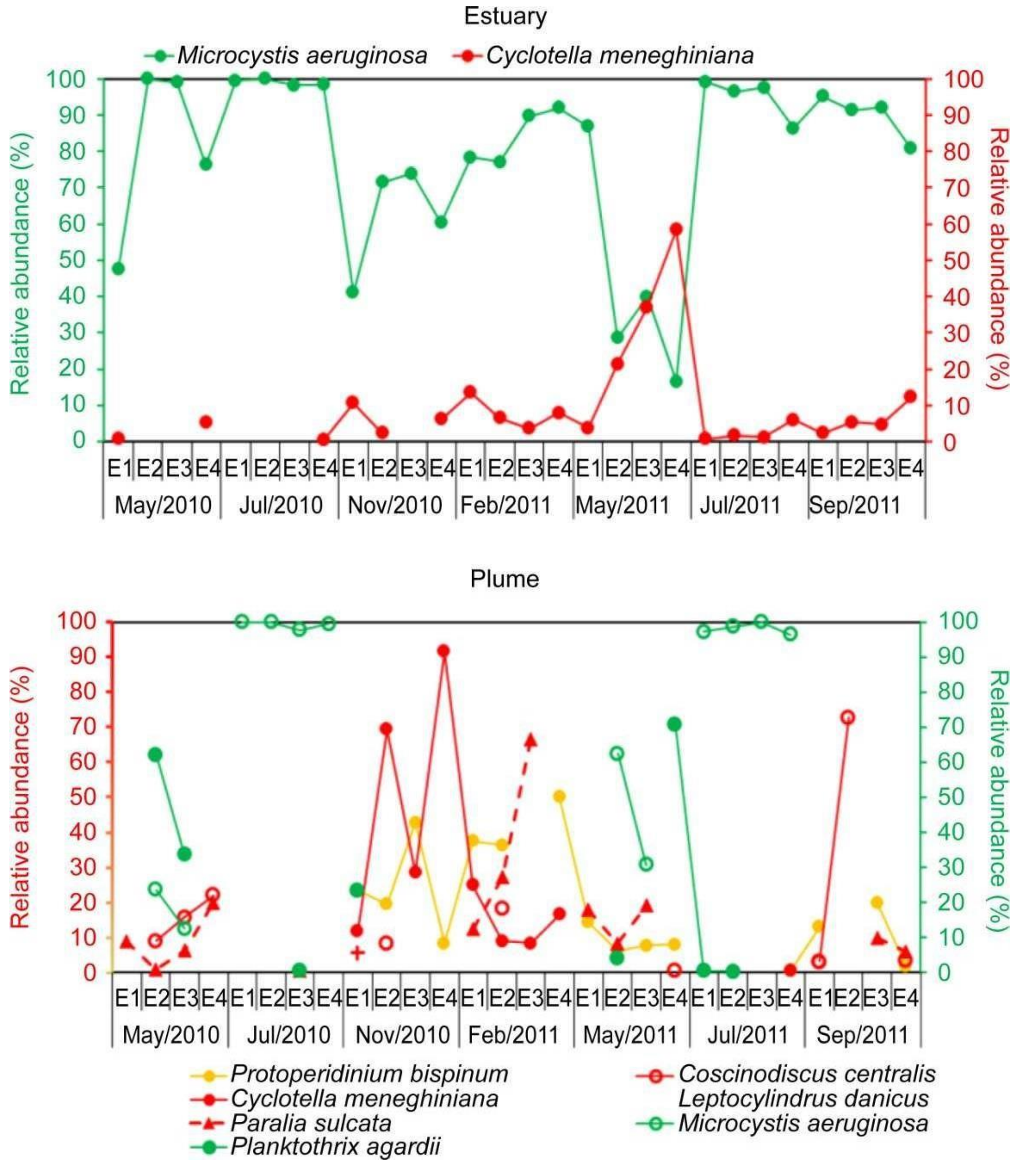

Figure 8. Relative abundance (%) of the most representative species in the studied areas.

In the estuary, the maximum density was 7255 cell.L^{-1}.10^{3}in July of 2010 and a minimum of 126 cell.L^{-1}.10^{3}in May of 2011. In the plume, the density remained below 500 cell.L^{-1}.10^{3}except in the months of July of 2010 and July of 2011, when it reached more than 7000 cell.L^{-1}.10^{3}. The minimum recorded in the plume region was cell.L^{-1}.10^{3} and the maximum 7618 cell.L^{-1}.10^{3} (Figure S2; Supplementary material).

The cell density in each season showed that the estuary had the highest densities in all stations, but the difference was not significant (*t* -test; *p*: 0.07; *α*: 0.05), with densities always above 3000 cell.L^{-1}.10^{3} (Figure S3; Supplementary material).

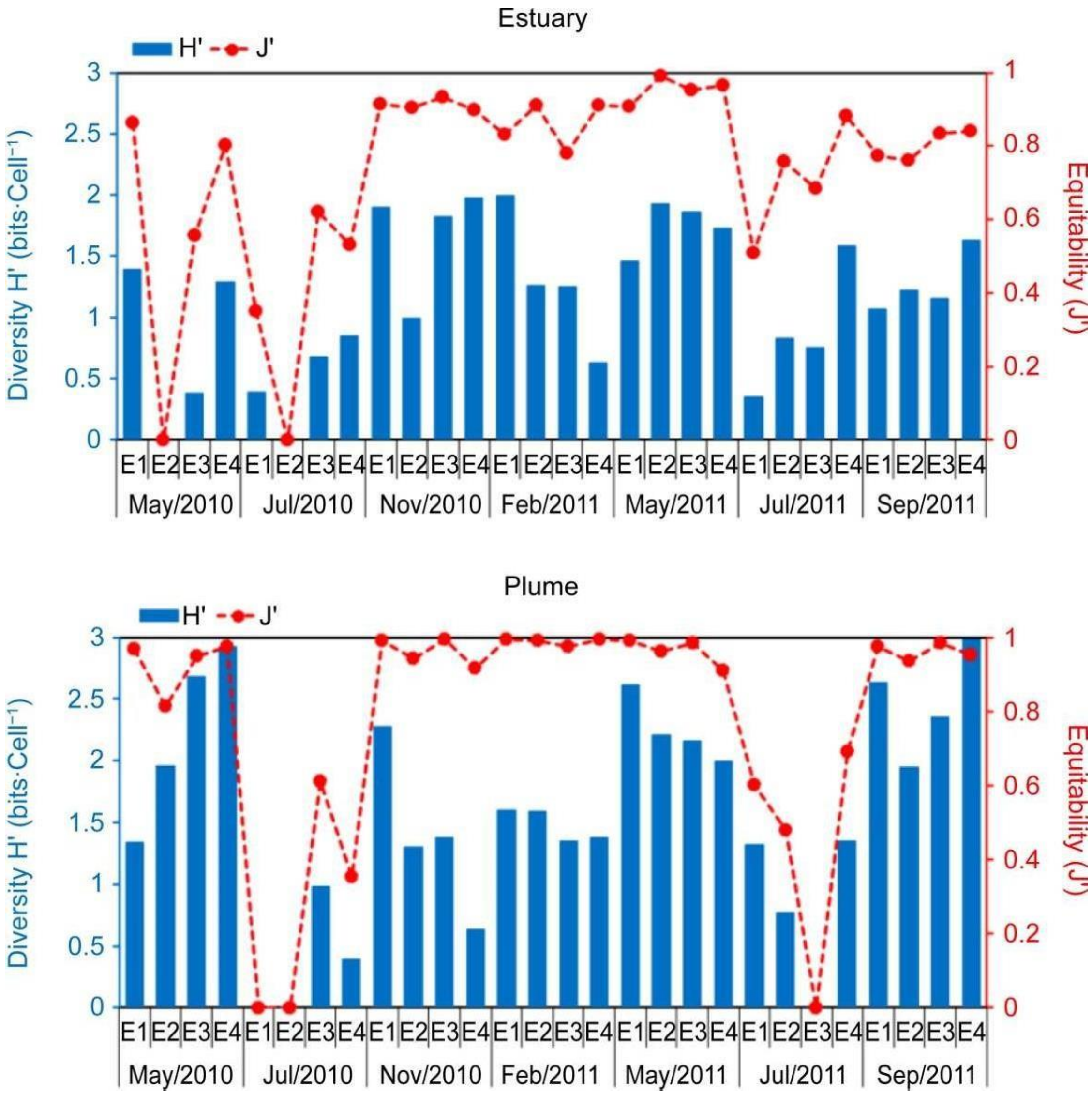

Figure 9. Specific diversity and equitability of the two studied areas.

There was also a decreasing downstream-upstream gradient. The species *Microcystis aeruginosa* was responsible for the predominance of cyanobacteria, both in the estuary and in the plume, dominating in 82% of the estuary and presenting a minimum density of 4 cell.L^{-1}.10^{3} and a maximum of 2560 cell.L^{-1}.10^{3}. During May of 2011, the density was lower than in the other months studied, with a density of less than 10 cell.L^{-1}.10^{3}.

In the plume, *M. aeruginosa* presented a minimum density of 8 cell.L^{-1}.10^{3} and a maximum of 2215 cell.L^{-1}.10$^{3.}$ This species showed seasonality in the area, occurring only in the months of the rainy season (May and Julyin both years) at well above its density in July of 2011. It was not possible to show a spatial difference (Figure S4;

Supplementary material).

Discussion

Temperature and Salinity

Studies of phytoplankton and its responses to environmental variables represent important tools for understanding and diagnosing the natural and/or anthropogenic impacts of aquatic ecosystems at the level of primary producers. Natural factors such as rainfall showed a temporal distribution that agreed with historical patterns, but in July 2010 (typical rainy month), the rainfall intensity was lower than the historical average. Thus, no seasonal variations were identified for some physical and chemical factors. Within these factors, the temperature did not show significant differences spatially and temporally. This is a typical pattern for estuaries in northeastern Brazil (GREGO et al., 2009; HONORATO DA SILVA et al., 2009).

This thermal stability is typical of tropical estuarine waters, which can range from 24˚C to 30˚C, and is related to the salinity gradient that can increase the temperature by up to 4˚C, especially in the less rainy season (MONTEIRO et al., 2015). Temperature directly influences phytoplankton, promoting an increase in reproduction and growth, especially in temperate regions. This effect is observed less noticeably in tropical waters (ESKINAZI-LEÇA et al., 1984; KOENING and MACEDO, 1999). The water temperature exerts a direct influence on the physiological processes of the organisms (FRAZAO and VITAL, 2004), whereas salinity is an important hydrological parameter in the spatial distribution of organisms, presenting gradients that make this fator preponderant in the distribution of aquatic organisms and constitute an ecological barrier for certain species (FRAZAO and VITAL, 2004).

In the present study, the salinity presented seasonal variation, and rainfall did not seem to influence the values. The plume showed the highest salinity values, as expected, due to the strong marine influence. Spatial variations in the plume, from meso to euhaline, were less evident than in the estuary, where station 1 had the highest salinities andstation 4 (upstream) the lowest, ranging from freshwater to polyhaline.

pH, DO and Saturation

In the plume, the pH remained always alkaline, evidencing the influence of the marine waters in the area. Another author (BRANCO, 2007) observed similar values in the same area of study. The pH in the estuary ranged from slightly acidic to alkaline, with the lowest values, generally slightly <7, coinciding with the months of more intense precipitation, when they were justified by the influence of freshwater, which is more acidic than the marine water. In tropical estuaries, the pH is generally in the range of alkalinity (GREGO et al., 2009; HONORATO DA SILVA et al., 2009; PAIVA et al., 2006).

Fluctuations of the acid, neutral and alkaline pH values in the studied environment are related to the degradation processes of organic matter and photosynthetic activities (BAMBI et al., 2008; TRAVASSOS et al., 2016), which cause an increase in inorganic dissolved nutrients, mainly ammonia and phosphate, that indicate the presence of domestic effluents rich in organic matter (NORIEGA and ARAÚJO, 2009). The environment showed a great variation of pH due to the low DO values (average: 1.57 $mL.L^{-1}$). According to Noriega et al. (2015) and Gaspar (2015), the decrease in pH is related to the increase of dissolved CO2 concentration as a consequence of the increase in organic matter degradation and reduction of photosynthetic activities, which are the main consumers of this gas and directly influence the carbonate system and consequently the pH.

The high organic load also reduced light penetration, reducing the photic layer and limiting the density and diversity of phytoplankton despite the high levels of dissolved inorganic nutrients.

These factors may alter the concentration and saturation rate of dissolved oxygen, which varied significantly in comparisons of the estuary and the plume, with the latter being much more oxygenated. However, neither site showed any evidence of seasonal variation. Spatially, the estuary became evident, with the oxygen content decreasing as it entered the more internal seasons. In estuarine areas, this variation in dissolved oxygen content is common (BRANCO, 2007). Similar values in the Recife basin were recorded by Santiago et al. (2010) (2.72 to 6.24 $mL.L^{-1}$), and Melo et al. (2014) recorded values between 1.73 and 7.78 $mL.L^{-1}$ at the plume of the Capibaribe River (close to our study area).

DO is one of the most important elements for maintaining the environmental quality of aquatic ecosystems as well as being an essential element for the oxidation, decomposition and cycling of organic matter circulating in ecosystems. In 1978 Macedo and Costa, classified the estuarine ecosystems of northeastern Brazil in terms of water quality based on the oxygen saturation rate, creating categories for supersaturated (>100%), saturated (75% to 100%), and low saturation (below 75%), semi-polluted (25% to 50%), and polluted (<25%). Except for one point where it was considered saturated, the estuary of the Jaboatao River ranged from polluted to low-saturation zones, evidencing the low quality of its waters. The plume remained saturated to super-saturated. The higher DO contents are related to the more alkaline values of pH in the plume.

Nutrients

DO and pH are altered by temporal and spatial variations of nutrient inputs. The main nutrients are regulated and defined by CONAMA Resolution 357 (CONAMA, 2005). According to the Resolution, the waters of the estuary and the plume of the Jaboatao River are considered brackish and salt I class, respectively, with the maximum limits 0.40 $mg.L^{-1}$ (0.30 $\mu mol.L^{-1}$) for nitrite, 0.40 $mg.L^{-1}$ (1.72 $\mu mol.L^{-1}$) for ammonia and 0.07 $mg.L^{-1}$ (0.30 $\mu mol.L^{-1}$) for nitrate. In the estuary, ammonia (average: 2.7 $\mu mol.L^{-1}$), nitrite (average: 1.07 $\mu mol.L^{-1}$) and nitrate (average: 8.86 $\mu mol.L^{-1}$) presented mean values above those specified by the CONAMA resolution. In the plume, ammonia (average: 0.26 $\mu mol.L^{-1}$) and nitrite (average: 0.27 $\mu mol.L^{-1}$) presented mean values below the maximum allowed, but nitrate (average: 2.4 $\mu mol.L^{-1}$) remained above the maximum allowed value.

The high values of nitrogen compounds and phosphate (average: 2.97 $\mu mol.L^{-1}$) in the Jaboatao estuary evidenced the high degree and the strong influence of the anthropic action in that environment. The same influence is not observed in the plume, where the nitrogenous compounds as well as phosphate (average: 0.39 $\mu mol.L^{-1}$) remained within an acceptable limit.

The concentrations of each of the nitrogen compounds are strongly influenced by the dynamic cycle of DO in the medium (NORIEGA and ARAÚJO, 2009; DAY et al., 1989). In estuarine areas, nutrients generally originate from rivers, usually in an inverse relationship between the concentration of these elements and the salinity (NORIEGA et al., 2005). This process was evidenced in the estuary and plume of the Jaboatao River, which presented na inverse relationship between salinity and nutrient concentration. In the estuary, where salinity was lower, nutrient concentrations were higher. In the plume, the reverse process occurred. According to Melo et al. (2014), in a study of the Capibaribe River plume, recorded higher values than those found in this study, except for silicate, and a defined seasonal variation, presenting higher concentrations in the rainy season.

The dissolved nutrients presented a spatial variation better evidenced in the estuary than in the plume, but it was not possible to establish a seasonal pattern in both. In estuarine plumes, the contribution is lower because the production of the estuary absorbs a good part of the nutrients, which is minimized in urban areas, where the nutrient supply is high.

Phytoplankton Distribution and AOU

The combined effect of the main physico-chemical factors of the pelagic environment, such as luminous intensity, nutrient concentration, temperature and salinity, determine the geographic distribution, specific composition and variability of the phytoplankton production rates (GAMEIRO et al., 2007). Knowledge of the taxonomic composition of phytoplankton is fundamental for the study of the spatial and temporal dynamics of the community and for the characterization of functional groups (GAMEIRO et al., 2007).

In the taxonomic composition of the studied environments, the greater representativeness of the diatoms is highlighted, considering the specific richness. In the estuary, after the diatoms, it is possible to show the representativeness of the cyanobacteria, a typical group of freshwater organisms. In the plume, the second most represented group was the dinoflagellates, a typical marine species.

This relationship also occurs in other estuaries, mainly in northeastern Brazil, where the predominance of diatoms has been established (BRANCO, 2007; HONORATO DA SILVA et al., 2009; ESKINAZI-LEÇA et al., 2004; PASSAVANTE, 1979; TRIGUEROS and ORIVE, 2001; ROSEVEL et al., 2005). According to Melo et al. (2014) also highlight the greater representativeness of diatoms in the plume of the Capibaribe River, followed by the dinoflagellates, which is the same pattern found for the plume of the Jaboatao River. Diatoms predominate in coastal and shelf regions, gradually decreasing to wards the open ocean, where the contribution of dinoflagellates increases significantly (FERNANDEZ and BRANDINI, 2004), whereas

Cyanobacteria can reach high densities in tropical marine waters, possibly constituting the group mainly responsible for primary productivity in cases of a shortage of larger phytoplankton components (LALLI and PARSONS, 1997).

The cell density of the Cyanobacteria *Microcystis aeruginosa* predominated in practically all the estuarine stations, with blooms in July of 2010 and September of 2011. In the plume region, however, its occurrence was punctual, with blooms in July of 2010 and 2011. Previous research on the estuarine ecosystem of the Jaboatao River (LACERDA et al., 2004; BRANCO, 2007; BRANCO et al., 2002) considers the diatoms *Bellerochea mallleus*, *Coscinodiscus centralis* and *Cyclotella meneghiniana* to be dominant and very frequent as the key species for that ecosystem. In the present study, *Microcystis aeruginosa* is considered the key species in the studied area due to its high density, dominance and frequency of occurrence at all estuarine stations.

Previous data analysed by Branco et al. (2006) referred to a specific diversity ranging from medium to high. A recent study by Lacerda et al. (2004) and Branco (2008) revealed a marked reduction of this diversity, and in the present study, the diversity reached a value of zero, a fact that is supported by the flowering of *Microcystis aeruginosa*, demonstrating a highly compromised ecosystem. Cyanobacteria are especially abundant in waters with high temperatures that are rich in nutrientes or in polluted waters with little oxygen where they can form a dense scum that can colour the water, forming blooms. Blooms of *M. aeruginosa* produce toxins and have been implicated in the mass mortality of aquatic animals and the destabilization of food webs (OBERHOLSTER et al., 2004; BLACK, 2011).

Additionally, the positive values shown by calculated AOU indicate higher rates of respiration (production-respiration), where DO is consumed and CO_2 released in the water column. According to CPRH (2010) the registration of a significant density of phytoplanktonic organisms against low species richness suggests that a habitat has received a polluting load, allowing a favourable environment for organisms that are tolerant of this condition. This was evidenced both in the plume and in the estuary, where the occurrence of other species was limited in the stations dominated by this Cyanobacteria group.

Principal Component Analysis (PCA)

We statistically analysed the physical, chemical, biological and rain data through a Principal Component Analysis (PCA) to obtain spatial and temporal correlations and correlations between the parameters analysed in this study (Figure 10(a), Figure 10(b)). According to the PCA, the first 4factors explained 72.70% of the environmental variations that were correlated with the species considered to be very frequent (Table S2; Supplementary material). In Figure 10(a), componente 1 explained 40.0% of the environmental variations analysed and showed a direct correlation between water transparency (Secchi), salinity, pH and DO.

These parameters had an inverse correlation with nutrients (ammonia—$NH4^{+}$, nitrate-NO^{3-}, nitrite-NO^{2-}, silicate-SiO^{2-}) and the Cyanophytes group. Component 2 explained 14.53% of the variability and showed an inverse correlation etween temperature (T˚C) and rainfall. Biological parameters were located in component 4 and showed an inverse correlation between Bacillariophyta (Bac) and Cyanobacteria (Cya).

We identified a clear spatial division between the estuary and the plume. A group of parameters was associated with the estuarine region (nutrients, Cyanobacteria, Bacillariophyta and Chlorophyta), while another group was associated with the plume region (DO, Secchi, salinity and pH).

A second PCA was performed to include temporal variability (months) in the biplot. We observed that salinity, pH and water transparency (Secchi) are associated with dry-season months (February and November), whereas nutrients are associated with the winter months. The biological groups of component 4 appear to be associated with the dry period (November). Temperature and rainfall did not show a defined pattern within the biplot (Figure 10(b)). Additionally, we included a time series of 12 years (1999 to 2011) based on similar studies carried out in this aquatic system. We used AOU calculated from the values of salinity, oxygen and temperature to compare the estuarine system with the fluvial system.

Trend of AOU and Change in the Phytoplankton Species

Data obtained from the CPRH database (1999 to 2011) (CPRH, 2010; CPRH, 2013), were used to calculate AOU in the Jaboatao River. We used data from the fluvial station with greater geographic and data coverage. The dataset in the estuarine region was limited to 28 data (months).

The results of this exercise can be seen in Figure 11(a), Figure 11(b). Figure 11(a) shows a positive AOU series with the exception of 2 months (negative values). The mean value in the river series was higher than that in the estuarine series. The calculated trend of AOU for the river was negative, whereas the estuarine series had a slight positive trend. In the estuarine region, the main biological components changed through 1999-2011 period. Bacillariophyta had been the dominant species inprevious studies, while in our study between 2010 and 2011, the Cyanophyta group was dominant.

Conclusion

We can conclude that the Jaboatao estuary is strongly impacted because of the lower values of salinity and dissolved oxygen and the high concentration of nutrients, mainly the nitrogenous and phosphate components indicative of high pollutant loads. Additionally, the cyanobacteria *Microcystis aeruginosa*, an opportunistic and potentially toxic species, constitutes the dominant species responsible for the low diversity of species in recent years, as demonstrated by the observations in the temporal series. The plume, with well-oxygenated waters, high salinity and low concentration of nutrients, indicates the influence of the marine flow in the area, allowing the dominance of other species and contributing to the increase of local diversity.

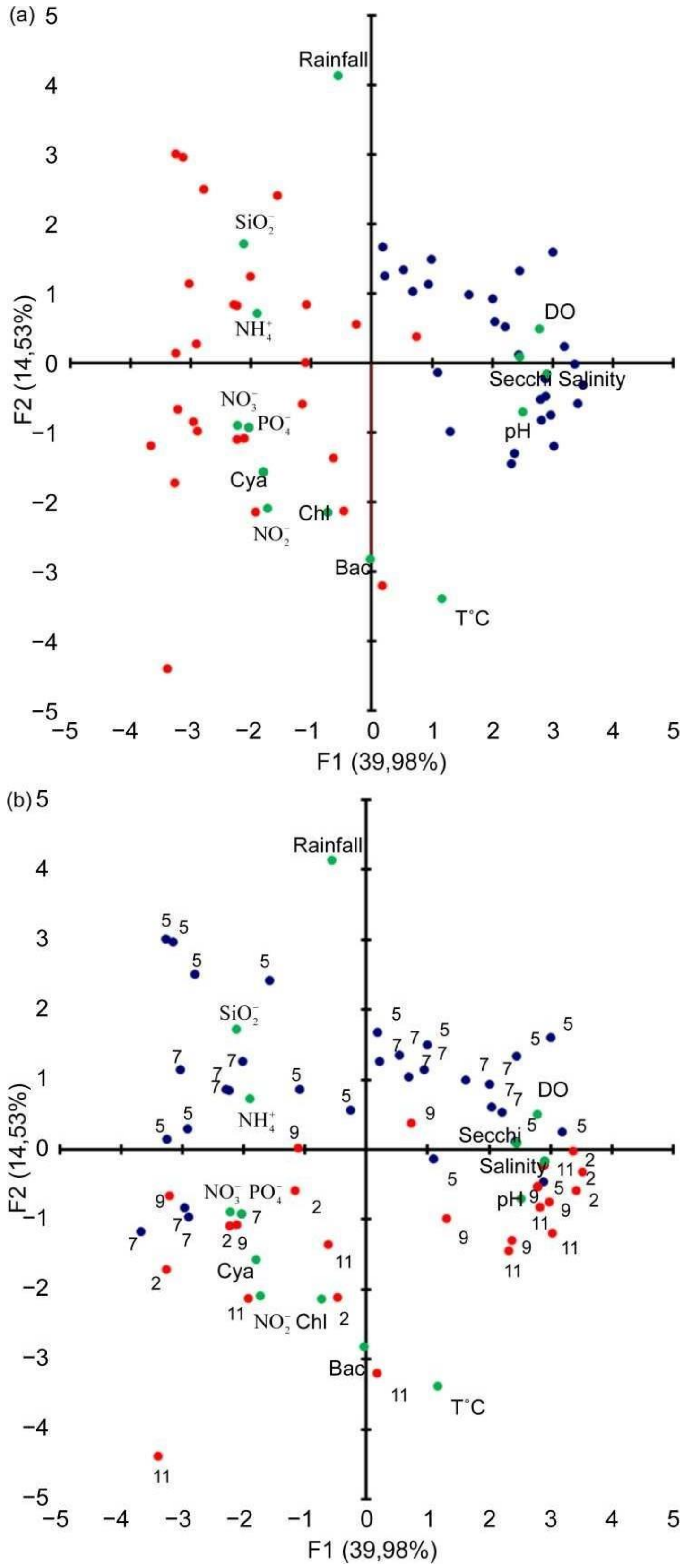

Figure 10. Spatial PCA of the chemical, physical and biological parameters. Green circles indicate the parameters; Red circles indicate the estuarine region; Blue circles indicate the region of the plume (a). Temporal PCA of chemical, physical and biological parameters. Green circles indicate the parameters; Red circles indicate the dry period; Blue circles indicate the rainy period (b).

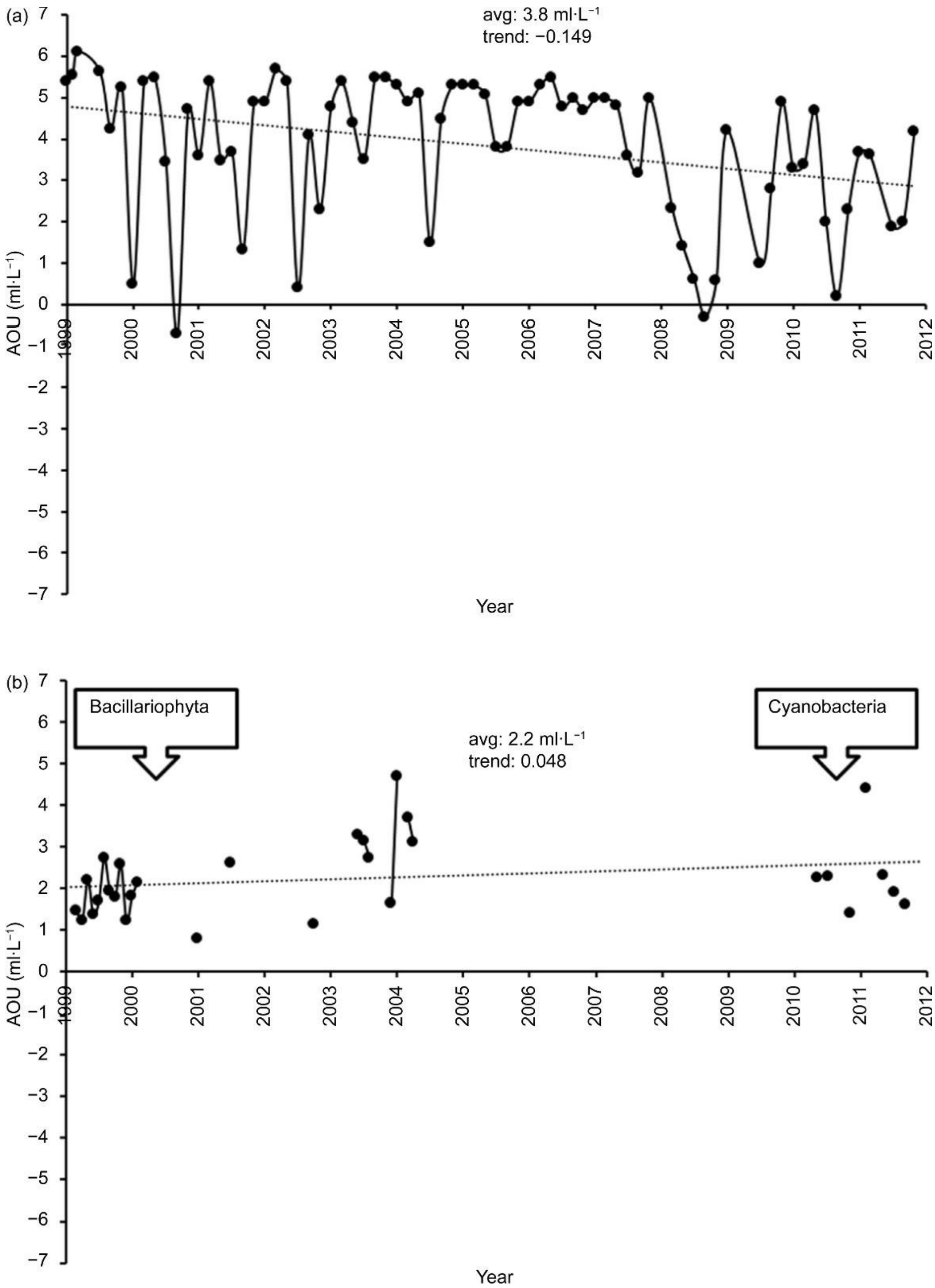

Figure 11. Time series (1999-2011) of the AOU calculated in the fluvial region (a) and in the estuarine region (b). The dotted line indicates the trend of the series (b).

Supplementary Material

Phytoplankton

The samples for the phytoplankton study were collected with Ninskin oceanographic bottles and later fixed with lugol solution. The analyzes were performed according to the sedimentation method of Utermohl (HASLE, 1978; EDLER, 1979; FERRARIO et al., 1995), and counts performedunder ZEISS Axiovert inverted microscope. Samples were homogenized and placed in 10 mL chambers, stained with Bengal Rose and placed to sediment for 24 hours. The counts were performed with 400X, using the technique of transection. The standardized counting of two transects was used in each chamber. In cases of sample poverty, counts covered the entire chamber. The values of phytoplankton density were expressed in cells per liter (cells.L^{-1}). Taxonomic identification was done by consulting specialized literature. For the framing of taxa and checking of all scientific names, the international database used was Algaebase (GUIRY e GUIRY, 2015; http://www.algaebase.org.).

The relative abundance of the taxa was determined by considering the categories: dominant, species whose numerical occurrences were greater than 50% of the total number of individuals in the sample; Abundant, species whose occurrence exceeds the average number of individuals in the sample; Rare, species whose occurrences are less than the average number of individuals in the sample. In order to calculate the frequency of occurrence, the number of samples, in which each taxon occurred, and the total number of samples were analyzed, using the formula described by Mateucci e Colma (1982), considering: Very common (≥70%), common (70%|−40%), infrequent (40%|−10%) or sporadic (<10%).

For the calculations of specific diversity, the Shannon index (SHANNON, 1948) was used; the values obtained were classified by Valentin classification (VALENTIM, 2000), being considered high when the results were ≥ 3.0 bits.cel^{-1}; average, with results between 2 and 3 bits.cel^{-1}; low, between 1 and 2 bits.cel^{-1}; and very low, with result ≤1 bits.cel^{-1}; the equitability (J = H' /logS) was calculated according to Pielou (1977). In order to calculate this index, the Plymouth Routines in Multivariate Ecological Research, PRIMER 6.0® statistical software program was used.

Table S1. List of taxa identified in the estuary and plume of the Jaboatao River, Pernambuco, Brazil.

TAXON	REGION	
	Estuary	**Plume**
CYANOBACTERIA		
CYANOPHYCEAE		
NOSTOCALES		
APHANIZOMENACEAE		
Dolichospermum spiroides (Klebhan) Wacklin, L.Hoffmann & Komárek	x	
Cylindrospermopsis raciborskii (Woloszynska) Seenayya & Subba Raju	x	
CHROOCOCCALES		
CHROOCOCCACEAE		
Chroococcus sp. Nägeli	x	
MICROSCYSTACEAE		
Microcystis aeruginosa (Kützing) Kützing X	x	x
OSCILLATORIALES		
OSCILLATORIACEAE		
Oscillatoria limosa C.Agardh ex Gomont		x
Oscilllatoria tenuis C.Agardh ex Gomont	x	
Phormidium sp. Kützing ex Gomont X	x	x
MICROCOLEACEAE		
Planktothrix agardhii (Gomont) Anagnostidis & Komárek	x	x
Trichodesmium thiebautii Gomont ex Gomont		x
EUGLENOPHYTA		
EUGLENOPHYCEAE		
EUGLENALES		
PHACACEAE		
Lepocinclis acus (O.F.Müller) Marin & Melkonian	x	x
Phacus sp. Dujardin	x	
EUGLENACEAE		
Euglena sp. Ehrenberg X	x	x
Trachelomonas sp. Ehrenberg	x	
MIOZOA		
DINOPHYCEAE		
DINOPHYSIALES		
DINOPHYSIACEAE		
Dinophysis dubia Balech		x
GONYAULACALES		
Gonyaulax polygramma Stein		x
CERATIACEAE		
Tripos furca (Ehrenberg) F.Gómez		x
Tripos teres (Kofoid) F.Gómez		x
PYROPHACACEAE		
Pyrophacus horologicum Stein		x

Continued

GYMNODINIALES		
GYMNODINIACEAE		
Gymnodinium sp. F.Stein		x
PERIDINIALES		
OXYTOXACEAE		
Oxytoxum scolopax Stein		x
PROTOPERIDINIACEAE		
Protoperidinium unipes (Balech) Balech		x
Protoperidinium bispinum (Schiller) Balech	x	x
Protoperidinium cassum (Balech) Balech		x
Protoperidinium divergens (Ehrenberg) Balech		x
Protoperidinium sp. R.S.Bergh		x
PROROCENTRALES		
PROROCENTRACEAE		
Prorocentrum compressum		x
Prorocentrum gracile Schütt		x
Prorocentum lima (Ehrenberg) F.Stein	x	
Prorocentrum micans Ehrenberg X	x	x
Prorocentrum sigmoides Böhm		x
Prorocentrum sp.	x	
BACILLARIOPHYTA		
BACILLARIOPHYCEAE		
THALASSIOPHYSALES		
CATENULACEAE		
Amphora angusta Gregory	x	x
Amphora arenaria Donkin	x	x
AULACOSEIRALES		
AULACOSEIRACEAE		
Aulacoseira granulata (Ehrenberg) Simonsen		x
SURIRELLALES		
SURIRELLACEAE		
Campylodiscus clypeus (Ehrenberg) Ehrenberg ex Kützing		x
Campylodiscus fastuosus Ehrenberg		x
Surirella febigerii F.W.Lewis	x	
COCCONEIDALES		
COCCONEIDACEAE		
Campyloneis grevillei (W.Smith) Grunow & Eulenstein		x
Cocconeis scutellum Ehrenberg		x
RHOPALODIALES		
ENTOMONEIDACEAE		
Entomoneis alata (Ehrenberg) Ehrenberg	x	x

Continued

EUNOTIALES		
EUNOTIACEAE		
Eunotia didyma Grunow		x
NAVICULALES		
DIPLONEIDACEAE		
Diploneis bombus (Ehrenberg) Ehrenberg	x	x
NAVICULACEAE		
Gyrosigma balticum (Ehrenberg) Rabenhorst	x	x
Navicula sp. Bory	x	x
Pleuro/Gyrosigma sp.		x
LYRELLALES		
LYRELLACEAE		
Lyrella lyra (Ehrenberg) Karajeva	x	x
Navicula humerosa Brébisson ex W. Smith		x
BACILLARIALES		
BACILLARIACEAE		
Bacillaria paxillifera (O.F.Müller) T.Marsson	x	
Nitzschia lorenziana Grunow		x
Nitzschia sigma (Kützing) W.Smith	x	x
COSCINODISCOPHYCEAE		
COSCINODISCALES		
AULACODISCACEAE		
Aulacodiscus sp. Ehrenberg	x	
COSCINODISCACEAE		
Coscinodiscus centralis Ehrenberg	x	x
Coscinodiscus oculus-iridis (Ehrenberg) Ehrenberg	x	x
RHIZOSOLENIALES		
RHIZOSOLENIACEAE		
Guinardia delicatula (Cleve) Hasle		x
MELOSIRALES		
MELOSIRACEAE		
Melosira dubia C.G.Kützing	x	x
Melosira moniliformis (O.F.Müller) C.Agardh		x
Melosira nummuloides C.Agardh		x
PARALIACEAE		
Paralia sulcata (Ehrenberg) Cleve	x	x
MEDIOPHYCEAE		
LITHODEAMIALES		
BELLEROCHEACEAE		
Bellerochea horologicalis Stosch	x	x

Continued

EUPODISCALES		
EUPODISCACEAE		
Odontella turgida (Ehrenberg) Kützing		x
Triceratium sp. Ehrenberg	x	x
TOXARIALES		
CLIMACOSPHENIACEAE		
Climacosphaenia moniligera Ehrenberg		x
THALASSIOSIRALES		
STHEPHANODISCACEAE		
Cyclotella styllorum Brightwell		x
Cyclotella meneghiniana Kützing	x	x
THALASSIOSIRACEAE		
Thalassiosira leptopus (Grunow ex Van Heurck) Hasle & G.Fryxell	x	x
Thalassiosira subtilis (Ostenfeld) Gran	x	
BIDDULPHIALES		
BIDDULPHIACEAE		
Isthmia enervis Ehrenberg		x
LEPTOCYLINDRALES		
LEPTOCYLINDRACEAE		
Leptocylindrus danicus Cleve		x
FRAGILARIOPHYCEAE		
RHABDONEMATALES		
GRAMMATOPHORACEAE		
Grammatophora marina (Lyngbye) Kützing		x
Grammatophora oceanica Ehrenberg		x
LICMOPHORALES		
LICMOPHORACEAE		
Licmophora abbreviata C.Agardh		x
Licmoplora remulus Grunow		x
FLAGIRALIALES		
FLAGILARIACEAE		
Podocystis adriatica (Kützing) Ralfs		
THALASSIONEMATALES		
THALASSIONEMATACEAE		
Thalassionema nitzschioides (Grunow) Mereschkowsky		x
OCHROPHYTA		
DICTYOCHOPHYCEAE		
DICTIOCHALES		
DICTYOCHACEAE		
Dictyocha fíbula Ehrenberg		x

Continued

CHLOROPHYTA		
CHLOROPHYCEAE		
SPHAEROPLEALES		
SCENEDESMACEAE		
Scenedesmus bijuga (Turpin) Lagerheim	x	
Scenedesmus quadricauda (Turpin) Brébisson	x	x
TREBOUXIOPHYCEAE		
TREBOUXIOPHYCEAE (ordo ircertae sedis)		
TREBOUXIOPHYCEAE (incertae sedis)		
Crucigenia fenestrata (Schmidle) Schmidle	x	
CHAROPHYTA		
CONJUGATOPHYCEAE		
DESMIDIALES		
CLOSTERIACEAE		
Closterium sp. Nitzsch ex Ralfs	x	x
DESMIDIACEAE		
Staurastrum sp. Meyen ex Ralfs	x	

Table S2. Factorial loads of the PCA analysis of first four components. In red and blue positive and negative correlations, respectively.

Parameters	F1	F2	F3	F4
Secchi	**0.794**	0.015	0.027	−0.309
T˚C	0.377	**−0.659**	0.194	−0.024
Salinity	**0.941**	−0.035	−0.089	−0.010
DO	**0.901**	0.095	−0.242	0.114
pH	**0.813**	−0.138	0.153	−0.140
NH4+	**−0.603**	0.138	0.551	−0.014
NO2−	**−0.552**	−0.408	−0.527	−0.178
NO3−	**−0.652**	−0.182	−0.429	0.028
PO4-	**−0.710**	−0.176	0.393	−0.301
SiO2-	**−0.676**	0.331	−0.371	0.215
Cya	**−0.571**	−0.307	0.379	0.075
Bac	−0.005	−0.550	−0.076	**0.641**
Chl	−0.232	−0.418	−0.320	**−0.607**
Rainfall	−0.176	**0.800**	−0.086	−0.138

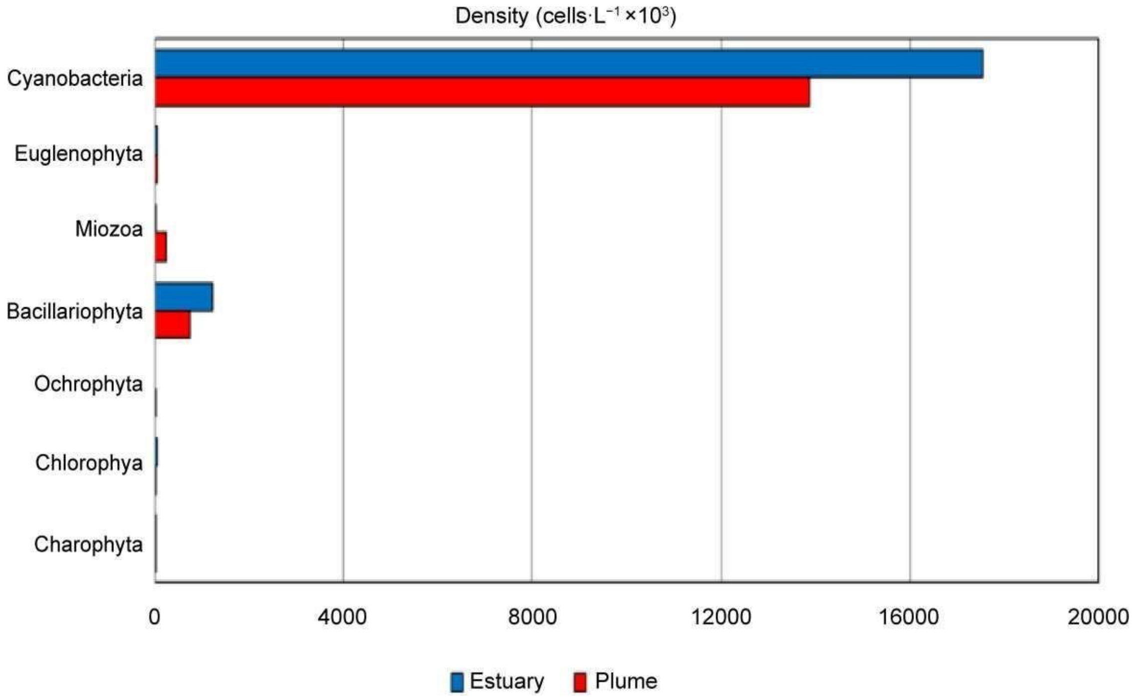

Figure S1. Total density of the groups in the studied areas.

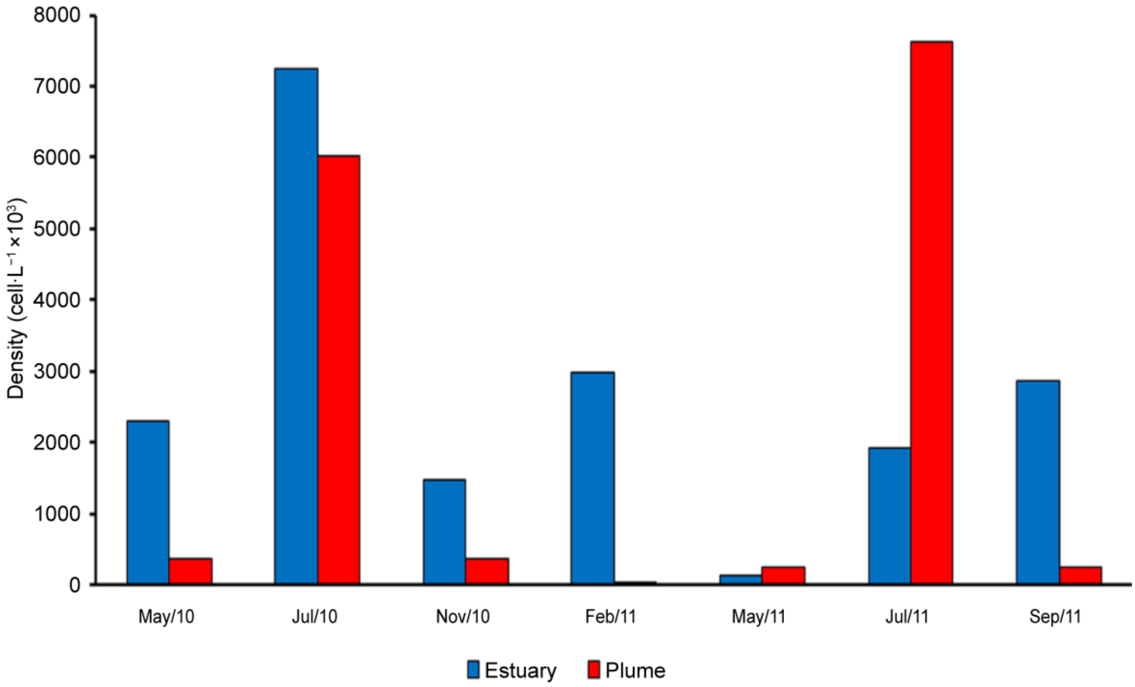

Figure S2. Total density for the months in the studied areas.

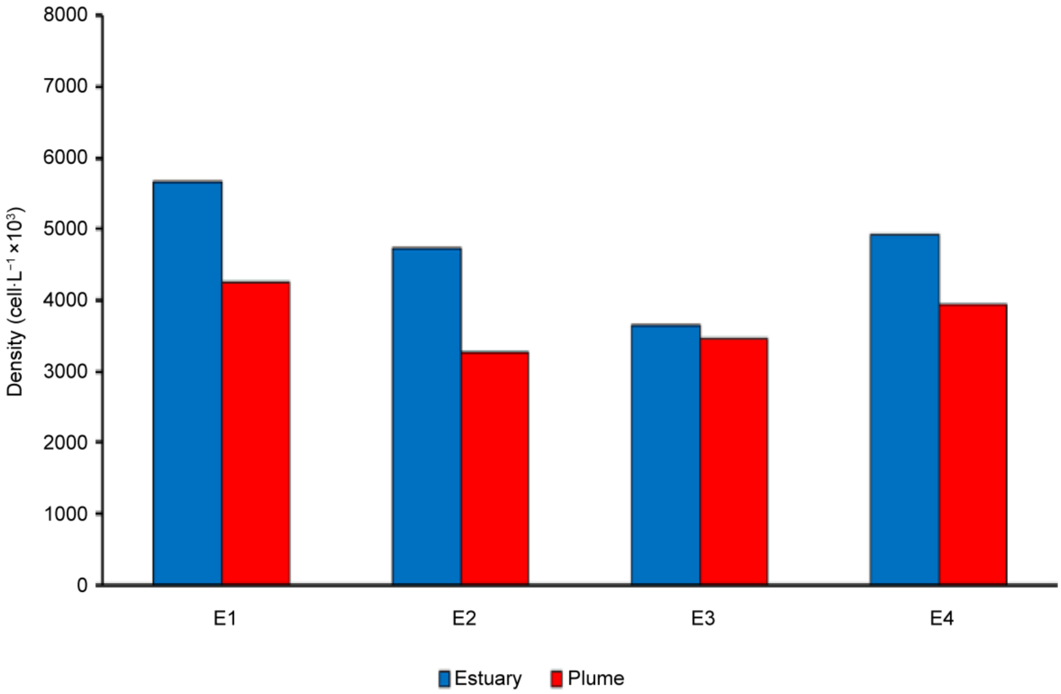

Figure S3. Total density for the stations in the studied areas.

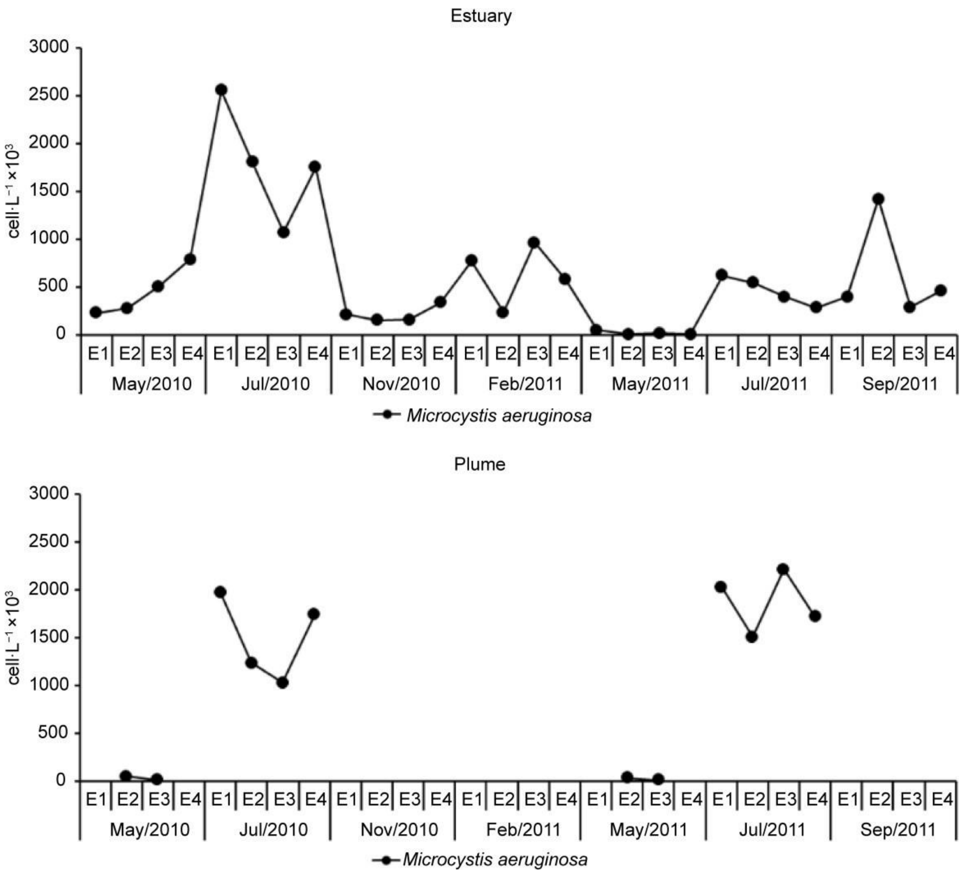

Figure S4. Total density of Microcystis aeruginosa.

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6 ARTIGO 3 - OCCURRENCE OF INTENSIVE CYANOBACTERIA (*Microcystis aeruginosa*) IN A MESOTIDAL TROPICAL ESTUARY

Situação

Em revisão para submissão

Revista

Revista de Biologia Marina y Oceanografia

Abstract

Samples were collected in a longitudinal profile from the Jaboatão River estuary, covering the marine area (estuarine plume) through four stations in the estuary and four in the plume during the dry and rainy seasons, with the objective of evaluating the occurrence and the distribution of *Microcystis aeruginosa* cyanobacterial blooms. In both regions, it is possible to observe the influence of *M. aeruginosa* on the local diversity, which was considered to range from very low to low where this species was dominant. *M. aeruginosa* represented on average 95% of the total cyanobacteria in the estuary, while in the plume, this percentage reached 65%. The species *M. aeruginosa* was responsible for the predominance of cyanobacteria, both in the estuary and in the plume. We also considered the N/P ratio as a factor that plays an important role in the occurrence of *M.aeruginosa* in the aquatic system. The N/P ratios in the estuary and the plume were <16:1, indicating N as a limiting factor. A key issue in eutrophication science is the potential for N-fixing cyanobacteria to compensate for any deficiency in biologically available N, principally during the dry period. The high-temperature, nutrient-rich and polluted waters with little oxygen contributed to the abundance and bloom formation of *M. aeruginosa.* The AOU positive values (average: +2.7 and +2.1 ml/L, for the wet and dry periods, respectively) indicate high respiration rates, and the values reported indicate that the model system has high rates of respiration for the organic matter (production - respiration) and permanent estuarine denitrification.

Keywords: cyanobacteria, algal blooms, nutrients, tropical estuary, Brazil.

Introduction

Eutrophication is the process of adding nutrients to recipient bodies and the effects of this addition. Therefore, it is a phenomenon associated with the nutritive enrichment of these bodies by substances, mainly nitrogenous and phosphorus compounds, that are organic and inorganic (MOLICA and AZEVEDO, 2009). The phytoplankton first responds to these changes in the water body, and one of the main consequences of this response is the formation of blooms.

Cyanobacteria can become dominant in a phytoplankton community in lakes, rivers and reservoirs affected by these conditions and may form these blooms (CARMICHAEL, 1992; TUNDISI, 2003). They are especially influenced by factors such as temperature increases, nutrient decreases and increases in water column stability, favoring the formation of blooms (OBERHOLSTER et al., 2004). Algal blooms are phenomena that are likely to occur in natural aquatic systems, and they are sometimes due to the direct or indirect intervention of man (TORGAN, 1989).

Global warming is one of the intensifiers of the occurrence of these blooms due to the increase in the average temperature of aquatic ecosystems, especially in temperate climates, promoting longer periods and thermal stratification, which favors cyanobacteria (PAERL and HUISMAN, 2008; PAERL and PAUL, 2012). In Brazil, however, phytoplankton development periods vary by region. In the northern, north-eastern and central-western regions, they are affected by longer seasonal periods (rainy and dry periods), which regulate the nutrient intake, considering the relative constancy of water temperature and light intensity (ESTEVES, 1998).

According to Meirelles (2006), climatic factors that favor the emergence of blooms are high temperatures and environments without rain. The population of cyanobacteria may appear to be dense when dispersed in the water column; however, when atmospheric conditions are favorable, the cells concentrate on the surface of the water in a few hours. These can then be drawn to the edges of the water body by wind action and generate a higher concentration of cells. The decomposition of enormous amounts of biomass accumulated by these microorganisms leads to the deoxygenation of the water, causing damages in the whole ecosystem.

According to Lourenço and Marques Júnior (2002), in addition to staining, blooms can cause the mass death of marine organisms, whether related to the total consumption of dissolved oxygen in the water column or to the fact that some algae are toxin producers. A striking fact in relation to cyanobacteria is that almost one-third of their approximately 150 genera are related to the production of potent toxins (APELDOORN et al., 2007).

Microcystis is composed of cyanobacteria that potentially form large blooms and possess gaseous vacuoles that give them the ability to disperse rapidly in the water column. The consequences of this state are a reduction in the dissolved oxygen of the water due to the increase in the metabolic activity of the aerobic bacteria responsible for the decomposition of the organic matter and the production of toxins by some species of cyanobacteria (SIVONEN and JONES, 1999). *M. aeruginosa* is generally associated with toxicity problems in water, and its occurrence is indicated at several localities in south and south-eastern Brazil (YUNES et al., 1996; TAKENAKA, 2007). Blooms of this species produce toxins and have been implicated in themass mortality of aquatic animals and the destabilization of food webs (OBERHOLSTER et al., 2004). The Jaboatão River estuary represents a very vulnerable area to the degradation provoked by the increase of urban pressure, real estate and pollution caused by domestic wastes and industrial effluents. The present work has the objective of evaluating the occurrence and the distribution of flowering of the *Microcystis aeruginosa* cyanobacteria in the estuary of the Jaboatão River and its plume.

Materials and Methods

Study area

The Jaboatão river basin belongs to the group of small coastal rivers (GL-2), located in the southern forest of Pernambuco, draining areas of cities of the Metropolitan Region of Recife and contributing significantly to the water supply of the region (MOREIRA, 2007). Jaboatão River constitutes the most important hydrographic system, with the Duas Unas River as main tributary, where the same name dam is located and supplies part of the Metropolitan Region of Recife.

With an approximate extension of 72 km, the drainage of the basin of the Jaboatão river is quite dense, with ramifications, characteristic of the alluvial plain. Outstanding in this region is the Olho D'Água lagoon and the wetlands surrounding it (www.apac.pe.gov.br).

The climate is hot and humid and rainfall regime is subdivided into dry season

(Sep-Feb) and rainy season (Mar-Aug). The estuary extends for approximately 14 km^2, with an average depth of 2.6 m (NORIEGA and ARAUJO, 2011).

The shortage of sanitation in the vicinity of the Jaboatão river basin is the main reason for the existence of numerous pollution points in the area, adding to it the discharge of untreated industrial effluents, the lack of solid waste management and the use of pesticides and chemical fertilizers (MOREIRA, 2007).

Organic matter pollution by the sugar-cane agroindustry substantially increases during the harvest and milling season, which is from September to February. CPRH (2003) reported a high biochemical oxygen demand (BOD) of 69.6 mg/L in the harvest periods (Jaboatão River).

Sampling and analysis

For this study, the estuarine region was divided into 2 segments (estuary and plume) based on the longitudinal saline gradient classification proposed by (Mc Lusky, 1993). Seven campaigns were carried out at low tide, in longitudinal profiles in the estuary and pen, with four seasons in each, during the rainy (May 2010, July 2010, May 2011 and July 2011) and the dry seasons (November 2010, February 2011 and September 2011) (Figure 1).

The samples for the phytoplankton study were collected with Niskin oceanographic bottles, fixed with a Lugol solution andanalyzed according to the sedimentation method of Utermohl (EDLER, 1979; FERRARIO et al. 1995). The abiotic and Apparent Oxygen Utilization (AOU) data used was those described by Silva et al. (2017) to the same location.

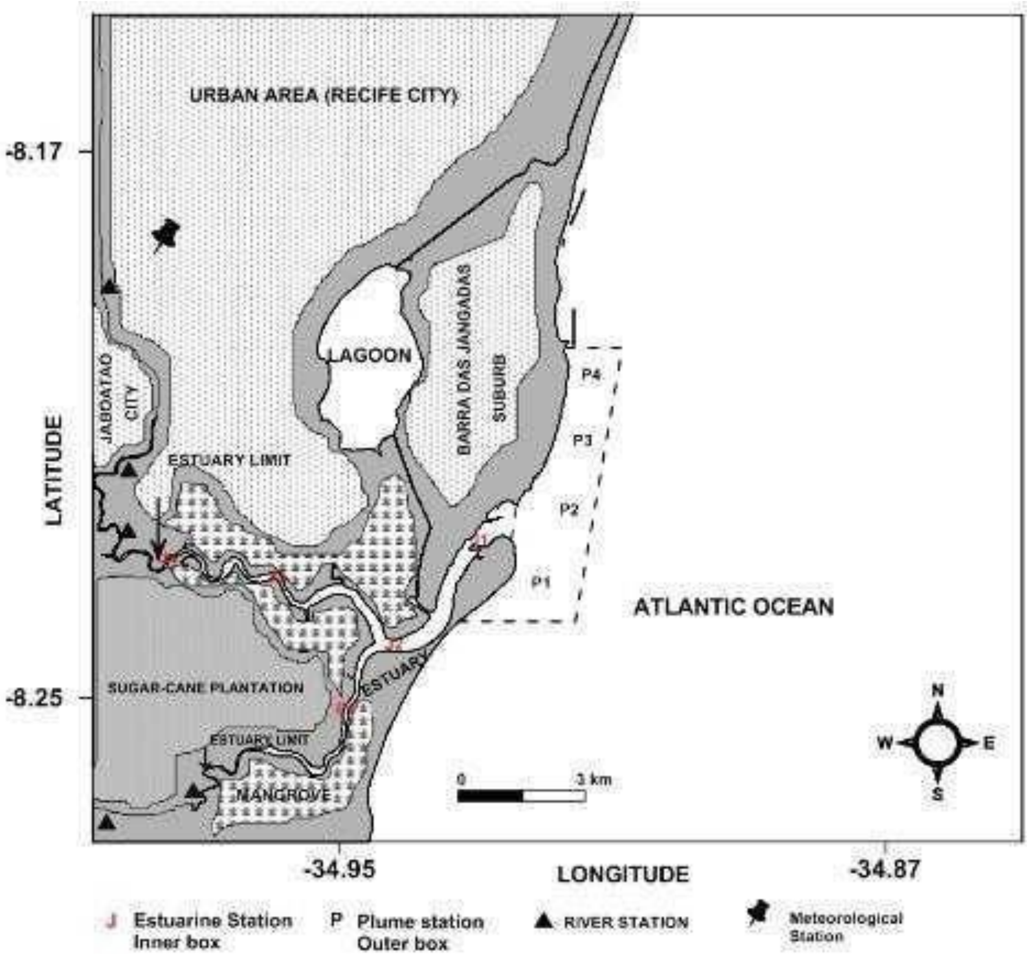

Figure 1. Sampling stations located in the estuary and plume of the Jaboatão River (northeastern Brazil). The targeted region indicates the plume's box boundary.

Meteorological data

The rainfall data were obtained through the website of the Pernambuco State Agency for Water and Climate (APAC) and the National Institute of Meteorology (INMET).

Nitrogen fixation / denitrification Model

The “Land Ocean Interactions in the Coastal Zone (LOICZ) Core Project”, that was established in 1993, is dedicated to understand the role of coastal sub- systems in the functioning of the world oceans, and includes the role of the coastal zones and cycles of carbon, nitrogen and phosphorus (GORDON et al. 1996). To use LOICZ model is not required an extensive datasets, being suitable for regions where datas of water quality are, such as the Brazilian Northeast. Even so, is considered a robust model is using a widely applicable, uniform methodology to provide information on the CNP fluxes in estuaries.

The mass balance of dissolved inorganic phosphorus (DIP) and nitrogen (DIN), allows estimates of rates of biological transformations and ecosystem processes, such as the net ecosystem metabolic (NEM) – i.e., the difference between primary production and community respiration – and the net nitrogen budget, assumed to depend on the difference between the nitrogen fixation and denitrification rates. The procedures of this modeling can be found in Gordon et al. (1996).

Statistical analyses

The Principal Components analysis (PCA) was based on the hydrological parameters and the M. aeruginosa cell density, applying the Pearson’s moment- to-product correlation coefficient, with the self-value of the main components and the auto-vector being extracted. For the tests, the program PRIMER 6R (Plymouth Routines in Multivariate Ecological Research) was used.

Results

Rainfall, Physical and Chemical Factors

Total monthly rainfall ranged from 32 mm (Nov 2010) to 639 mm (May 2011), following the historical trend for the region (Figure 2a). The salinity showed no significant difference between the rainy and dry periods, but it varied significantly between the two study regions (estuary and plume) (Figure 2b, Table 1).

Temperature showed significant differences between wet and dry periods, however, no significant differences between the estuarine and plume regions (Figure 2c, Table 1). Table 1 presents the climatic, physical and chemical parameters evaluated by Silva et al. (2017) for the same place and period of study.

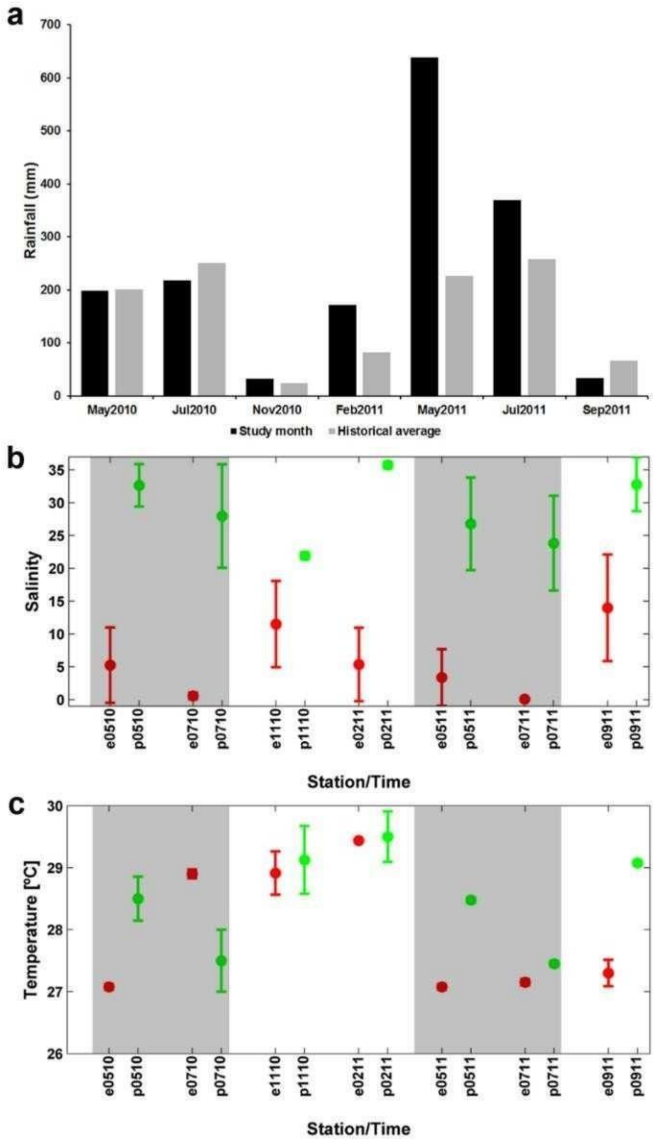

Figure 2. Rainfall (a) (study period and historical average); salinity (b); surface temperature (°C) in the estuary and plume of the Jaboatão River. The gray region indicates the wet period. e= estuary, p=plume. The 4 digits in the axis of the abscissa indicate: month and year, respectively.

Table 1. Statistical *t*-test for the categories. The means with significant differences are in bold (α= 0.05). The average and standard deviation values are between brackets.

Category/Parameters	Wet period	Dry period	P valor	Estuary	Plume	P valor
Secchi disk (m)	(1.1±1.2)	(1.4±1.1)	0.37	**(0.5±0.2)**	**(2.2±1.1)**	**0.0001**
Temperature (˚C)	**(27.7±0.7)**	**(28.8±0.8)**	**0.0001**	(28.0±1.0)	(28.4±0.8)	0.046
Salinity (psu)	(14.5±14)	(19.0±12.2)	0.24	**(5.7±7.2)**	**(27.7±7.7)**	**0.0001**
DO (ml/L)	(2.8±1.6)	(3.2±1.7)	0.45	**(1.6±1.1)**	**(4.4±0.3)**	**0.0001**
pH	(7.7±0.7)	(7.8±0.6)	0.83	**(7.2±0.4)**	**(8.2±0.3)**	**0.0001**
Ammonia (µmol/L)	(1.9±2.8)	(1.0±1.3)	0.12	**(2.7±2.8)**	**(0.2±0.3)**	**0.0001**
Nitrite (µmol/L)	(0.6±0.6)	(0.8±1.1)	0.36	**(1.0±1.0)**	**(0.2±0.3)**	**0.0001**
Nitrate (µmol/L)	(5.4±4.1)	(6.0±8.5)	0.73	**(8.8±7.2)**	**(2.4±2.0)**	**0.0001**
Phosphate (µmol/L)	(1.8±2.0)	(1.5±2.0)	0.57	**(2.9±2.1)**	**(0.4±0.3)**	**0.0001**
Silicate (µmol/L)	(63.0±53.0)	(42.1±45.0)	0.14	**(81.1±52.0)**	**(26.0±30.0)**	**0.0001**
Cyanophyta (cell/L)	**(786.0±800.0)**	**(270.0±380.0).**	**0.006**	626.0±617.0)	(514.0±780.0	0.56
M. aeruginosa (cell/L)	**(764.0±810.0)**	**(259.0±360.0).**	**0.008**	(602.0±609.0)	(502.0±790.0)	0.60
Bacillariophyta (cell/L)	**(15.0±16.0)**	**(65.0±70.0)**	**0.0002**	(44.0±66.0)	(27.0±33.0)	0.24
Chlorophyta (cell/L)	(0.2±0.9)	(1.7±7.3)	0.25	(1.6±6.6)	(0.1±0.3)	0.24
Rainfall (mm)	**(356.0±179.0)**	**(75.0±65.0)**	**0.0001**	-	-	-

Biological Factors: Phytoplankton

Considering the structure of the phytoplankton community recorded, the phylum Bacillariophyta represented the majority (55%), with Cyanobacteria representing 11%. There was no significant differences between the estuarine (*t*-test; *p*: 0.24; α: 0.05) and plume regions (*t*-test; *p*: 0.56; α: 0.05) (Figure 3a, b). However, considering total cell count cyanophyte group was higher in both studied regions, making93% of the total cells in the estuary and 97% in the plume. Bacillariophyta does not reach 10% of the total in both regions (Figure 3c, d).

In the estuary, only two species were dominant: the cyanophyta *M. aeruginosa* Kützing and the bacillariophyta *Cyclotella meneghiniana* Kützing, with the first occurring in all seasons and months in the estuary (Figure 4a). In Figure 4a and 4b, we observed these two species alternating dominance in the system, especially in the plume region during the dry period.

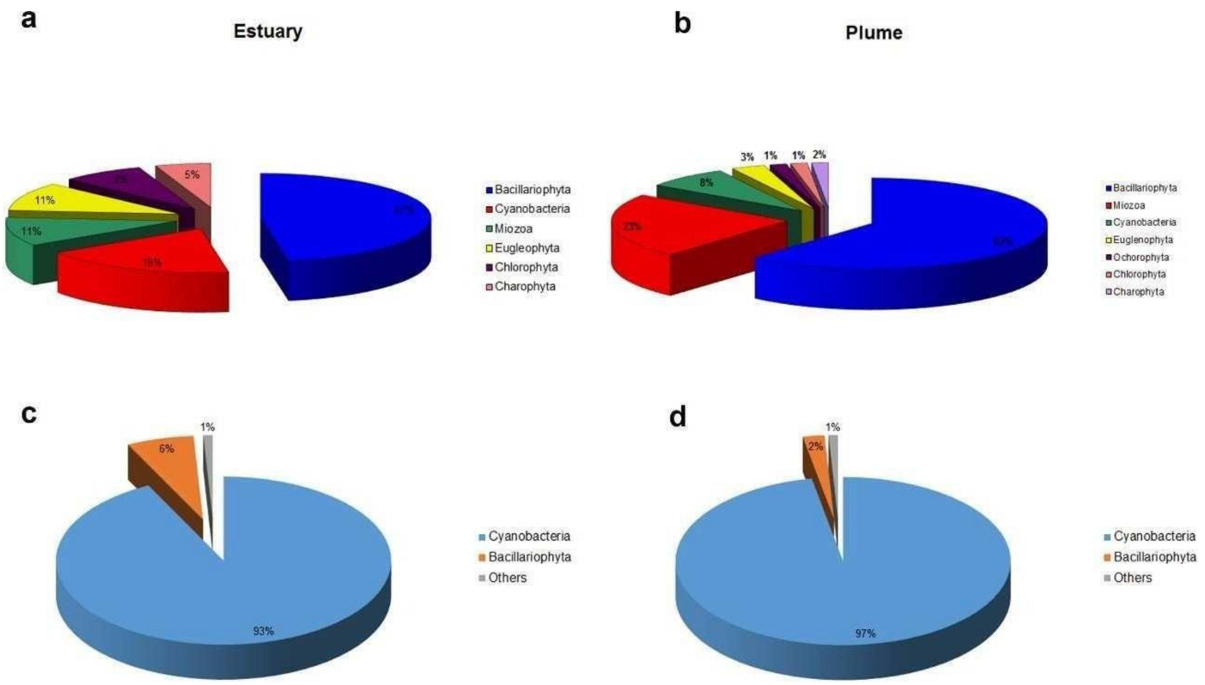

Figure 3. Percentage of occurrence of the phyla (a-b) and total cells (c-d) in each studied area.

M. aeruginosa, *Planktothrix agardhii* (Gomont) Anagnostidis & Komarek, *Lepocylindrus danicus* (O. F. Muller) Marin & Melkonian, *Protoperidinium bispin*um (Schiller) Balech, *Coscinodiscus centralis* Ehrenberg, *Cyclotella meneghiniana* and *Paralia sulcata* (Ehrenberg) Cleve dominated the plume (Figure 4b). It is possible to observe M. aeruginosa and C. meneghiniana alternating dominance in the system, with this more evident in the plume (Figure 4a, b).

Also, *M. aeruginosa* represented on average 95% of the total cyanobacteria in the estuary, while in the plume, this percentage reached 65%. This species was responsible for the predominance of cyanobacteria, both in the estuary and in the plume (Figure 5).

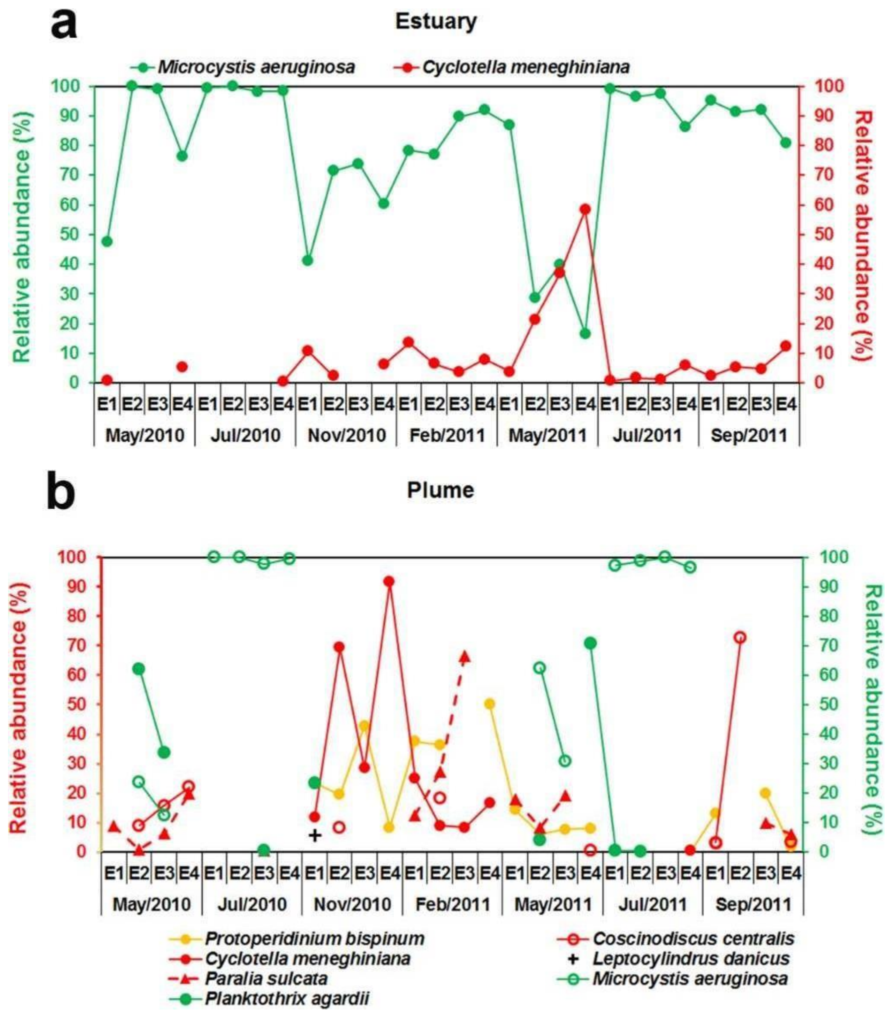

Figure 4. Relative abundance (%) of the most representative species in the studied areas (SILVA et al., (2017).

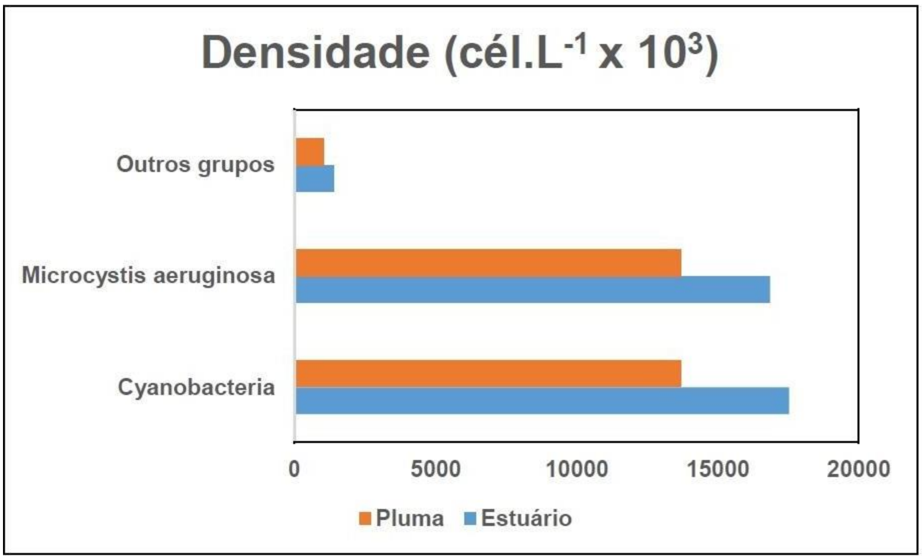

Figure 5. Total density of *Microcystis aeruginosa* in the studied areas, in comparison with total density of cyanobacteria and the other groups.

In both regions, it is possible to observe the influence of *M. aeruginosa* on the local diversity. Where there was dominance, the specific diversity was considered from very low to low (Figure 6 a, b).

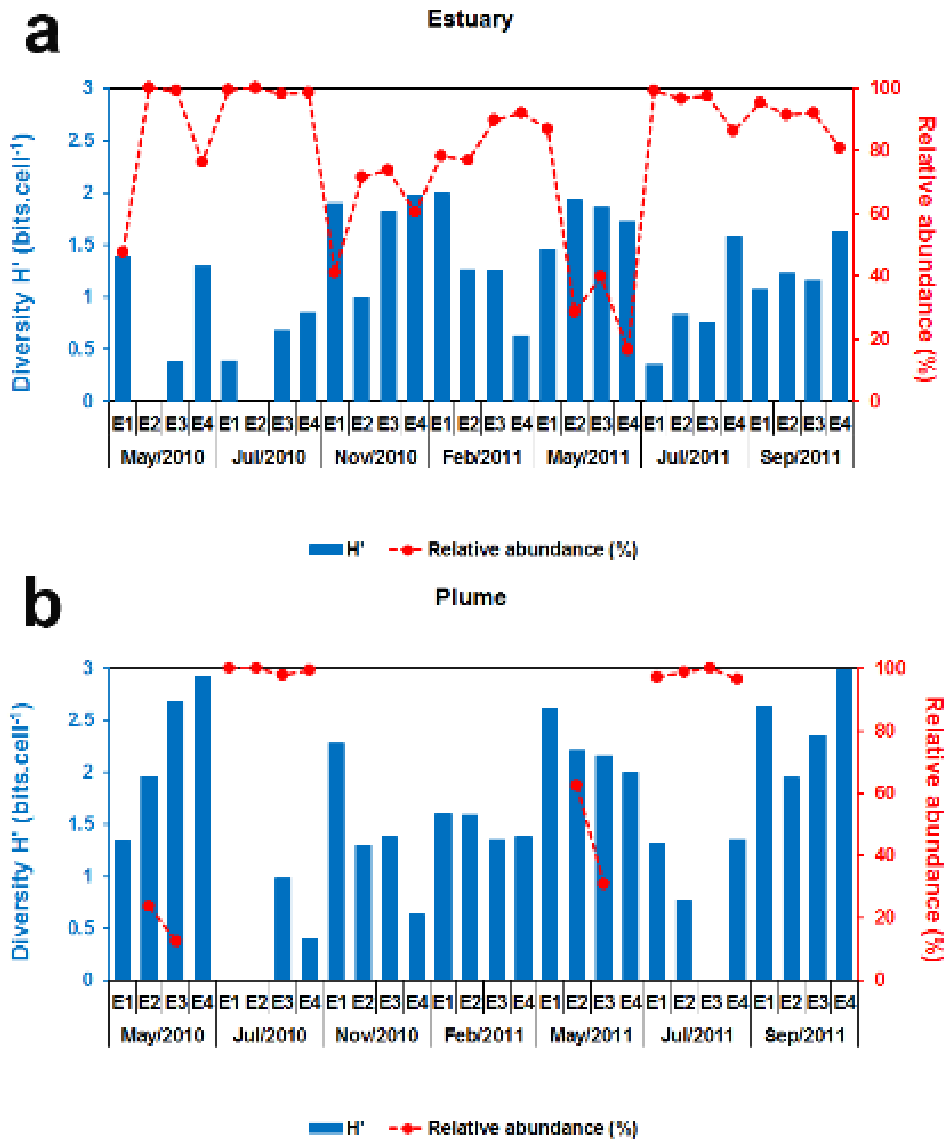

Figure 6. Relative abundance and diversity index of *M. aeruginosa* in the studied areas.

Discussion

Physical and Chemical Factors

Changes in the composition and structure of the phytoplankton community can cause profound changes in all trophic levels, considering the dynamic of these organisms, their high reproduction rates and rapid response to changes in environmental conditions. This importance is even more relevant when there are processes of eutrophication of aquatic ecosystems, through massive blooms and quantitative changes in their populations (VALIELA, 1995; ESTEVES, 1998; RICKLEFS, 2003).

The lack of planning in the use and occupation of the soil in the Jaboatão river basin has caused a degradation in the environmental quality, with one of the main consequences the degradation of the quality of the superficial water resources, characterized by the discharge of urban and industrial wastewaters and solid residues in their water bodies, and run-off water from agro-industrial areas (GOMES et al., 2003).

In addition, another important contribution of organic load to the estuarine system is the presence of Lagoon Olho d'água, with an area of 3.7 km^2 (Figure 1), a population of 35,000 and a low environmental sanitation coverage. According to CPRH (2011), the remaining organic load for the Jaboatão River was 20.58 t BOD / day, while the organic load (BOD) calculated for the urban area around the lagoon was 756 kg / BOD / day. This value represents approximately 4% of the total generated by the urban area surrounding the estuary system of the Jaboatão River.

DO values obtained for the Jaboatão River estuary showed lower values than those recommended by Brazilian legislation (3.5 ml/L). During the wet period observed, no sample in the estuarine region reached the required minimum value (3.5 ml/L). Throughout the year, 7% of the samples reached this limit, which shows low water quality and a change in the processes of oxidation, decomposition and cycling of organic matter in the aquatic system (Figure 7).

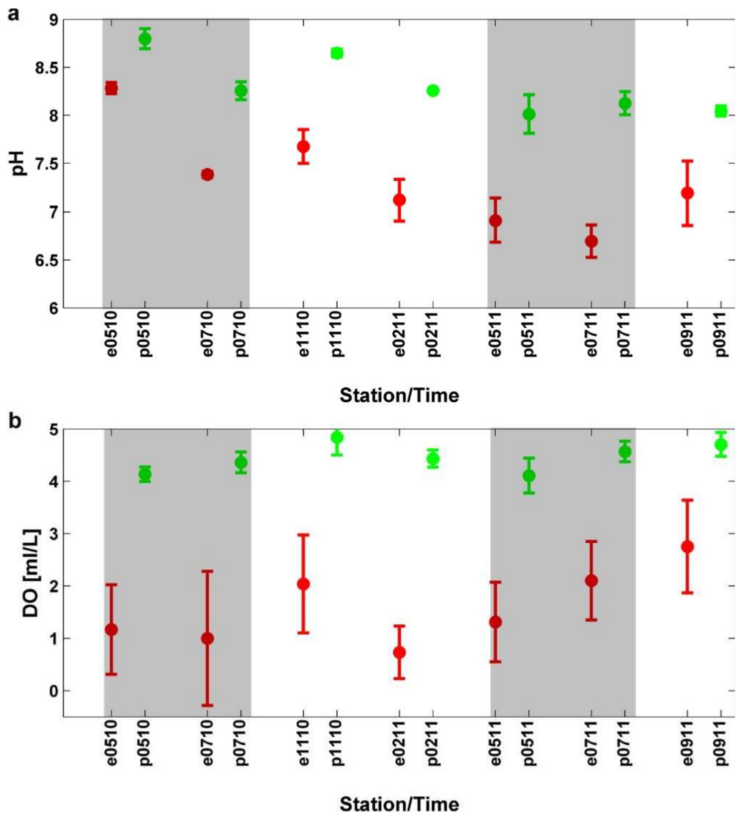

Figure 7. Surface pH (a) and DO (b) in the estuary (red) and plume (green) of the Jaboatão River. The gray region indicates the wet period. e= estuary, p=plume. The 4 digits in the axis of the abscissa indicate: month and year, respectively.

Analyzing data from nitrogen compounds from 2000 to 2011 obtained from the monitoring station of the CPRH near the estuary showes that during this period there was an increase in the concentrations of nitrogen compounds (mainly NH_4^+) entering the estuary system of the Jaboatão River during the dry period. This positive trend for the dry period can be observed in Figure 8a. The PO_4^- did not show a trend according to the data obtained for the dry and rainy periods between 2001 and 2011.

In addition, we use demographic data (population density) obtained from IBGE (2000-2011) for the main city (Jaboatão dos Guararapes) adjacent to the aquatic system studied. We observed that the population growth rate of this municipality was 11%, and the population density grew from 2,249 inhab/km^2 in 2000 to 2,513 inhab/ km^2 in 2011. Population growth is the main direct input of nitrogenous and phosphate compounds to the adjacent aquatic system.

During the dry season, the river discharge also decreases. According to Noriega and Araujo (2011), 75% of the annual rainfall occurs during the wet season in this region, and the residence time in the dry period can reach 13 days in the estuarine system.

According to Smith (2003) and Dodds et al. (2006), in some rivers and streams with reduced water replacement times, phytoplankton blooms can become problematic, with cyanobacterial blooms more likely in excess-nutrient conditions.

These factors directly affect the water quality of this system, increasing the nutrient load and causing changes in the biota of the site. These observations showed that the anthropic factor added to climatic factors can generate important changes in the phytoplankton biomass of the estuarine system and may be mainly responsible for the change in the dominant species of this aquatic system.

M. aeruginosa predominated at most estuarine stations, with blooms in July 2010 and September 2011. In the plume region its occurrence was punctual, with blooms in July 2010 and 2011.

It was observed an alternating dominance between *M. aeruginosa* and *Cyclotella meneghiniana* in the plume region during the dry period. During the month of greatest density for *Cyclotella meneghiniana* (November of 2010), NO_3^- was the element available in the water column. Other elements such as NH_4^+ and PO_4^- had low concentrations (Figure 8).

This alternation entails changes in the relative abundance of species in a community, in a typical sequence. These organisms respond to a rapid increase in the availability of limiting nutrients by increasing their growth rate and changing their composition favoring the fastest growing species (r-strategists). With the depletion of nutrients, the relative abundance of species changes again, favoring species with adaptations for nutrient scarcity (k-strategists) (LEWIS Jr., 1978).

In this case, if it is possible to identify the direction of planktonic succession, then qualitative changes through increase or decrease of nutrients concentration can be predicted. However, environmental disturbances can lead to a complete or partial initial return, with high levels of nutrients, causing abrupt change in community composition. This constitutes a reverse direction, a fact common to estuarine areas.

As in highly dynamic systems species adaptability is an important factor, different specific sets of the community reach high rates of growth at specific moments. Thus, the temporal distribution patterns would not be a reflection of the phytoplankton community as a whole, but of certain populations that respond to fluctuations of certain environmental factors (Santander et al., 2003), that is the case of *M. aeruginosa*.

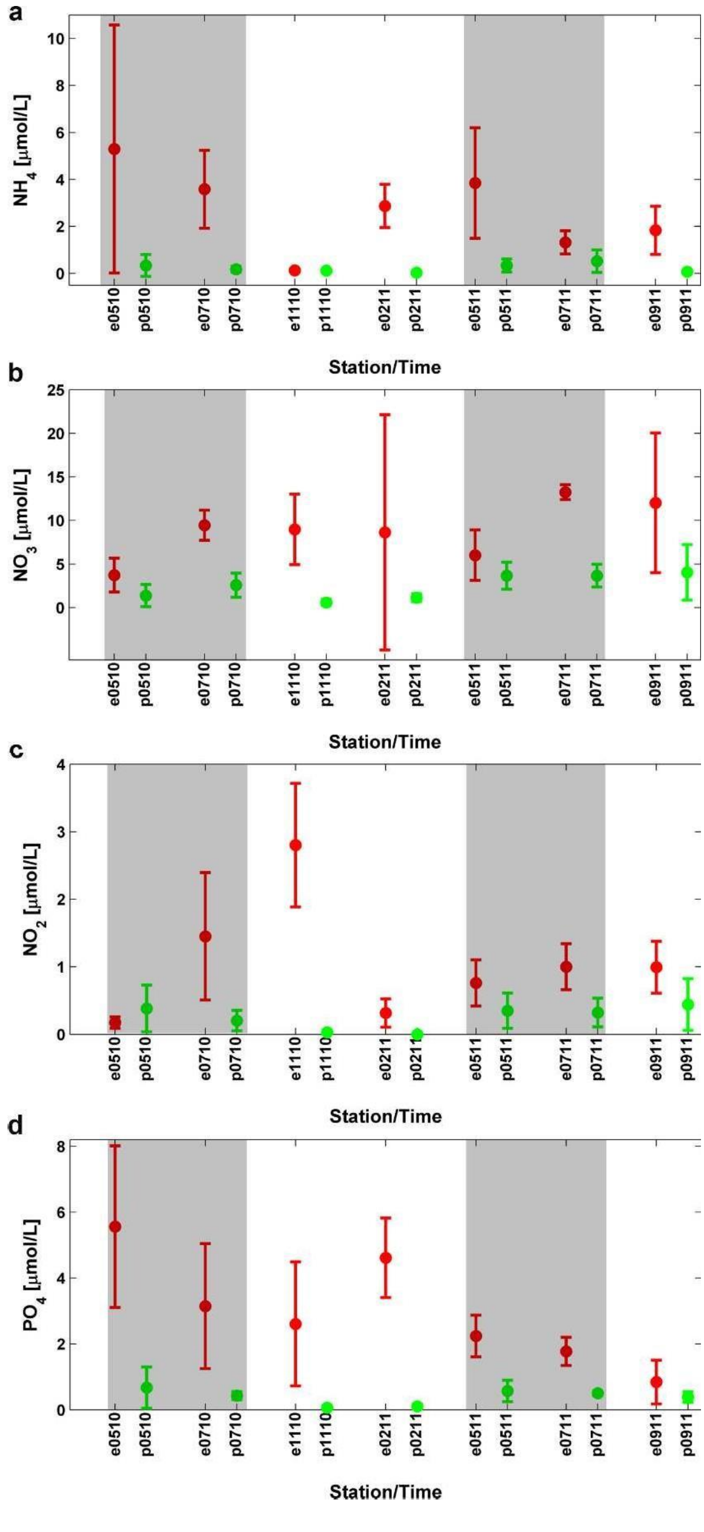

Figure 8. Concentrations of the dissolved nutrients in the two studied areas: ammonia (a); nitrate (b); nitrite (c) and phosphate (d). The gray region indicates the wet period. e= estuary (red), p=plume (green). The 4 digits in the axis of the abscissa indicate: month and year, respectively.

There is no consensus on an operational definition of flowering, and it is agreed that blooms cannot be characterized by a single universal criterion of cell density or biomass. The biomass value that characterizes flowering differs from species to species; it is only possible to determine if the population of a species is flowering or not when its relative contribution is evaluated within the totality of the community (CETESB, 2007), which in the case of the present study, can be understood as the direct influence on local diversity and species richness.

Omori and Ikeda (1984) report that specific diversity indicates the degree of complexity of community structure, decreasing with the dominance of one or a few species, with individuals of rare species replaced by individuals of more common species, or when some species reproduce more quickly.

High density of phytoplanktonic organisms against low species richness suggests that the habitat received a polluting load, favoring organisms tolerant of this condition (ESTEVES, 1998; BLACK et al., 2011).This was evidenced both in plume and estuary, where the occurrence of other species was limited by *M. aeruginosa.*

Other researches in the same region (LACERDA et al., 2004; BRANCO, 2007; BRANCO et al. (2002) point the diatoms *Bellerochea mallleus*, *Coscinodiscus centralis* and *Cyclotella meneghiniana* as the key species for that ecosystem. In the present study, *M. aeruginosa* is considered to be, given its dominance, frequency and high cell density.

AOU (Apparent Oxygen Utilization) and Nitrogen fixation – Denitrification rates

AOU was used to obtain the apparent respiration rate in the estuarine system, where DO is consumed and $CO2$ is released into the water column. The increase in algal blooms can produce a reduction in the DO of the water due to the increase in the metabolic activity of the aerobic bacteria responsible for the decomposition of the organic matter and the production of toxins by some species of cyanobacteria. AOU indicates the apparent variations between production and respiration. Positive values were observed and were indicative of high respiration rates (average: +2.7 and +2.1 ml/L, for both climatic periods, respectively) (Figure 9b).

According to Smith and Hollibaugh (1997), the term “trophic status” describes the net balance (net respiration or net synthesis) of organic carbon in an ecosystem. The results of these budgets and the use of stoichiometric tools provide estimates of processes such as net production / respiration and nitrogen fixation / denitrification (Gordon et al. 1996). We used these modeling techniques to estimate the balance of the boxes for the Jaboatão River (river), estuary (inner box), plume (outer box) and ocean through the data obtained in this study and the monitoring database of the CPRH for the Jaboatão River in the period of 2010-2011 (Figure 9c).

Nitrogen fixation and denitrification are important processes in coastal systems. Again, because the major source of the reacting matter is unclear, two N/P ratios are used. The decomposing material has a mean C/P of 106/1, and an N/P of 16/1 (outer box), which is near the N/P value of 11/1 (inner box) quoted for mangrove litter (Gordon et al. 1996).

The results are shown in Figure 8c and indicate spatial and temporal variations. During the dry period, the balance between nitrogen fixation and denitrification was negative in both boxes (-2.5 mmoles N m^{-2} d^{-1} and -1.1 mmoles N m^{-2} d^{-1} in the inner and outer boxes, respectively).

During rainy season, the balance ranged between -2.3 mmoles N m^{-2} d^{-1} for the inner box and +4.4 mmoles N m^{-2} d^{-1} for the plume region. The release rate of N2 during the dry period was constant (denitrification) throughout the study region. During this period, the nitrogen compound inputs were approximately 1.5 times (130/88 mmoles DIN m^{-3}, see Table 2) that of the contribution via rivers during the wet period.

Camacho and Smith (2000) estimated that the differences between N fixation and denitrification are generally close to zero (with a dominance of denitrification) and that values above 5 moles m^{-2} yr^{-1} are rare. Our results generally suggest denitrification (Figure 9c).

The nitrogen fixation process is ordinarily slow in marine systems (< 1 mmoles m^{-2} d^{-1}), according to Swaney and Smith (2003), although they suggested that some coral reef, mangrove and tropical seagrass communities may exhibit rates >20 times this upper limit. As a general rule, few systems exhibit nitrogen fixation faster than this rate.

The value reported for the Jaboatão plume in the wet period (outer box) was moderate, submitting to this limit and indicating that the adjacent mangrove forest did accelerate nitrogen fixation in the plume. The apparently high denitrification during the inner boxes (-2.5 and -2.3 mmoles N m^{-2} d^{-1}) indicates high benthic respiration (driven by high loads with labile organic matter such as sewage). Typical rates in benthic systems are approximately 0.5 - 2 mmoles N m^{-2} d^{-1}. Systems with high benthic respiration may have denitrification rates >10 mmoles m^{-2} d^{-1} (Swaney and Smith 2003).

Table 2. Input data for the seasonal variation budgets of the Jaboatão River estuary. The bold values correspond to the outer box

Variable	Mean dry season Inner Box	Mean rainy season Inner Box	Mean dry season Outer Box	Mean rainy season Outer Box
Runoff (VQ) (10^3 m^3 d^{-1})	630	1365	-	-
Groundwater (VG) (10^3 $m^3 d^{-1}$)	23	49	-	-
Precipitation (VP) (10^3 m^3 d^{-1})	35	120	35	120
Evaporation (VE) (10^3 m^3 d^{-1})	-65	-56	-65	-56
River DIN (mmol m^3)	130	88	-	-
River DIP (mmol m^3)	5.5	8.2	-	-
River Salinity	0.13	0.12	-	-
System DIN (mmol m^3)	12.1	12.4	1.8	3.5
System DIP (mmol m^3)	2.7	3.1	0.2	0.5
System Salinity	10.3	2.3	29.3	26.7
Ocean DIN (mmol m^3)	**1.8**	**3.5**	0.6	0.8
Ocean DIP (mmol m^3)	**0.2**	**0.5**	0.02	0.07
Ocean Salinity	**29.3**	**29.7**	35.6	35.3

Other tropical estuaries, such as the Piauí River estuary (Brazil), presented a denitrification rate of -0.13 mmoles N m^{-2} d^{-1}, while the Sergipe River estuary (Brazil) appears to fix nitrogen at 0.1 mmoles N m^{-2} d^{-1} (Souza 2000). During a recent study in the Jaboatão estuary, Noriega and Araujo (2011) estimated -5 mmoles N m^{-2} d^{-1}as the annual mean for the system. During wet and dry periods, they reported -7 and -2 mmoles N m^{-2} d^{-1}, respectively. These values are close to those obtained in our study. The values reported here indicate that the model system has high rates of respiration for organic matter (production - respiration) and permanent estuarine denitrification.

According to Kuwate and Miyazaki (2000), aquatic systems where

Microcystis usually forms blooms have low water changes (high residence time) and a high influx of nutrients. According to Noriega and Araujo (2011), higher residence times were observed during the dry season (>13 days), while during the rainy months, they did not exceed 9 days.

We also considered the N/P ratio as a factor that plays an important role in the occurrence of *M. aeruginosa* in the aquatic system. The N/P ratios in the estuary and the plume were <16:1, indicating N as a limiting factor. According to Dodds and Smith (2016), a key issue in eutrophication science is the potential for N-fixing cyanobacteria to compensate for any deficiency in biologically available N.

Stelzer and Lamberti (2001) performed an experimental study in which nutrients were manipulated for a month and observed that low N:P supply ratios did not lead to a shift to cyanobacterial dominance. However, Scott and Marcarelli (2012) considered grazing and scouring to be more important determinants of benthic cyanobacterial dominance in streams than nutrient conditions.

Moreover, because streams are dominated by benthic habitats, the potential for denitrification is high (Mulholland et al. 2008), perhaps leading to greater proportional N losses in the N budgets of streams and shallow estuaries (Jaboatão estuary). The *Microcystis* species also requires high light irradiation (Havens et al., 1998). In temperate reservoirs, the *M. aeruginosa* species appears in the water column at the end of spring and forms blooms during the summer. After this excessive growth, it sinks and reaches the sediment in the autumn (Latour and Giraudet 2004). On the other hand, *M. aeruginosa* can be considered a species adapted to store phosphorus, with a high capacity to absorb inorganic phosphorus (Olsen 1989).

The concentrations of phosphate observed in this study were considered high and outside the limit of the environmental resolution (0.1 mg/L~1.6 mol/L) in both climatic periods. Finally, we suggest that the system varies between autotrophy (outer box) and heterotrophy (inner box) during the year due to the rainfall regime, human activities in the basin (density population and sugarcane plantations), and associated DIP and DIN riverine loads.

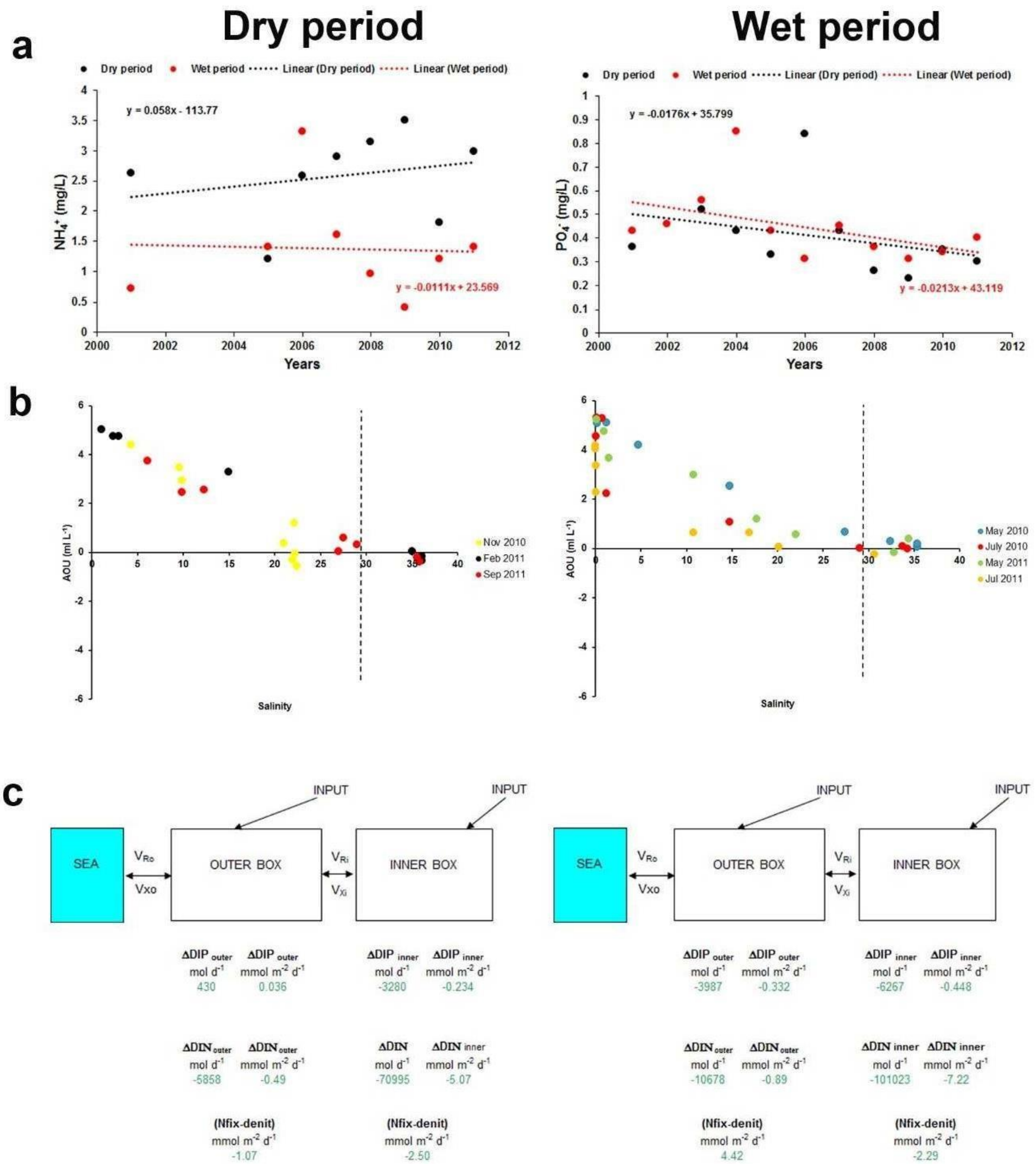

Figure 9. Tendency of nitrogenous and phosphate compounds in the Jaboatão River between 2001 and 2011 (9a); AOU (9b) (the segmented line indicates the division between the estuary and plume); nitrogen fixation process modeling system (9c).

Principal Component Analysis (PCA)

We used the estuarine, plume and river observations of the main nitrogenous (NH_4^+) and PO_4^-. Additionally, we included observations of the salinity, DO and density of *M. aeruginosa*. The PCA showed that ~82% of the observed variability was explained by components F1 and F2. In the first component (F1), NH_4^+, PO_4^- and *M.*

aeruginosa showed a positive correlation, whereas these elements showed a negative correlation with DO and salinity. Figure 10 (biplot) shows a direct association between the nutrient observations (NH_4^+ and PO_4^-) from the river and estuary and *M. aeruginosa* (gray region). The observations obtained for the plume region showed an association with DO values and salinity.

The fluvial influence of NH_4^+ and PO_4^- correlates directly with this species of Cyanobacteria. According to this statistical analysis and trend analysis (Figure 8a), we can conclude that the increasing nutrient load (mainly NH_4^+) for the estuarine region offers a favorable substrate for these cyanobacteria, affecting the spatial and temporal biodiversity of the aquatic system.

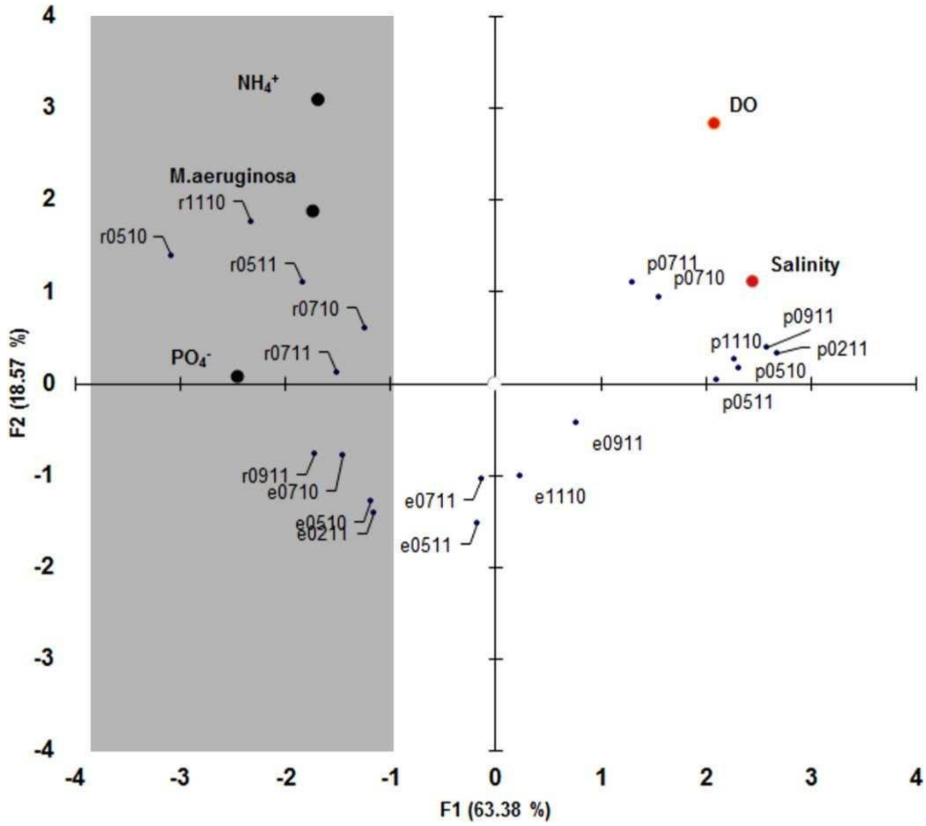

Figure 10. PCA of the chemical, physical and biological parameters. The black circles indicate the nutrients and *M. aeruginosa*; the red circles indicate the salinity and DO. The gray region indicates the positive correlation in Factor 1 between *M. aeruginosa* and the nutrients (NH_4^+ and PO_4^-). The codes of the observations indicate (r) = river; (e) = estuary and (p) = plume. The number labels for the observations indicate the month and year of the sampling data.

Conclusions

It is possible to observe, both in the estuarine and plume regions, the influence of *M. aeruginosa* on the local diversity. *M. aeruginosa* represented on average 95% of the total cyanobacteria in the estuary, while in the plume, this percentage reached 65%. The species *M. aeruginosa* was responsible for the predominance of cyanobacteria, both in the estuary and in the plume. The DO values obtained, which are lower than those recommended by Brazilian legislation (3.5 ml/L), show low water quality and a change in the processes of oxidation, decomposition and cycling of organic matter in the aquatic system.

The high values of the nitrogen compounds and phosphate evidenced the high degree and the strong influence of the anthropic action in that environment. The model system shows high rates of respiration in the organic matter (production - respiration) and a permanent estuarine denitrification.

The concentrations of phosphate observed in this study were considered high and outside the limit of the environmental resolution, suggesting that the system varies between autotrophy and heterotrophy during the year due to the rainfall regime, human activities in the basin and the associated DIP and DIN riverine loads. The N/P ratio is a factor that plays an important role in the occurrence of *M. aeruginosa* in the aquatic system. The N/P ratios in the estuary and the plume were <16:1, indicating N as a limiting factor.

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7 CONSIDERAÇÕES FINAIS

O rio Jaboatão sofre *inputs* urbanos e industriais que produzem significantes variações na qualidade do ecossistema e podem causar alterações nas populações de espécies fitoplanctônicas, muitas vezes ocasionando blooms algais, sendo possível determinar quais os grupos ou espécies fitoplanctônicas bioindicadoras da qualidade ambiental.

Considerando as concentrações de oxigênio dissolvido, o estuário do rio Jaboatao variou de zonas poluídas a de baixa saturação, o que evidencia a baixa qualidade de suas águas. A pluma permaneceu saturada a supersaturada. A mais alta concentração de nutrientes no estuário em relação à pluma está relacionada ao fato de que o estuário absorve boa parte do aporte de nutrientes.

A AOU indica uma maior taxa de respiração (produção-respiração), com consumo de OD e liberação de CO2. A tendência calculada de AOU para o rio foi negativa, enquanto a série estuarina teve uma tendência ligeiramente positiva. A modelagem também mostrou uma desnitrificação estuarina permanente. Como os fluxos são dominados por habitats bentônicos, o potencial de desnitrificação é alto (Mulholland et al., 2008), talvez levando a maiores perdas proporcionais de N nos *budgets* de córregos e estuários pouco profundos (estuário de Jaboatão).

Além de *M*. *aeruginosa*, destacou-se também a diatomácea *C. meneghniana,* espécie dominante em algumas amostras, principalmente na pluma, onde se pode observar uma dominância alternada, governada principalmente pelo fluxo de nutrientes.

A dominância de *Microcystis aeruginosa*, espécie oportunista, revelou um ambiente altamente comprometido e limitou a ocorrência de outras espécies. A diminuição da qualidade da água ao longo do tempo (1999-2011) influenciou na mudança dos principais componentes biológicos, com a substituição de espécies de diatomáceas por esta cianobactéria como representativa da área. O aumento de blooms algais pode produzir uma redução do DO da água devido ao aumento da atividade metabólica das bactérias aeróbicas responsáveis pela decomposição da matéria orgânica e acarretar a produção de toxinas.

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