BIODIVERSIDADE E INFLUÊNCIAS CLIMÁTICAS E ANTRÓPICAS NA MACROFAUNA BÊNTICA DO ENTREMARÉS DE PRAIAS ARENOSAS NA COSTA NORTE DO ESTADO DO RIO DE JANEIRO, BRASIL

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UNIVERSIDADE ESTADUAL DO NORTE FLUMINENSE DARCY RIBEIRO
CAMPOS DOS GOYTACAZES – RJ
JUNHO DE 2016

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Orientadora: Profª Drª Ilana Rosental Zalmon

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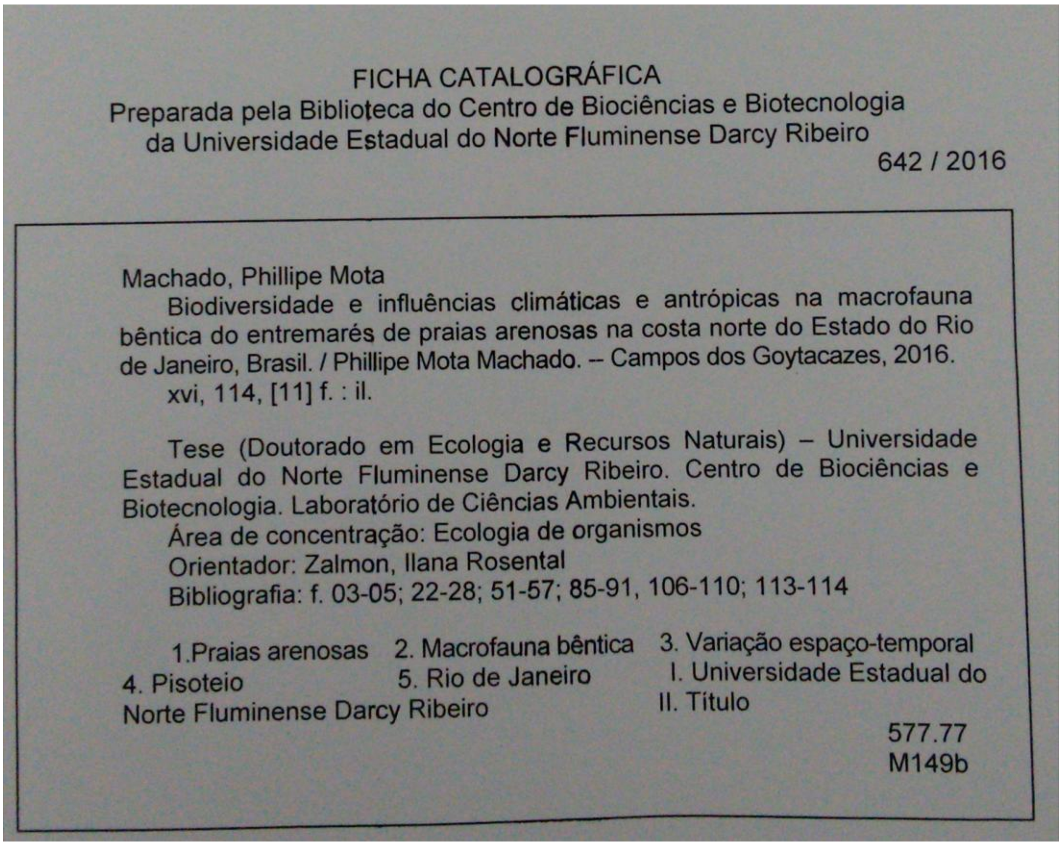

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CAMPOS DOS GOYTACAZES – RJ
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DEDICATÓRIA

Dedico aos meus pais, ao meu irmão e a minha orientadora.

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1. Introdução Geral

Praias arenosas constituem a maior parte das áreas costeiras do mundo, formando uma faixa litorânea que se estende desde a linha da costa até o limite extremo de correntes originadas pela ação das ondas e são consideradas importantes áreas de crescimento para várias espécies (McLachlan *et al.*, 1981). Sua geomorfologia resulta da ação de fatores como ventos, ondas e marés, que associados determinam a granulometria do sedimento (McLachlan & Brown, 2006). Os limites são marcados internamente pelos níveis máximos da ação de ondas, tempestades ou pelo início da ocorrência de dunas, e externamente pelo início da zona de arrebentação, onde ocorrem processos significativos de transporte de sedimentos (Hoefel, 1998).

Os primeiros estudos em morfodinâmica de praias ocorreram a partir de 1940 e determinavam a classificação dos estados praiais em função do clima de ondas, tipo de sedimento e perfil topográfico, como objetivo central descrever a variabilidade espaço-temporal do estoque sedimentar de uma praia (Veloso & Neves, 2009). Segundo suas características morfodinâmicas, as praias podem ser classificadas em dissipativas, intermediárias e reflectivas. As dissipativas apresentam areia fina, declividade suave e larga zona de surfe (Veloso *et al.*, 1997). Nessas praias, geralmente observa-se maior riqueza de espécies e estabilidade na composição da macrofauna bêntica em relação às praias reflectivas (Dexter, 1984; McLachlan *et. al.*, 1993) que, por sua vez, são caracterizadas por areia grossa, declividade abrupta, intensa ação de ondas e estreita zona de surfe (Veloso *et al.*, 1997). Já as praias intermediárias são caracterizadas por possuírem uma alta deposição do sedimento tanto na zona de surfe quanto na praia. Em eventos de alta energia, o sedimento é retirado da praia tornando-a plana e assim que as condições de energia diminuem o sedimento volta a se depositar (Short, 1999), ou seja, suas características se encontram entre os dois extremos, o dissipativo e reflectivo.

O sedimento de praias serve como habitat para diversos organismos, incluindo a macrofauna bêntica, cujos indivíduos de diferentes grupos taxonômicos ficam retidos em peneira de malha de 0,5 mm e são caracterizados principalmente por Crustacea, Polychaeta e Bivalvia (McLachlan & Brown, 2006). Esta fauna é extremamente relacionada com as características físicas e químicas do sedimento, granulometria, teor de matéria orgânica e intensidade de ondas, sendo uma ferramenta importante em estudos que visem avaliação de impactos antrópicos e climáticos (Keough & Quinn, 1991; Alves & Pezzuto, 2009).

O aumento das alterações humanas na paisagem coloca em risco a manutenção da biodiversidade e equilíbrio ecológicos de vários ecossistemas, portanto os trabalhos com enfoque no entendimento dessas influências são fundamentais para que medidas gerenciais sejam tomadas permitindo tornar as atividades humanas mais compatíveis com a manutenção dos recursos naturais (Nordstrom, 2010). Na costa norte do estado do Rio de Janeiro, a principal ação antrópica nas praias locais está relacionada ao intenso turismo no período de verão, que pode influenciar essa comunidade através do pisoteio. Além disso, ocorre um intenso tráfego de veículos tanto na faixa de vegetação, no supralitoral e mesolitoral. Segundo Jaramillo *et al.* (1996), a macrofauna bêntica é bem adaptada às variações dos perfis das praias, promovidas pela hidrodinâmica e remobilização do sedimento, mas tal comunidade é muito vulnerável às atividades humanas.

McLachlan *et al.* (2013) ressalta a importância de estudos ecológicos em praias como base para elaboração de estratégias de manejo e conservação desse ecossistema, destacando sua vulnerabilidade à crescente expansão humana, além das influências decorrentes de mudanças climáticas, como eventos extremos e aumento do nível dos mares. Portanto, é primordial a utilização de ferramentas que avaliem a curto e médio prazo de que forma efeitos antrópicos e de variações climáticas previstas, como o aumento de tempestades, frentes frias, ressacas, dentre outras, influenciam a comunidade bêntica no entremarés em praias arenosas. A carência dessas informações em praias promove uma grande vulnerabilidade na manutenção desses recursos costeiros. Dessa forma, o estudo integrado de efeitos antrópicos e de mudanças climáticas torna-se fundamental, como já sugerido por outros autores (Schlacher *et al.*, 2008; McLachlan *et al.*, 2013; Turra *et al.*, 2013).

As respostas da macrofauna bêntica oscilam naturalmente de acordo com a periodicidade cíclica das variações temporais que ocorrem ao longo do ano (Schoeman *et al.*, 2000), mas podem responder igualmente a eventos ambientais estocásticos como ressacas, tempestades, frentes frias, dentre outros (Machado *et al.*, 2016). Estudos que considerem as conseqüências desses eventos são necessários, uma vez que as previsões climáticas consideram aumento na freqüência e intensidade de eventos extremos, como ressacas (IPCC, 2013).

O presente estudo faz parte de uma rede de monitoramento de habitats bentônicos costeiros (REBENTOS), de âmbito nacional, que visa avaliar possíveis efeitos das mudanças climáticas em zonas costeiras. Este estudo foi realizado na costa Norte do estado do Rio de Janeiro, área com escassez de informações sobre comunidades bênticas de praias arenosas. Dessa forma, informações de caracterização, distribuição, variações temporais (intra e interanuais) e espaciais em pequena e média escala (intra e inter praias) dessa comunidade, assim como a avaliação como tais organismos respondem à potenciais pressões antrópicas locais (como o pisoteio no período de verão) e às variações climáticas (eventos de ressacas) são primordiais para entender seu funcionamento e respostas à impactos naturais ou humanos.

Com base no exposto, o objetivo principal desta tese foi realizar um levantamento integrado da biodiversidade bêntica da zona costeira de ambientes praiais da costa norte do Estado do Rio de Janeiro, considerando praias intermediárias e dissipativas, para determinar os padrões espaciais e sazonais e a influência de interferências antrópicas e de eventos climáticos extremos, sempre relacionado-os às características ambientais do sistema. A referida tese foi dividida em quatro artigos, sendo assim intitulados:

Capítulo 1: Determinantes ambientais da comunidade bêntica em praias arenosas: variações temporais e morfodinâmicas

Capítulo 2: Influência turística sobre a comunidade bêntica de praias arenosas

Capítulo 3: Influência de eventos de ressacas na macrofauna de praias arenosas com distintas pressões antrópicas

Capítulo 4: Efeitos de eventos extremos e urbanização na densidade populacional do caranguejo-fantasma *Ocypode quadrata*: uma estratégia de monitoramento

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Capítulo 1

Determinantes ambientais da comunidade bêntica em praias arenosas: variações temporais e morfodinâmicas

Resumo

O objetivo desse estudo foi identificar os principais determinantes que regulam a distribuição e composição da macrofauna bêntica de praias com distintas características morfodinâmicas, Grussaí (intermediária) e Manguinhos (dissipativa), na costa norte do Rio de Janeiro, Brasil. Quatro campanhas de amostragem da macrofauna do entremarés foram realizadas no período chuvoso e quatro no período seco. A riqueza de espécies foi mais elevada na praia dissipativa de Manguinhos, enquanto valores superiores de densidade e diversidade ocorreram na praia intermediária de Grussai. Esta praia, apesar de possuir maior hidrodinamismo, possui calhas longitudinais que previnem a quebra de ondas diretamente na face praial, tornando o ambiente mais estável do que praias reflectivas e, consequentemente, favorece a presença de táxons com maior mobilidade, como os crustáceos *Atlantocherstoidea brasiliensis, Emerita brasiliensis* e *Excirolana braziliensis*, principalmente nos meses de inverno. Os resultados evidenciaram variações nos indicadores de comunidade e na composição de espécies, principalmente em escalas espaciais, considerando praias morfodinamicamente distintas e sazonais, sobretudo pelas variações de temperatura e pluviosidade, com decréscimo nos descritores de estrutura em cenários de maior intensidade destas variáveis ambientais. Da mesma forma, é preciso considerar fenômenos naturais, como ressacas, mais frequentes no inverno na região. Tais resultados podem servir de base para estudos sobre mudanças climáticas e respostas de invertebrados bênticos de praias arenosas, uma vez que espera-se modificações na temperatura, regime de chuvas, frequência e intensidade de ressacas.

Palavras-chave: macrofauna; morfodinamismo; praia arenosa; sazonalidade, temperatura, pluviosidade.

1. Introdução

Praias arenosas são sistemas costeiros determinados pelo hidrodinamismo e tipo de sedimento, constituindo um dos ambientes marinhos mais dinâmicos pela habilidade de absorver energia das ondas, dissipada na zona de surf (McLachlan & Brown, 2006). As praias podem diferir a partir das interações entre os parâmetros físicos, como o regime de ondas, granulometria e regime de marés, que variam espaço e temporalmente e promove distintos estados morfodinâmicos. Tais estados têm uma forte relação com a estrutura e distribuição da macrofauna bêntica (Brown & McLachlan, 2002).

A riqueza, abundância e biomassa da macrofauna seguem um gradiente de aumento de praias reflectivas em direção às dissipativas (Defeo & McLachlan, 2005; McLachlan & Dorvlo, 2005). McLachlan *et al.* (1993) indicaram que em praias reflectivas ocorre a exclusão de algumas espécies em função do intenso regime de ondas, segundo a *Swash Exclusion Hypothesis*. De acordo com essa hipótese, todas as espécies da macrofauna de praias podem ocorrer em ambientes dissipativos, porém apenas as mais robustas e móveis são capazes de tolerar o intenso hidrodinamismo das praias reflectivas. Isso corrobora a *Multicausal Environmental Severity Hypothesis*, que propõe que a dinâmica de acresção/erosão de sedimento exclui algumas espécies em praias reflectivas (Brazeiro, 2001). Defeo & McLachalan (2005) propuseram que, em larga escala, a riqueza de espécies é controlada principalmente por fatores físicos. Já em escalas menores e sob condições dissipativas, os efeitos biológicos podem se tornar mais importantes. Defeo *et al.* (2001; 2003) formularam a *Habitat Harshness Hypothesis*, demonstrando que em praias reflectivas, os organismos gastam mais energia para sobreviverem e, portanto, a taxa de fecundidade diminui. Já a *Habitat Favorability Hypothesis* sugere que em praias dissipativas ou sem pressão humana a densidade populacional depende principalmente das interações ecológicas.

Algumas espécies podem ocupar todos os tipos de praias, porém, a maioria prefere ambientes dissipativos, devido à menor intensidade de ondas e, consequentemente, a maior estabilidade ambiental. McLachlan & Brown (2006) propuseram um modelo baseado na capacidade das populações se estabelecerem em diferentes condições morfodinâmicas de praias arenosas com três categorias: 1) especialistas que compreendem organismos com formas delicadas, como a maioria dos poliquetas e quase todos os depositívoros; 2) formas intermediárias, beneficiadas pelas alterações constantes na intensidade de ondas e que colonizam um amplo espectro de praias (embora ocorram em maior abundância em praias dissipativas), são representadas principalmente por moluscos; 3) generalistas que compreendem organismos com elevada capacidade de mobilidade e de escavação do sedimento, e estabelecem suas populações em todos os tipos de praias, desde o extremo dissipativo ao reflectivo, como os crustáceos dos gêneros *Emerita* e *Excirolana*.

Segundo Souza (1998), a estrutura de comunidades é o principal aspecto utilizado para o entendimento do fluxo de energia em um ecossistema, pois indica a rede de interações existentes. As praias arenosas apresentam um ciclo de matéria e energia próprio, que pode variar espacialmente, dependendo das características morfodinâmicas, e temporalmente em função de variações na temperatura e disponibilidade de recursos (Veloso & Neves, 2009). Esses processos ocorrem devido à existência de células de circulação formadas na zona de surf que são capazes de reter a matéria orgânica dentro do sistema, que pode variar com o estado morfodinâmico. Nas praias refletivas, por exemplo, a ausência da zona de surf inviabiliza a retenção de células fitoplanctônicas dentro do sistema, tornando-o dependente de outros ambientes (Veloso *et al*., 2003).

Mudanças na precipitação pluviométrica podem influenciar as variações na estrutura, distribuição e composição de comunidades bênticas, e temperaturas extremas podem influenciar diretamente as taxas de sobrevivência e abundância da macrofauna bêntica, ou indiretamente, diminuindo o desempenho de atividades do animal, direcionando o período de cópula e de recrutamento de algumas populações (Neves *et al*., 2008, McLachlan & Brown, 2010). Temperaturas altas podem inibir a movimentação de alguns invertebrados da região entremarés que ficam a maior parte do dia dentro de suas tocas para evitar a dessecação por exposição a altas temperaturas (McLachlan & Brown 2010). A precipitação pluviométrica, que tende a aumentar a vazão dos rios, pode influenciar nos valores de salinidade, temperatura e nutrientes, interferindo na distribuição da macrofauna (Lercari & Defeo, 2006).

Em síntese, as características do sedimento, a estabilidade do ambiente e a disponibilidade de alimento afetam a distribuição, ocorrência e abundância dos organismos da macrofauna ao longo do tempo. Os padrões morfodinâmicos da praia podem variar temporalmente, resultando em alterações na comunidade bêntica (Martins, 2007).

O objetivo desse estudo foi identificar os principais determinantes estruturais da comunidade bêntica de praias arenosas na costa norte do estado do Rio de Janeiro com diferentes características morfodinâmicas, e testar a hipótese de que a macrofauna difere espacial e temporalmente, com valores crescentes de riqueza, diversidade e abundância de espécies em praias morfodinamicamente distintas, principalmente nos meses de verão, com maior temperatura do sedimento e precipitação pluviométrica na região.

2. Material e Métodos

2.1. Área de estudo

O estudo foi realizado em duas praias: Grussaí e Manguinhos, localizadas respectivamente nos municípios de São João da Barra e São Francisco de Itabapoana, costa norte do Estado do Rio de Janeiro (Fig. 1). Grussaí é uma praia intermediária, com intenso hidrodinamismo e Manguinhos é uma praia tipicamente dissipativa, com extensa zona de surfe e declividade amena. Áreas não urbanizadas de cada praia foram selecionadas na amostragem do sedimento para a macrofauna e análises geoquímicas para excluir o efeito antrópico.

A região norte do estado do Rio de Janeiro possui clima subtropical quente (Marengo & Alves, 2005), com vento nordeste predominante que atinge maiores velocidades de agosto a dezembro (Dominguez *et al.*, 1983). No verão ocorre maior frequência e intensidade de chuvas, enquanto os meses do inverno são caracterizados como secos, sendo a precipitação pluviométrica anual de 800 mm a 1.200 mm (ana.gov.br). Ambas as praias são influenciadas pela vazão do rio Itabapoana e principalmente do rio Paraíba do Sul, com papel importante no aporte de material dissolvido e particulado para a costa adjacente (Souza *et al*., 2010). Os meses de maior precipitação pluviométrica são acompanhados de maior vazão nesses rios (Almeida *et al*., 2007).

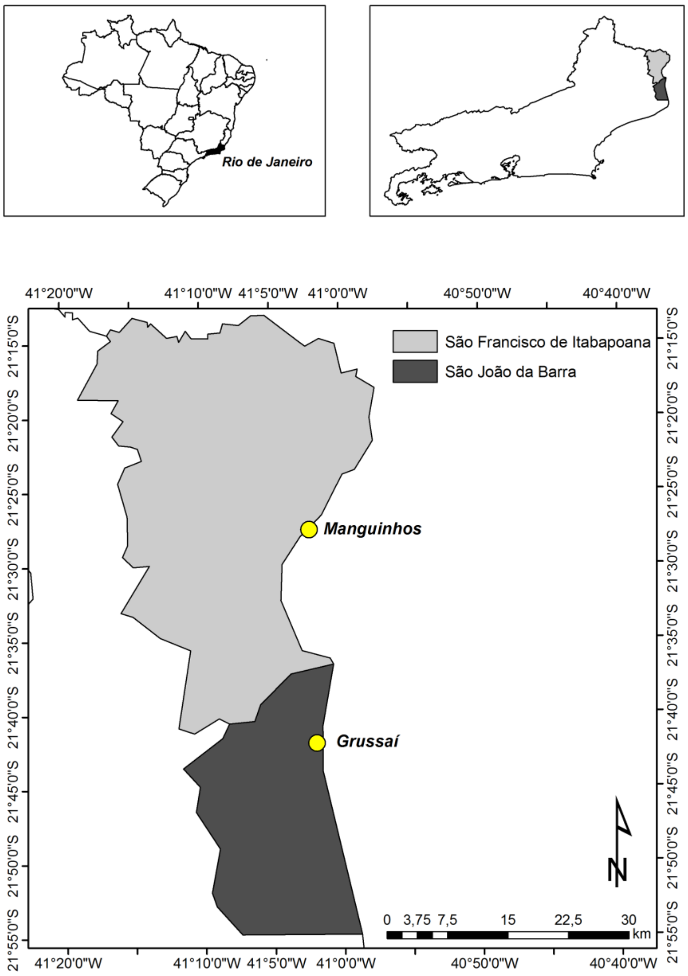

Figura 1. Mapa indicando a área de estudo e desenho amostral na costa norte do estado do Rio de Janeiro.

2.2. Estratégia de amostragem

Entre 2012 e 2014 foram realizadas oito campanhas de amostragem por praia, quatro no período chuvoso e quatro no período seco. Um testemunhador cilíndrico (*corer*), com 20 cm de diâmetro e 20 cm de profundidade foi utilizado para a coleta das amostras ao longo de três transectos perpendiculares à linha da costa, fixados a 50 m de distância entre si. Três pontos eqüidistantes (dois metros) por nível da região entremarés (mesolitoral superior, médio e inferior) foram determinados para a coleta do sedimento para a macrofauna, totalizando 27 amostras (Fig. 2) em cada campanha de amostragem. As amostras de sedimento foram peneiradas em malha de 500 µm, e fixadas em formaldeído a 10%. Os organismos foram triados com o auxílio de um estereomicroscópio e identificados até o menor nível taxonômico possível com o auxílio de manuais de identificação específicos (Abbott, 1974; Amaral & Nonato, 1996; Serejo, 2004; Amaral *et al*., 2006).

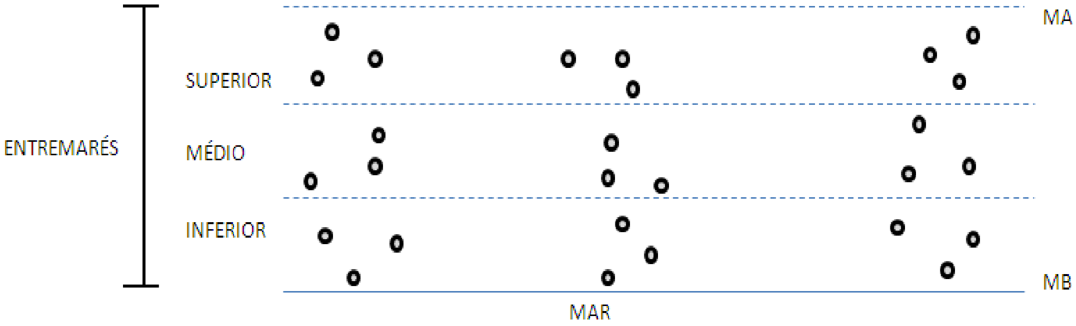

Figura 2. Desenho amostral utilizado nas praias de Manguinhos e Grussaí, com representação esquemática do esforço amostral na região entremarés.

2.3. Variáveis ambientais

Os dados de temperatura do ar e precipitação pluviométrica foram fornecidos pelo Instituto Nacional de Meteorologia (www.inmet.gov.br). A temperatura do sedimento foi mensurada diariamente nos níveis médio e superior da região entremarés no mesmo horário em 2013 e 2014.

Para caracterização morfodinâmica da praia foram registrados em cada campanha dados de altura média de ondas (observações visuais) e período médio das ondas (cronômetro digital). O regime de espraiamento foi determinado através da medição da extensão e do tempo de espraiamento (McArdle & McLachlan, 1992). A zona de espraiamento corresponde à distância da linha d'água até o limite superior do varrido. O tempo de espraiamento é determinado pelo intervalo de tempo cronometrado entre a formação e o término de cada espraiamento.

As amostras do sedimento para análise granulométrica e de matéria orgânica foram coletadas em cada nível do entremarés de cada transecto, perfazendo nove amostras por campanha. As seguintes classes granulométricas foram determinadas através de peneiras acopladas (Suguio (1973): cascalho (> 2 mm), areia grossa (< 2 mm e > 0.5 mm), areia média (<0.5 mm e > 0,25 mm), areia fina (< 0.5 mm). O sedimento foi liofilizado, homogeneizado e pesado em uma balança analítica de precisão de 0.0001 g para avaliar o teor de matéria orgânica total nas nove amostras separadas por campanha para análise granulométrica. O conteúdo de matéria orgânica foi obtido a partir da diferença entre o sedimento úmido e seco após incineração em mufla a 350°C pelo período de 12 horas (Goldin, 1987).

2.4. Análise dos dados

As variações espaciais e temporais na estrutura da comunidade bêntica foram avaliadas a partir dos descritores composição específica, riqueza média de espécies, densidade média (número de indivíduos/m^2), diversidade média de espécies de Shannon *&* Weaver e dominância média de Simpson (ZAR, 1984)

As diferenças estatísticas nos descritores numéricos considerando os tratamentos espaciais (praia dissipativa X praia intermediária) e temporais (período seco X período chuvoso em cada praia) foram testadas por Análise Multivariada Permutacional de Variância (PERMANOVA). Quatro fatores foram considerados na PERMANOVA: praia (fixo), nível do entremarés (fixo), tempo (fixo) e meses (aleatório *nested in* tempo). Para avaliar o grau de similaridade da macrofauna entre tratamentos foi realizada uma análise de ordenamento nMDS, com Bray Curtis como medida de dissimilaridade. Os dados foram transformados em raiz quarta para balancear a importância de espécies raras e espécies numericamente dominantes na determinação da similaridade entre duas amostras (Clarke *&* Warwick, 2001). A PERMANOVA com o mesmo design usado nos descritores univariados foi utilizada com o objetivo de avaliar a significância das diferenças entre os grupos pré-definidos a partir do nMDS. Nos casos de diferenças significativas ($p<0,05$) foi realizado um teste *a posteriori* de *pair-wise* visando identificar as diferenças entre as praias em cada período (verão e inverno) e nível do entremarés. O Simper foi utilizado para indicar os táxons que mais contribuíram para as diferenças entre os grupos definidos no nMDS. As análises multivariadas e a PERMANOVA foram realizadas no software PRIMER 6.0.

A distribuição dos organismos da macrofauna nas diferentes praias e suas relações com as características sedimentológicas (matéria orgânica, granulometria e temperatura, precipitação atmosférica, altura de ondas e tamanho de espraiamento foram analisadas através de Análise de Correspondência Canônica – CCA, utilizando o programa CANOCO. Para a realização dessa análise foi construída duas matrizes com os parâmetros ambientais supracitados e a densidade dos táxons que juntos totalizavam cerca de 75% da comunidade. Para testar a significância dos eixos canônicos realizou-se teste de permutação de Monte Carlo.

3. Resultados

3.1. Variáveis ambientais

Os valores de temperatura atmosférica foram superiores durante os meses mais chuvosos (novembro a março), variando de 17 a 39 °C, enquanto no período seco variou de 13 a 35 °C (Fig. 3). Os valores de temperatura do sedimento foram mais próximos das temperaturas máximas do ar, tanto no nível superior (26 °C a 36 °C) quanto no nível médio da região entremarés (25 °C a 33 °C), também superiores nos meses de primavera e verão (Fig. 3).

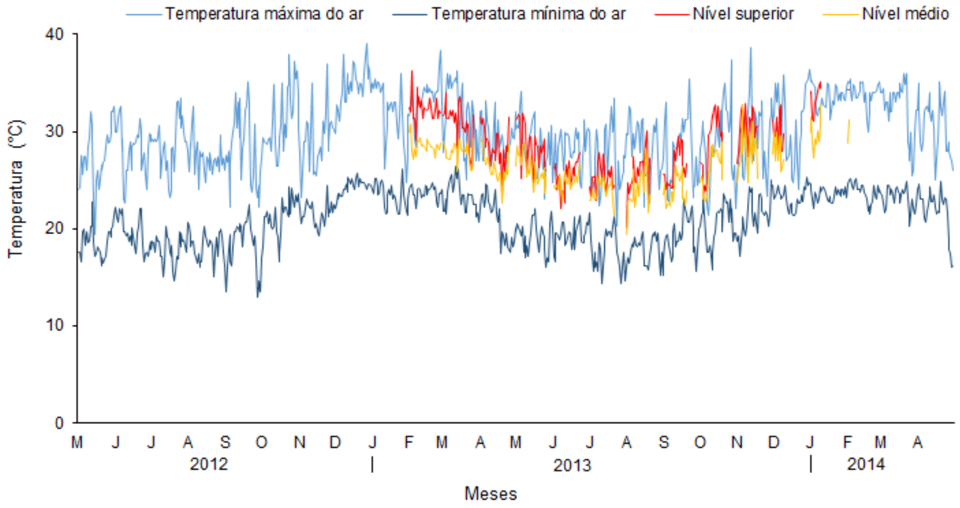

Figura 3. Temperatura diária do ar de maio/2012 a abril/2014 e temperatura diária do sedimento nos níveis superior e médio da região entremarés de fevereiro/2013 a fevereiro/2014. Fonte da temperatura do ar: http://www.inmet.gov.br/portal/.

A pluviosidade diária variou de 0 a 82 mm (Fig. 4). De modo geral, os meses com maior intensidade e dias chuvosos foram de dezembro a abril e julho de 2013 (Fig. 4)

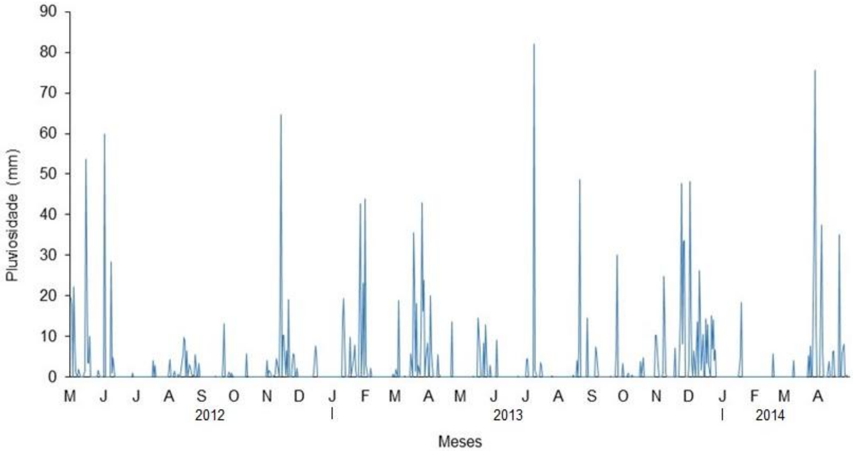

Figura 4. Precipitação pluviométrica diária de maio de 2012 a abril de 2014 no município de Campos dos Goytacazes. Fonte: http://www.inmet.gov.br/portal/

Em ambas as praias, o sedimento foi composto principalmente por areia fina (60% e 80%, respectivamente) e areia média (31% e 10%, respectivamente) (Anexo 1), sem diferenças temporais significativas. O teor de matéria orgânica também não diferiu significativamente entre os períodos (Grussaí: período chuvoso = 0,03% e período seco = 0,02%; Manguinhos: período chuvoso = 0,02% e seco = 0,03%) (Anexo 2).

O parâmetro hidrodinâmico altura de ondas foi significativamente ($p<0.05$) superior no período chuvoso (1,1 m) em relação ao seco (0,9 m) na praia de Grussaí, com maiores ondas no verão (Anexo 2). Já em Manguinhos, com valores inferiores (período chuvoso: 0,5 m; período seco: 0,4 m), não houve diferenças temporais significativas (Anexo 2). Em ambas as praias, o período de ondas foi significativamente superior nos meses chuvosos de verão. Por outro lado, tempo e tamanho do espraiamento não variaram temporalmente (Anexo 2).

3.2. Macrofauna bêntica

Um total de 15 táxons foi amostrado na praia de Grussaí, com os crustáceos *Excirolana braziliensis*, *Emerita brasiliensis*, *Atlantorchestoidea brasiliensis* e Nemertea ocorrendo em todas as amostragens (Anexo 3). Na praia de Manguinhos, 23 táxons foram identificados, e os crustáceos *Excirolana braziliensis*, *Atlantorchestoidea brasiliensis* e *Talorchestia tucurauna* ocorreram em todas as amostragens (Anexo 4). Em ambas as praias, Crustacea foi o grupo com maior número de táxons e abundância, seguido de Polychaeta e Mollusca (Anexos 3 e 4).

A riqueza, diversidade e densidade de espécies diferiram significativamente ($p<0,005$) entre a praia dissipativa de Manguinhos e a praia intermediária de Grussaí, com valores superiores nesta última, exceto para riqueza (Tab. 1). Diferenças temporais foram registradas apenas em Grussaí entre meses de amostragem mas não entre períodos seco e chuvoso, destacando significativamente Setembro 2013 e Abril 2014 para a riqueza e Setembro 2014 para a densidade (Tab. 1).

Tabela 1. PERMANOVA e teste *pair wise* relacionados à riqueza, densidade e diversidade da macrofauna na praia de Grussaí e Manguinhos, southeastern Brazilian coast. *p<0.05

Factor		Richness			Density			Diversity index		
	df	MS	F	*P*	MS	F	*P*	MS	F	*P*
Beach (intermediate x dissipative)	1	11882	34	0.005*	39423	32	0.001*	9479.4	50	0.002*
Intertidal level (upper, medium, lower)	2	596.35	29	0.1	2345.6	19	0.169	71	0.68	0.538
Time (dry x wet)	1	539.67	0.69	0.43	5347.3	22	0.153	117.21	0.32	0.591
Month (time)	6	779.34	26	0.019*	2419.7	23	0.011*	365.49	17	0.118
Beach x Intertidal level	2	97	0.31	0.803	895	1	0.485	48	0.16	0.857
Beach x Time	1	80	0.23	0.671	1607.3	13	0	338.27	18	0.248
Intertidal level x Time	2	605.18	29	0.074	2121.8	17	0	390.02	37	0.056
Beach x Month (Time)	6	345.67	12	0.339	1229.6	12	0.318	190.66	0.89	0.506
Intertidal level x Month (Time)	12	207.64	0.69	0.758	1242.1	12	0.256	105.5	0.49	0.925
Beach x Intertidal level x Time	2	88	0.28	0.815	545	0.52	0.711	37.23	0.12	0.896
Beach X Intertidal level x Month (Time)	12	314.84	11	0.397	1045.1	0.99	0	309.99	15	0.138
Residuals	384	299.19			1047.2			213.52		
Total	431									
Pair-wise test	Groups	Richness			Density					
		P(MC)			P(MC)					
Beach (Grussaí) x Time	September/13	<0.005			<0,005					
Beach (Grussaí) x Time	April/14	<0.005								

Na praia de Grussaí, em Setembro 2013 ocorreu a maior densidade total (136.9 inds/m^2) em função, do incremento dos crustáceos *E. braziliensis* (56.9 inds/m^2) e *E. brasiliensis* (40.0 inds/m^2). Em fevereiro 2013 foi registrado a menor densidade (22.1 inds/m^2), com um decréscimo significativo de *E. braziliensis* e *A. brasiliensis* (Anexo 3). Na praia de Manguinhos, maior densidade total foi verificada em agosto 2012 (25.9 inds/m^2), com maiores abundâncias dos crustáceos *E. braziliensis* (7.5 inds/m^2), *Puelche* sp. (6.3 inds/m^2) e *T. tucurauna* (5.7 inds/m^2). A menor densidade também foi verificada em fevereiro 2013(11.4 inds/m^2), em que a população de crustáceos reduziu cerca de 1/3 (Anexo 4).

A análise de ordenação nMDS evidenciou dois grupos, separando claramente as amostras da praia de Manguinhos a direita e as da praia de Grussaí a esquerda, independente de padrões temporais (Fig. 5). Os crustáceos foram os que mais contribuíram para dissimilaridade de 94% entre as praias, com 44% (*E. braziliensis*: 22.9%, *A. brasiliensis*: 10% e *E. brasiliensis*: 8.63%), seguido por poliquetas com 27% (*H. californiensis*: 13.17%, *Scolelepis* sp.: 8.49% e *Pisionidens indica*: 5.20%) e Nemertea (10.41%).

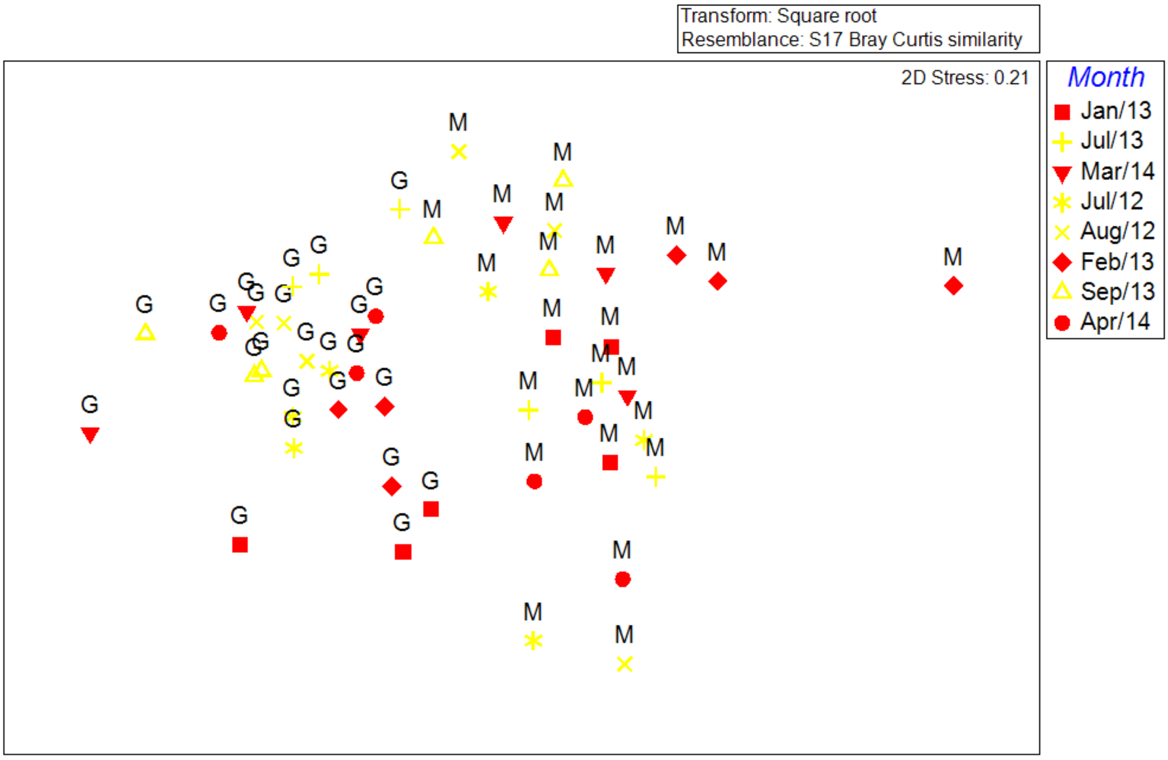

Figura 5. Non-metric multidimensional scaling ordination (nMDS) baseada na matriz de dissimilaridade de Bray-Curtis da macrofauna nas praias de Grussai (G) e Manguinhos (M). Jan: janeiro; Feb: fevereiro; Mar: março; Apr: abril; Jul: julho; Aug: agosto; Sep: setembro; 12: ano de 2012; 13: ano de 2013; 14: ano de 2014.

De acordo com a CCA, o percentual de explicação da relação das variáveis ambientais com a macrofauna bêntica na Praia de Grussai foi de 83%, com os eixos 1 e 2 significativos ($p<0.05$). De modo geral, houve uma separação das amostras do período chuvoso em relação ao seco. As amostras do período seco foram fortemente relacionadas à fração mais grossa do sedimento e com Nemertea (Fig. 6). Nos meses chuvosos, houve maior relação das amostras com maiores temperaturas, pluviosidade e teor de matéria orgânica no sedimento e com o crustáceo *Atlantochestoidea brasiliensis* (Fig. 6).

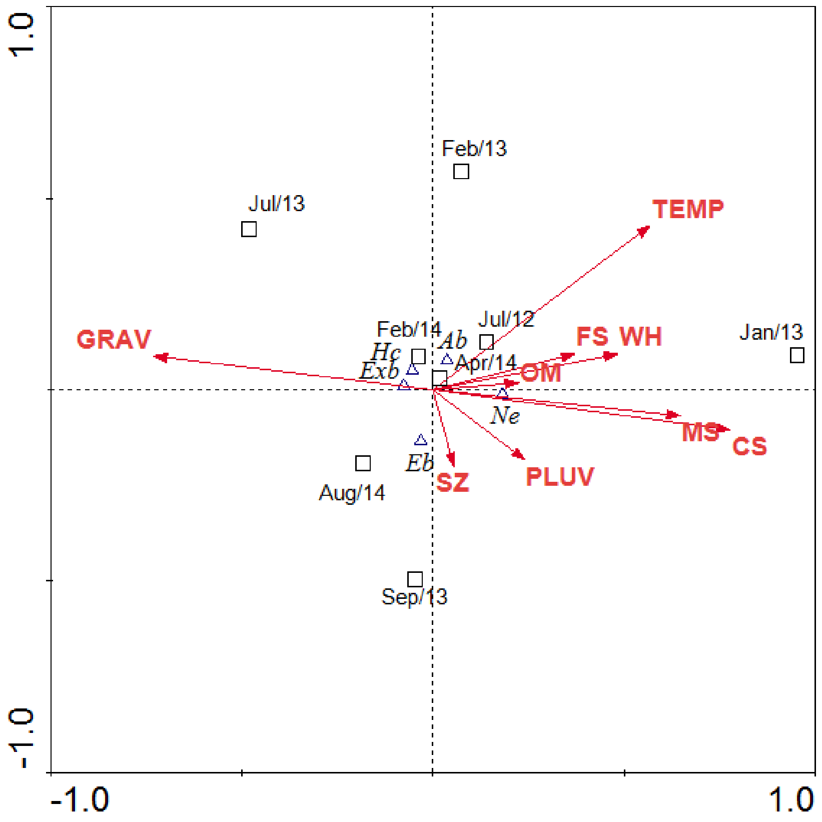

Figura 6. Análise de correspondência canônica (CCA) incluindo os táxons da macrofauna bêntica que contribuíram com 75% da abundância total de indivíduos em cada período amostral e as variáveis ambientais areia grossa (CS), areia média (MS), areia fina (FS), cascalho (GRAV), altura de ondas (WH), tamanho de espraimento (swash zone - SZ), temperatura do sedimento (TEMP), pluviosidade (PLUV) e teor de matéria orgânica (OM) na praia de Grussaí. Eb: *Emerita brasiliensis*, Exb: *Excirolana braziliensis*, Ab: *Atlantorchestoidea brasiliensis*, Hc: *Hemipodia californiensis*, Ne: Nemertea.

Na praia de Manguinhos, a CCA demonstrou um poder de explicação em torno de 73%, com os eixos 1 e 2 significativos. Nesta praia também ocorreu a separação dos meses referentes ao período seco em relação ao chuvoso. As variáveis ambientais que mais explicaram as relações da macrofauna com o período seco foram as frações mais grosseiras do sedimento como cascalho, variáveis hidrodinâmicas e teor de matéria orgânica, relacionados aos crustáceos *Atlantorchestoidea brasiliensis*, *Talorchestia tucurauna e Puelche* sp.. As amostras do período chuvoso foram mais associadas as frações de areia do sedimento, as maiores temperaturas e pluviosidade , que estiveram relacionadas aos poliquetas *Scolelepis* sp. e *H. californiensis*, Oligochaeta e ao crustáceo *E. braziliensis* (Fig. 7).

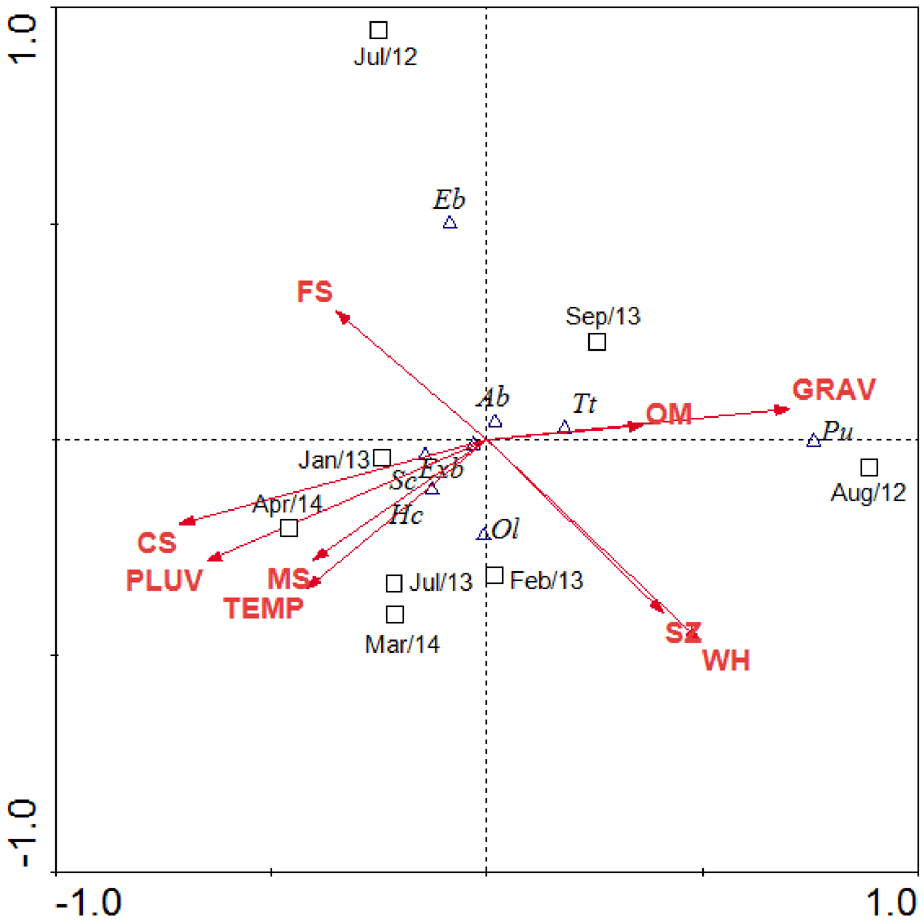

Figura 7. Análise de correspondência canônica (CCA) incluindo os táxons da macrofauna bêntica que contribuíram com 75% da abundância total de indivíduos em cada período amostral e as variáveis ambientais areia grossa (CS), areia média (MS), areia fina (FS), cascalho (GRAV), altura de ondas (HW), tamanho do espraimento (swash zone- SZ), temperatura do sedimento (TEMP), pluviosidade (PLUV) e teor de matéria orgânica (OM) na praia de Manguinhos. Eb: *Emerita brasiliensis*, Exb: *Excirolana braziliensis*, Ab: *Atlantorchestoidea brasiliensis*, Tt: *Talorchestia tucurauna*, Pu: *Pulche* sp.; Sc: *Scolelepis* sp., Hc: *Hemipodia californiensis*, Ne: Nemertea.

4. Discussão

A determinação da influência do morfodinamismo em comunidades bênticas de praias arenosas se depara com algumas limitações logísticas, que dificultam a identificação de respostas da macrofauna a fatores isolados. Nesse sentido, fatores físicos como granulometria e regime hidrodinâmico das praias são considerados os principais determinantes da composição e distribuição da macrofauna (McLachlan *et al.*, 1981; McLachlan *et al.*, 1993; Defeo *et al.*, 2001; Nel *et al.*, 2001). As praias estudadas evidenciaram claramente características morfodinâmicas distintas, com maior tamanho de ondas na praia de Grussaí, e maior tempo e tamanho da zona de espraiamento na praia de Manguinhos. Essas diferenças ambientais refletiram em comunidades macrofaunais distintas, com maiores valores de riqueza na praia dissipativa de Manguinhos e de densidade e diversidade na praia intermediária de Grussaí.

O tempo e o tamanho da zona de espraiamento normalmente são maiores em praias dissipativas (Muehe, 1998) e criam condições mais favoráveis para o deslocamento e alimentação de algumas espécies (McLachlan, 1990), o que contribui para o aumento da riqueza nessas praias, conforme verificado nesse estudo. Em praias intermediárias e reflectivas, o intenso hidrodinamismo reduz o tempo de alimentação, desencadeia maior instabilidade do substrato, deixando algumas espécies mais vulneráveis ao deslocamento que, por sua vez, podem ser lançadas para áreas mais externas da praia, onde são incapazes de cavar (McLachlan, 1990; McArdle & McLachlan 1991; McLachlan *et al.*, 1993). Esses fatores podem favorecer uma menor riqueza em praias intermediárias, como verificado na praia de Grussaí. Os menores valores de diversidade e densidade de espécies na praia dissipativa de Manguinhos decorreu do maior número de espécies raras, comparada à praia intermediária. Segundo Lastra *et. al.* (2006), a menor riqueza em praias na Espanha esteve associada à ausência de espécies raras.

O teor de matéria orgânica e a granulometria não explicaram as variações temporais da macrofauna em ambas as praias ao longo dos anos de amostragem, com frações granulométricas predominadas por areia fina e média. Apesar do sedimento não diferir significativamente entre praias e períodos amostrais, em Manguinhos a contribuição de cascalho foi maior em relação à praia de Grussaí, tornando-o mais heterogêneo, o que pode favorecer a riqueza de espécies (Rodil & Lastra, 2004; McLachlan & Dorvlo, 2005; Fernandes & Gomes, 2006). Enquanto McLachlan (1990; 1996), McLachlan *et al.* (1993) e Brazeiro (2001) argumentam que a granulometria é um fator imprescindível na determinação da riqueza ao longo do gradiente morfodinâmico, Jaramillo (1987) sugere que a macrofauna de praia está adaptada a um amplo espectro de condições granulométricas, indicando que esta variável não é um fator limitante para os organismos. Nosso estudo demonstrou a influência da granulometria na macrofauna, comparando praias com distintas características morfodinâmicas.

A tendência da riqueza de espécies ser maior em praias dissipativa em relação às intermediárias e reflectivas é amplamente corroborada em outros estudos (Defeo *et al*., 1992; Jaramillo & McLachlan, 1993; McLachlan *et al*. 1993; Brazeiro & Defeo, 1999; Veloso *et al*.,, 2003; Rodil & Lastra, 2004). Entretanto, os resultados de densidade e diversidade não seguiram esse padrão, pois foram significativamente superiores na praia de Grussaí, chegando a atingir o triplo dos valores encontrados em Manguinhos. Outros estudos também verificaram maiores densidades em praias intermediárias ou reflectivas (Vanagt *et al.,* 2007; Veloso & Cardoso, 2001; Santos *et al,* 2014). A praia de Grussaí, apesar de possuir maior hidrodinamismo, tem a formação de calhas longitudinais que previnem a quebra de ondas diretamente na face praial, tornando o ambiente mais estável do que praias reflectivas e, consequentemente, favorável à presença de táxons generalistas, que possuem maior mobilidade, como crustáceos *Atlantorchestoidea brasiliensis, Emerita brasiliensis* e *Excirolana braziliensis*.

As variações nos descritores de comunidades seguiram, em geral, um padrão sazonal com menores valores no verão, período chuvoso. A temperatura média do ar e do sedimento foram superiores nos meses de verão, assim como o regime pluviométrico. Esses fatores podem influenciar a comunidade bêntica, caracterizando-se, em algumas situações, como estressores para os organismos (Somero, 2012). Embora adaptados a um amplo espectro de variações de temperatura, a macrofauna do entremarés de praias possui faixas ótimas de variação térmica (Veloso *et al*., 1997; Hochachka & Somero, 2002). Portanto elevadas temperaturas (acima do limite térmico) podem ser estressantes para alguns organismos (Somero, 2012), prejudicando sua estrutura populacional.

A maior pluviosidade no verão e consequentemente a maior vazão dos rios Paraíba do Sul e Itabapoana na região intensificam o aporte de material orgânico para a região costeira adjacente (Souza *et al*., 2010; Figueiredo *et al.*, 2011). No entanto, o teor de matéria orgânica não variou temporalmente e os descritores de comunidade mostraram uma relação inversa aos valores de pluviosidade na região. O aumento da precipitação pode ter influenciado negativamente a densidade da macrofauna, em razão da descarga de água doce (Lercari *et al.*, 2012; Shoeman & Richardson, 2002; Lercari & Defeo, 2003), principalmente pelos rios Paraíba do Sul e São Francisco de Itabapoana. Souza et al. (2013) encontraram um decréscimo de uma população de poliqueta próximo a um estuário e relacionou ao aumento pluviométrico. Da mesma forma, Lercari *et al.* (2012) verificaram a influência negativa da descarga de água doce na macrofauna de uma praia uruguaia.

As espécies dominantes *Excirolana braziliensis* e *Emerita brasiliensis* tiveram um aumento nas densidades no mês de agosto, quando foi registrado maiores intensidades e frequência de ressacas em Grussaí. Estes eventos promovem o revolvimento do sedimento e a ressuspensão da matéria orgânica (Alves & Pezzuto, 2009), favorecendo esses crustáceos que possuem hábito detritívoro e suspensívoro, respectivamente (Bock & Miller, 1995). O aumento na densidade dessas espécies de crustáceos cerca de um mês após os eventos de ressaca foi observado nesta mesma praia por Machado *et. al.* (2016). Estes autores sugerem que tais eventos climáticos extremos em ambientes sem perturbação antrópica podem promover um incremento na densidade, riqueza e diversidade da macrofauna, mas quando em alta frequência e intensidade, podem ter efeito contrário na comunidade bêntica. A dominância de *E. braziliensis* e *E. brasiliensis* nas duas praias pode ser explicada pela capacidade de ambas as espécies ocuparem um amplo espectro de condições morfodinâmicas (Brazeiro, 1999).

Os crustáceos talitrídeos *Talorchestia tucurauna* e *Atlantorchestoidea brasiliensis* foram amostrados em todas as campanhas na praia de Manguinhos, com picos de abundância em agosto e setembro para *T. tucurauna*. O padrão de variação anual na abundância desses crustáceos, com maiores valores nos meses de inverno e menores no verão, já foi encontrado na costa brasileira (Gómez & Defeo, 1999; Aluízio, 2007; Capper, 2011). Segundo Cardoso & Veloso (1996) variações na abundância dos talitrídeos podem ser uma boa indicação de períodos reprodutivos. Os talitrídeos possuem uma boa tolerância a variações latitudinais na temperatura (Ramos, 2014), mas podem permanecer enterrados durante períodos muito quentes para evitar a dessecação (Adin & Riera, 2003). É importante ressaltar que as temperatura do sedimento nas praias estudadas foram bem próximas das temperaturas máximas do ar no nível superior e médio da região entremarés, com variações de 32 a 38 ^{o}C nos meses de verão.

A ausência de padrão temporal dos parâmetros hidrodinâmicos e sedimentares refletiu diretamente nas mudanças temporais das assembléias bênticas, pouco evidentes ao longo dos meses amostrados. A influência de múltiplas variáveis atuando em praias arenosas torna desafiante a identificação de fatores isolados controladores das diferentes populações. No presente estudo foi possível identificar principalmente no inverno picos de abundância de espécies chave comuns em praias arenosas brasileiras, como os crustáceos *E. braziliensis*, *E. brasiliensis* e *A. brasiliensis*, assim como verificado em outros estudos (Fonseca & Veloso, 1996; Veloso *et al.*, 1997; Gómez & Defeo, 1999; Aluízio, 2007; Capper, 2011). Segundo Cardoso & Veloso (1996), características climáticas como temperatura e precipitação parecem ter influência direta nessas espécies. Da mesma forma, é preciso considerar fenômenos naturais, como ressacas, mais frequentes no inverno na região (Machado *et al.*, 2016). Tais resultados podem servir de base para estudos sobre mudanças climáticas e respostas de invertebrados bênticos de praias arenosas, uma vez que espera-se modificações na temperatura, regime de chuvas, frequência e intensidade de ressacas (IPCC, 2013).

Este foi o primeiro estudo focando variações espaço-temporais da comunidade macrofaunal do entremarés de praias arenosas na costa norte do Estado do Rio de Janeiro. Os resultados evidenciaram variações nos indicadores de comunidade e na composição de espécies, principalmente em escalas espaciais, considerando praias morfodinamicamente distintas e sazonais, sobretudo pelas variações de temperatura e pluviosidade, com decréscimo nos descritores de estrutura em cenários de maior intensidade destas variáveis ambientais. Assim, a hipótese testada foi parcialmente aceita, uma vez que a macrofauna difere espacial e temporalmente. No entanto, apenas a riqueza de espécies foi mais elevada na praia dissipativa de Manguinhos, enquanto valores superiores de densidade e diversidade ocorreram na praia intermediária de Grussai, principalmente no inverno, período de menor intensidade de chuvas e temperaturas na região.

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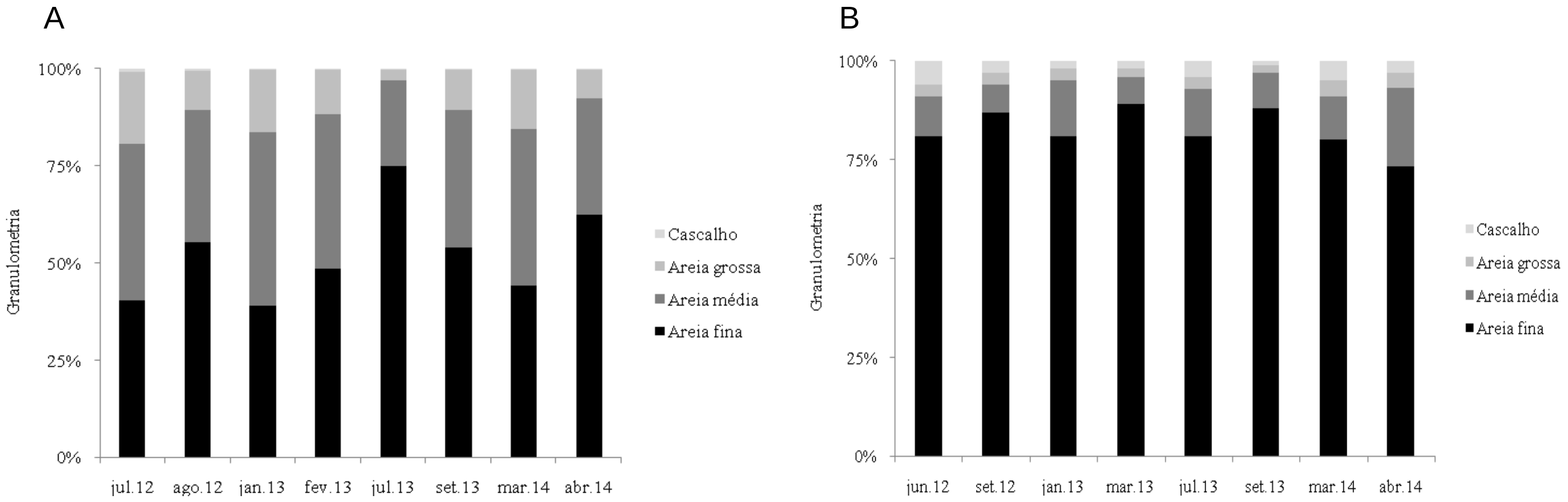
6. Anexos

Anexo 1. Composição granulométrica do sedimento das praias de Grussaí (A) e Manguinhos (B) nos períodos amostrais.



Anexo 2. Valores médios (± DP) das variáveis ambientais altura e período de ondas, zona e tempo de espraiamento, e teor de matéria orgânica monitoradas em todas as campanhas amostrais nas praias de Grussaí (A) e Manguinhos (B).

A

Grussaí	jul/12	aug/12	jan/13	feb/13	jul/13	sep/13	mar/14	apr/14
Altura de onda (cm)	88.00 ±20.40	110.00 ±38.10	145.00 ±38.10	92.00 ±19.90	98.00 ±14.8	88.0 ±19.90	116.00 ±36.40	76.00 ±15.80
Período de onda (s)	5.20 ±1.40	2.40 ±0.50	3.00 ±0.90	2.00 ±0.50	3.00 ±0.00	3.10 ±0.70	2.60 ±0.50	2.20 ±0.40
Zona de espraiamento (m)	4.00 ±0.00	4.30 ±1.50	7.00 ±1.60	6.10 ±2.30	7.00 ±1.60	7.60 ±2.50	4.40 ±2.00	6.30 ±2.50
Tempo de espraiamento(s)	2.40 ±0.50	2.60 ±0.90	2.80 ±1.30	2.50 ±0.50	4.10 ±0.30	2.60 ±0.50	3.50 ±0.70	3.10 ±0.30
Matéria orgânica (%)	0.01 ±0.02	0.01 ±0.00	0.04 ±0.03	0.05 ±0.05	0.03 ±0.02	0.04 ±0.03	0.01 ±0.00	0.02 ±0.02

B

Manguinhos	jul/12	aug/12	jan/13	feb/13	jul/13	sep/13	mar/14	apr/14
Altura de onda (cm)	40.00 ±15.50	55.00 ±18.70	45.00 ±21.2	44.00 ±7.00	42.00 ±9.20	44.00 ±9.70	50.00 ±16.30	52.00 ±13.2
Período de onda (s)	5.00 ±0.00	2.70 ±0.50	1.70 ±0.5	1.00 ±0.00	2.00 ±0.00	1.50 ±0.50	2.00 ±0.50	2.00 ±0.00
Zona de espraiamento (m)	4.30 ±0.60	8.70 ±2.90	5.80 ±1.90	8.90 ±1.70	9.60 ±3.40	9.90 ±2.50	9.20 ±1.10	8.90 ±3.00
Tempo de espraiamento(s)	9.20 ±2.30	3.00 ±0.70	3.60 ±0.90	4.30 ±0.90	6.80 ±0.40	6.30 ±1.30	4.20 ±0.60	6.30 ±2.40
Matéria orgânica (%)	0.01 ± 0.00	0.02 ±0.01	0.02 ±0.01	0.04 ±0.07	0.02 ±0.00	0.06 ±0.14	0.01 ±0.00	0.01 ±0.01

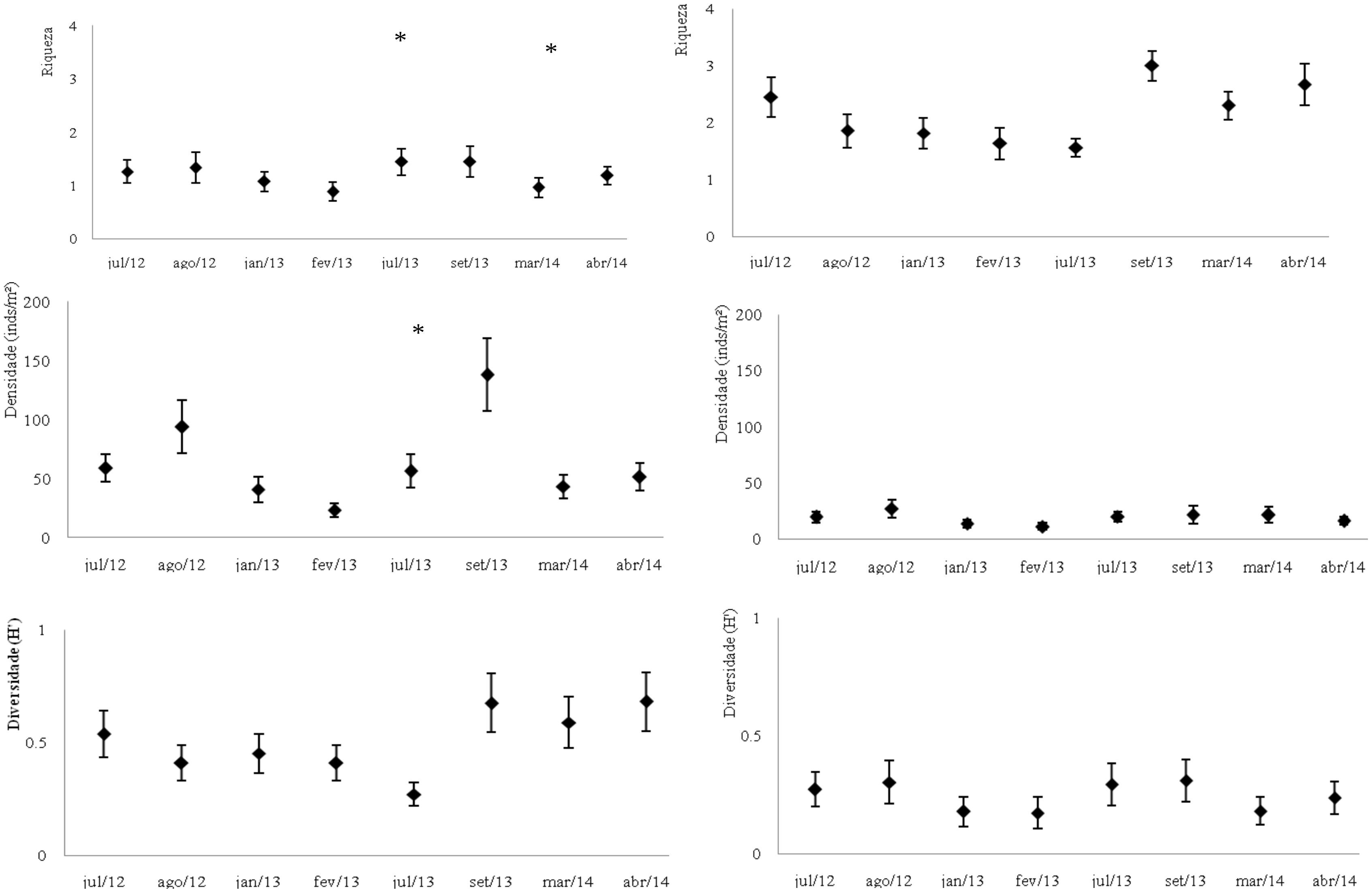
Anexo 3. Composição taxonômica da macrofauna bêntica do entremarés da praia de Grussaí.

Filo	**Classe**	**Família**	**Espécie**	**Jul/12**	**Ago/12**	**Jan/13**	**Fev/13**	**Jul/13**	**Set/13**	**Mar/14**	**Abr/14**
Arthropoda	Crustacea	Albuneidae	*Lepidopa richimondi* Benedict, 1903		0,2		0,4	0,4		0,4	0,4
		Cirolanidae	*Excirolana braziliensis* Richardson, 1912	14,2	58,3	2,6	8,3	20,9	56,9	21,9	33,1
		Hippidae	*Emerita brasiliensis* Schmitt, 1935	9,5	13,2	0,6	0,2	5,7	40,0	2,4	3,3
		Talitridae	*Atlantorchestoidea brasiliensis* (Dana, 1853)	6,3	6,7	3,7	3,9	2,0	3,0	2,6	4,1
			Talorchestia tucurauna (Müller, 1864)		0,2				0,2		
		Mysidae	*Mysida* sp.	0,2			0,4	2,2		1,4	
		Phoxocephalidae	*Puelche* sp. Bernard & Clark, 1982	0,6	0,4						1,0
Annelida	Polychaeta	Glyceridae	*Hemipodia californiensis* Hartman, 1938	11,6	4,5		3,7	5,7	8,7	5,1	1,2
		Psionidae	*Pisionidens indica* Aiyar & Alikunhi, 1940	0,8	0,2			1,6	5,1	5,1	2,4
		Spionidae	*Dispio* sp. Hartman, 1951			0,4					
			Scolelepis sp. Blainville, 1828	0,4	0,2	2,8		0,2			
	Oligochaeta			1,2	3,9	8,5	0,6	0,8	1,0	0,2	
Mollusca	Bivalvia	Donacidae	*Donax hanleyanus* Phillipi, 1842	2,2	0,4	4,5	1,2		4,7		1,0
	Gastropoda	Olividae	*Olivancillaria vesica* (Gmelin, 1791)						0,2		
Nemertea				12,0	5,7	16,5	3,3	8,9	17,1	3,9	0,4
			Densidade total (nº de indivíduos/m^2)	**58,9**	**94,0**	**39,6**	**22,1**	**48,3**	**136,9**	**42,9**	**46,9**

Anexo 4. Composição taxonômica da macrofauna bêntica da praia de Manguinhos.

Filo	**Classe**	**Família**	**Espécie**	**jul/12**	**ago/12**	**jan/13**	**fev/13**	**jul/13**	**set/13**	**mar/14**	**abr/14**
Arthropoda	Crustacea	Albuneidae	*Lepidopa richimondi* Benedict, 1903						0,2		
		Cirolanidae	*Excirolana braziliensis* Richardson, 1912	7,9	7,5	8,3	2,2	7,1	9,3	11,2	7,7
		Hippidae	*Emerita brasiliensis* Schmitt, 1935	4,5	0,2	0,2		0,2	1,4		
		Talitridae	*Atlantorchestoidea brasiliensis* (Dana, 1853)	1,8	0,8	0,4	1,2	0,2	1,8	0,8	0,8
			Talorchestia tucurauna (Müller, 1864)	1,2	5,7	0,6	1,4	1,4	7,1	0,2	2
		Mysidae	*Mysida* sp.	0,4			0,8	0,2	0,2		
		Paguridae	*Pagurus* sp. Fabricius, 1775		0,4		3				
		Phoxocephalidae	*Puelche* sp. Bernard & Clark, 1982		6,3						
		Peneidae	Peneidae	0,2				0,4			
		Diogenidae	*Clibanarius vittatus* Bosc, 1802		0,4						
Annelida	Polychaeta	Glyceridae	*Hemipodia californiensis* Hartman, 1938	0,2	0,6	0,4		1,2	1	0,4	0,2
		Psionidae	*Pisionidens indica* Aiyar & Alikunhi, 1940		0,4	0,2					
		Spionidae	*Dispio* sp. Hartman, 1951	0,6	0,2	0,4		0,4	0,2	0,4	
			Scolelepis sp. Blainville, 1828	2,8	1	2,8	1	5,5	2	4,1	5,5
		Nephtydae	*Nephtys magellanica* Augener, 1912				0,6				
	Oligochaeta				1	0,2	0,8	2	0,4	3,9	0,6
Echinodermata		Ophiuroidae	Ophiuroidae								0,2
Mollusca	Bivalvia	Donacidae	*Donax hanleyanus* Phillipi, 1842	0,2	0,6			0,2			
		Mactridae	*Mulinia cleryana* d'Orbigny, 1846					0,2			
		Tellinidae	*Tellina lineata* Turton, 1819		0,2						
			Stringilla pisiformis (Linnaeus, 1758)		0,2						
	Gastropoda	Olividae	*Olivancillaria vesica* Gmelin, 1791				0,4	1,2			
Nemertea					0,4	0,2		0,2	0,4		0,2
			Densidade total (nº de indivíduos/m^2)	**19,8**	**25,9**	**13,7**	**11,4**	**20,4**	**24,0**	**21,0**	**17,2**

Anexo 5. Variação temporal (média ±EP) dos valores de riqueza, densidade e diversidade de Shannon da macrofauna bêntica do entremarés da praia de Grussaí (à esquerda) e Manguinhos (à direita) nos períodos amostrais.



Capítulo 2

Tourism impact on benthic communities in sandy beaches

Abstract

This study evaluated the effect of human trampling on the benthic macrofauna in two beaches with different tourism intensities, Grussaí (more impacted) and Manguinhos (less impacted) in southeast Brazil at two periods (high and low tourism activities). In each beach, the macrofauna of urbanized (U) and non-urbanized (NU) sectors of the intertidal zone was sampled and the number of visitors was recorded. General linear models showed the decrease in abundance of macrofauna in the sector exposed to more intense trampling. Macrofauna richness, diversity, and density were lower in the U sector of Grussaí Beach, which is exposed to 2 to 3 visitors/m² in summer. In Manguinhos Beach, trampling did not affect macrofauna (<1 visitors/m²), except for the polychete *Scolelepis* sp., which was more vulnerable in U sector. *Atlantorchestoidea brasiliensis, Hemipodia californiensis, Scolelepis* sp., and Nemertea were more abundant in winter and may be used as potential bioindicators of tourism impact. Management plans should consider the mitigation of these effects, like the decentralization of human occupation in one beach.

Keywords: Anthropic effects; Macrofauna; Sandy beach; Trampling.

1. Introduction

The potential touristic of sandy beaches has economic importance worldwide, and it is also observed in Brazil, along the 7,000-km-long coastline. Nevertheless, the constant population growth influences the occupation and recreational use of this environment, promoting considerable changes especially in sandy beaches, where anthropic impact manifests at various temporal and spatial scales (McLachlan & Brown, 2006).

The anthropic impacts in beaches include mainly recreational activities, motor vehicle traffic, marine debris, mechanical cleaning and trampling (Brown & McLachlan, 2002; Dugan, 2003; Malm *et al.*, 2004; Fanini *et al.*, 2005; Davenport & Davenport, 2006; Veloso *et al.*, 2006, 2008; Barca-Bravo *et al.*, 2008; Ugolini *et al.*, 2008; Schlacher & Thompson, 2012; Vieira, 2012). However, beach nourishment techniques (Peterson *et al.*, 2000; Brown & McLachlan, 2002; Defeo *et al.*, 2009), breakwaters (Kohn & Blahm, 2005; Do Carmo *et al.*, 2010), dune suppression (Ranwell & Rosalind, 1986; Nordstrom, 2000; Weslawski *et al.*, 2000; Bessa *et at*. 2013), and reduction of beach width (Hall & Pilkey, 1991; Jaramillo *et al.*, 2012) are also important stressorss against the macrofauna inhabiting the intertidal zone.

As a rule, the main factors governing the structure and composition of sandy beach macrofauna are wave exposure, grain size, organic matter content, food availability, and beach slope, width and length (McLachlan, 1993; McLachlan & Defeo, 2001). Due to the intrinsic relationship between macrofauna and sediment, any change in this compartment triggers spatial and temporal changes in this community (Haynes & Queen, 1995; Lercari *et al.*, 2012). Therefore, the effects of anthropic activities on this coastal ecosystem may be evaluated through the benthic community, since these organisms normally have sedentary habits and are relatively long-lived (McLachlan & Brown, 2006).

Despite the negative effects of anthropic activities on benthic macrofauna (Jaramillo *et al.*, 1996, Moffet *et al.*, 1998, Veloso *et al.*, 2006, Veloso *et al.*, 2008, Weslawski *et al.*, 2000), few studies have used control areas to evaluate these impacts (Schlacher & Thompson, 2012; Bessa *et al.*, 2014; Reyes-Martinez, 2015; Reyes-Martinez *et al.*, 2015).

Despite the growing interest in this topic, most research has evaluated the effects of anthropic disturbances on specific populations that are considered more susceptible, especially crustaceans Talitridae (Weslawski *et al.*, 2000; Fanini *et al.*, 2005; Barca-Bravo *et al.*, 2008; Ugolini *et al.*, 2008; Veloso *et al.*, 2008, 2010; Ungherese *et al.*, 2010, 2012; Bessa *et al.*, 2013; Gonçalves *et al.*, 2013; Ugolini *et al.*, 2013), Ocypodidae (Steiner & Leatherman, 1981; Neves & Bemvenuti, 2006; Lucrezi *et al.*, 2009; Lucrezi & Schlacher, 2010; Schlacher *et al.*, 2011, Stelling-Wood *et al.*, 2016), Cirolanidae (Matuela, 2007; Veloso *et al.*, 2011; Hubbard *et al.*, 2014), and the mollusk *Donax* sp. (Defeo & De Alava, 1995).

Along the north coast of Rio de Janeiro state, the summer tourism activities stand as the main anthropic action in some local beaches. Therefore, knowing the effects of different intensity of anthropic activities such as human trampling is essential in the formulation and development of management, conservation and sustainable tourism policies in sandy beaches. In this scenario, the present study evaluated the consequences of this impact on the structure and composition of the benthic macrofauna in two southeast Brazilian beaches with different tourism intensity.

2. Materials and methods

2.1. Study area

This study was conducted in Grussaí and Manguinhos beaches, northern coast of Rio de Janeiro (Fig. 1). Grussaí Beach is characterized by intense hydrodynamic and intermediate topography, with approximately 150,000 tourists on summer months (www.sjb.rj.gov.br), due to leisure activities, restaurants, guesthouses, and concerts. Grussaí Beach is also popular among tourists who practice sports like surf, bodyboarding, soccer, volleyball, in addition to jogging and hiking. Manguinhos is a dissipative bech, and it is a local tourist destination.

We surveyed two areas in each beach, an urbanized (U, exposed to higher numbers of visitors) and a non-urbanized sector (NU, with lower anthropic exposure). The supralittoral of both NU sectors is bordered by sand dune vegetation. The U sector of Grussai beach is restricted by buildings and roads, while Manguinhos beach is limited by small houses and a narrow street. The distance between U and NU sectors is about 3-4 km.

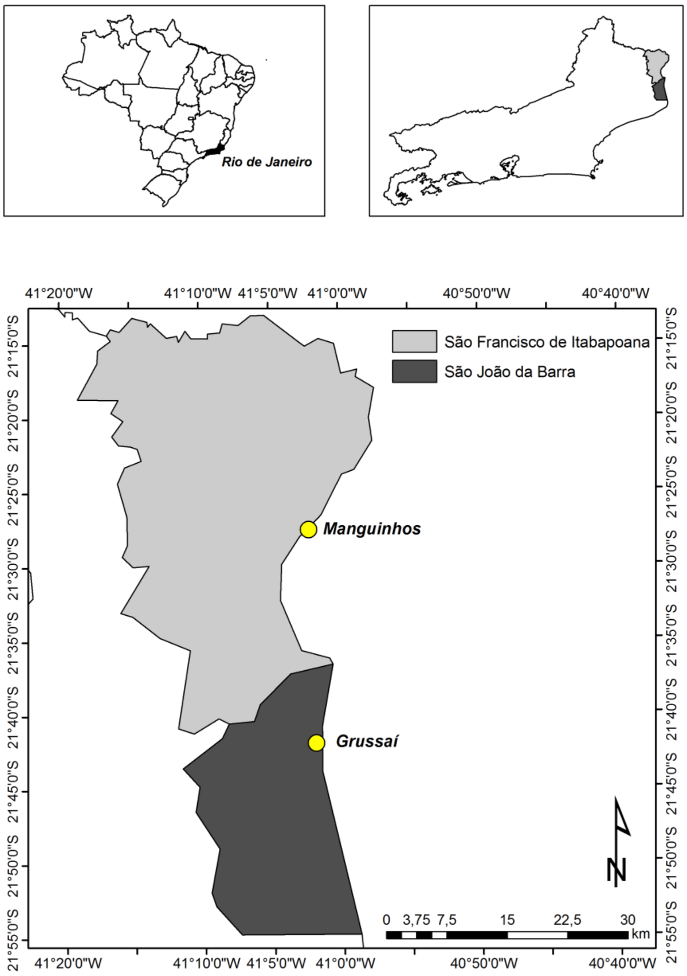


Figure 1. Map of the study beaches (Manguinhos and Grussai) at north Rio de Janeiro, southeast Brazil coast.

2.2. Sampling procedure

Eight surveys were carried out at U and NU sectors of each beach (Grussaí and Manguinhos), four in winter 2012-2013 and four in summer 2013-2014. Macrofauna collection was performed with a corer (20 cm diameter and height) and sediment samples were sieved on a 500- μm mesh in the field (Holme and McIntyre, 1984) and fixed with 10% formaldehyde. In the laboratory, the sediment was screened and organisms were identified to the lowest taxonomic level (Abbott, 1974; Amaral and Nonato, 1996; Serejo, 2004; Amaral et al., 2006) and preserved in 70% ethanol.

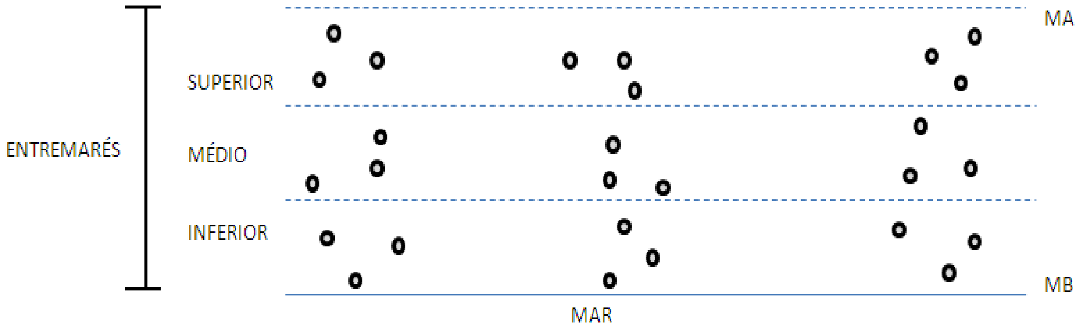


Figure 2. Sampling design used on Manguinhos and Grussaí beaches, northern coast of Rio de Janeiro state.

2.3. Sediment and hydrodynamic analyses

Sediment samples used in the grain size analysis were collected at each intertidal level of each transect, totaling nine samples per campaign. Gravel (>2 mm), coarse sand (<2 mm and >0.5 mm), medium sand (<0.5 mm and >0.25 mm), fine sand (<0.5 mm and >0.063 mm), and silt/clay (<0.063 mm) proportions were determined by sieving (Suguio, 1973). Only fractions b0.5 mm were used in the laser diffraction particle analysis (SALD-3101, Shimadzu). Total organic matter content in nine samples of the sediment was also analyzed. The sediment wasfreeze-dried, homogenized (macerated), and weighed on an analytical balance (0.0001-g precision). The sediment was placed in an oven at 350 °C and weighed again after approximately 12h (Goldin, 1987). Organic matter was calculated following the formula OM (%) = $\{(IW - FW) / IW\} * 100$, where PI = Initial weight and PF = Final weight.

Mean wave period was estimated visually during a 5-min interval. Wave height estimates considered the distance between the top sea surface and the top of the wave, that is, the crest (Alves and Pezzuto, 2009). The swash zone includes the climate considered the swash zone distance stretch of sand between the waterline and the upper limit of the backshore. Spreading time was determined based on the time interval between the formation and the end of each swash (McArdle and McLachlan, 1992).

2.4. Human trampling

The number of visitors recorded during 30-min intervals between 9:00 am and 3:00 pm in each sector (U and NU) was used as parameter to quantify the human trampling intensity in the the same area surveyed for macrofauna, according to Veloso *et al.* (2006).

2.5. Data analysis

The effect of trampling intensity on the structure and composition of the benthic community was evaluated in the U and NU sectors of Grussaí and Manguinhos beaches using the descriptors taxonomic composition, mean species richness, density (number of individuals/m^2) and Shannon-Weaver diversity index (Zar, 1984).

The statistical differences of visitor number, structure descriptor values and species abundance between U and NU sectors were evaluated for each survey using the permutational multivariate analysis of variance (PERMANOVA). The macrofauna association pattern on both sectors (U and NU) and periods (summer and winter) was analyzed using the non-metric multidimensional scaling (nMDS, Bray Curtis dissimilarity index). The data were square-rooted in order to balance the importance of rare species (Clarke & Warwick, 2001). PERMANOVA was used to evaluate the significance of the differences between nMDS groups. When significant differences were observed ($P < 0.05$), *a posteriori* pairwise test was carried out to identify the differences between sectors in each period (summer and winter) and level of the intertidal zone. The similarity percentage (SIMPER) analysis showed the taxa that most contributed to the differences between the groups formed by nMDS. The multivariate analyses and PERMANOVA were carried out in the software PRIMER 6.0.

The trampling effect on the macrofauna density was also evaluated using generalized linear mixed models (GLMMs) (Bolker *et al.*, 2009). Specifically, we analyzed the density of the most frequent species as functions of visitors degree (U and NU sectors).This method allowed to analyze non-normal data (i.e. count data), accounting for over-dispersion caused by high frequency of zeroes and spatial correlations due to successive sampling in the same sites (Tavares *et al.*, 2015; Zuur *et al.*, 2009). Random-intercept models were fitted with beaches, which were considered as random effects to account for spatial pseudo-replication (Zuur *et al.*, 2009). Models were fitted using the Laplacian Approximation, with a negative binomial family as the best error distribution. We checked data for outliers, zero inflation, residuals distribution and other potential problems indicated by Zuur *et al.* (2010).

3. Results

3.1. Physical environment

Grain size distribution did not differ significantly between U and NU sectors in Grussaí and Manguinhos beaches. Fine sand was the main grain size in Grussaí (60%) and Manguinhos (80%) beaches, followed by medium sand (31% and 10%, respectively). Higher organic matter levels were registered on U (Manguinhos: 0.30%, Grussaí: 0.14%) compared to NU sectors (Manguinhos: 0.02%, Grussaí: 0.02%) (Appendix 1). Hydrodynamic parameters did not differ significantly between sectors, but varied between winter and summer periods, mainly wave period and height in Grussaí beach and wave period in Manguinhos beach (Appendix 2).

3.2. Human trampling

The number of visitors during summer surveys was significantly greater in U sector compared with NU sector in both beaches (P <0.05). However, the results show that Grussaí Beach is exposed to higher trampling intensity, due to the larger number of visitors, 20 times as many tourists when compared with Manguinhos Beach (Fig 3A). In winter surveys, the number of visitors in both beaches remained below three people on U and NU sectors (Fig. 3B).

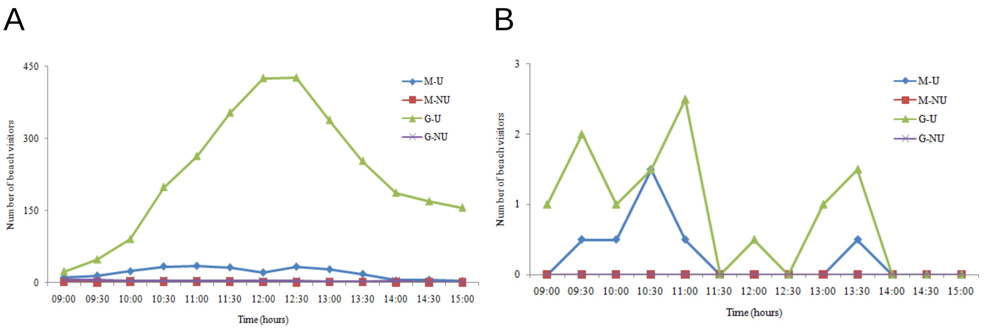


Figure 3. Mean number of visitors recorded in summer (A) and winter (B) surveys in the urbanized (U) and non-urbanized (NU) sectors of Grussaí (G) and Manguinhos (M) beaches, southeast Brazilian coast. The figures have different scales.

3.3. Macrofauna of Grussaí Beach

In total, 25 *taxa* were sampled in the U and NU sectors of Grussaí Beach.

Crustacea was the most abundant group (75%), followed by Polychaeta (10%), Nemertea (9%), Oligochaeta (4%), and Mollusca (2%), with the prevalence of all groups in the NU sector (Fig. 4).

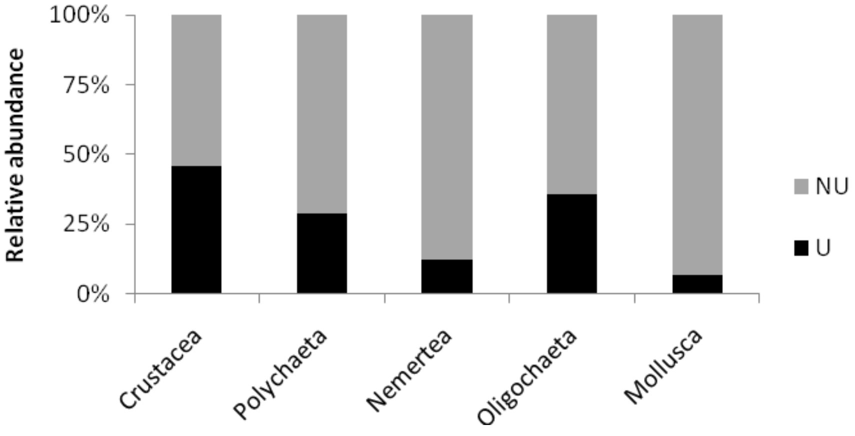


Figure 4. Relative abundance of the main taxonomic groups sampled in the urbanized (U) and non-urbanized (NU) sectors of Grussaí Beach, southeast Brazilian coast.

Significant higher values of species richness, density, and diversity values were recorded in NU sector, especially in the medium intertidal level (Tab. 1, Fig. 5A, B, C). Species density was also significantly higher in the winter surveys, due to the dominance of crustaceans *Excirolana braziliensis* and *Emerita brasiliensis* and polychete *Hemipodia californiensis* (Appendix 3).

Table 1. PERMANOVA and pairwise test related to species richness, density, and diversity between non-urbanized and urbanized sectors of Grussaí Beach in summer and winter surveys (*p< 0.05), southeast Brazilian coast.

Factor		Richness			Density			Diversity index		
	df	MS	F	*P*	MS	F	*P*	MS	F	*P*
Sector (urbanized x non-urbanized)	1	3776	18.81	0.001*	6288	10.966	0.001*	2572	22.308	0.001*
Time (Winter x Summer)	1	3	0.016	0.967	1893	3.301	0.051*	118	1.021	0.325
Intertidal level (upper, medium x lower)	2	4568	22.755	0.001*	20198	35.228	0.001*	1362	11.812	0.001*
Sector x time	1	122	0.607	0.474	283	0.494	0.517	0	0.003	0.986
Sector x intertidal level	2	775	3.861	0.015*	980	1.709	0.168	1048	9.086	0.001*
Time x intertidal level	2	442	2.2	0.091	1346	2.347	0.087	221	1.916	0.138
Sector x time x intertidal level	2	111	0.555	0.623	304	0.53	0.629	196	1.7	0.186
Residuals	420	84313	200.75		240810	573.37		48430	115.31	
Total	431	100000			294930			56774		
Pair-wise test (sector x level)	Groups	Richness						Diversity index		
		t	P(MC)					t	P (MC)	
Upper	UxNU	1.807	0.085					0.256	0.811	
Medium	UxNU	4.803	0.001*					6.018	0.001*	
Lower	UxNU	0.931	0.356					1.84	0.069	

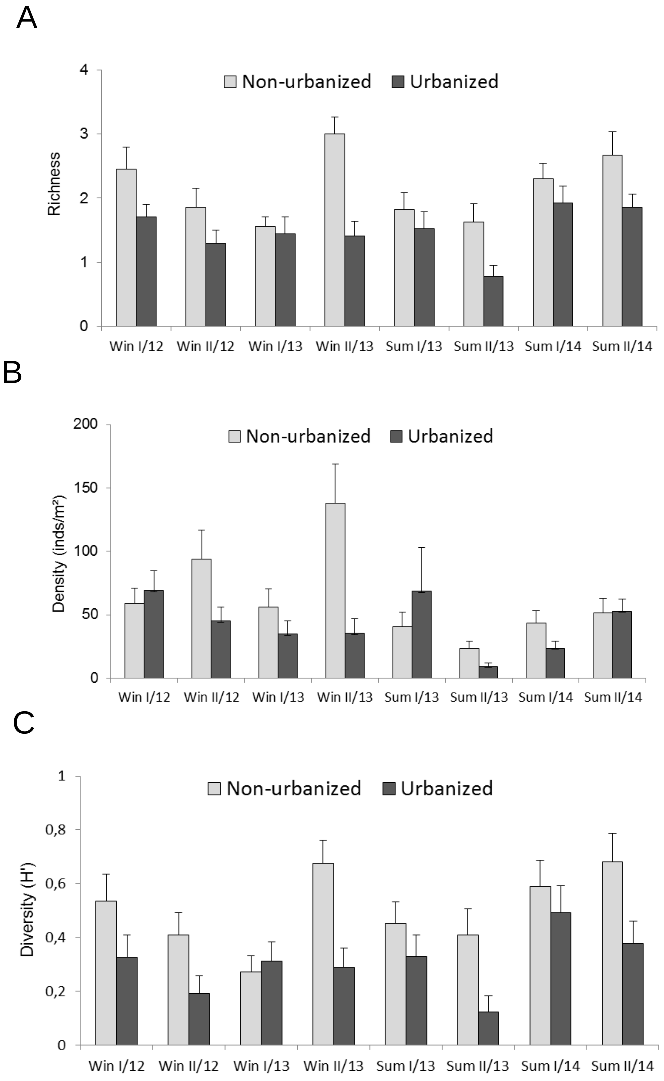


Figure 5. Temporal variation (mean ± SE) of species richness (A), density (B), and diversity index (C) values in the urbanized (U) and non-urbanized (NU) sectors of Grussaí Beach, southeast Brazilian coast.

The species association pattern of the macrofauna at Grussai Beach differed between U and NU sectors, survey periods and intertidal level (Fig. 6, Tab. 2). PERMANOVA and pairwise test showed that macrofauna assemblages on both sectors were different in winter and summer, mainly in the medium level of the intertidal zone (Tab. 2). The taxa that most contributed to these differences (dissimilarity index of 89%) were the crustacean *Excirolana braziliensis* (26.27%), the polychete *Hemipodia californiensis* (13.49%), the crustaceans *Emerita brasiliensis* and *Atlantorchestoidea brasiliensis* (11% each), and Nemertea (10.55%), respectively, generally more abundant in the NU sector (Appendix 3).

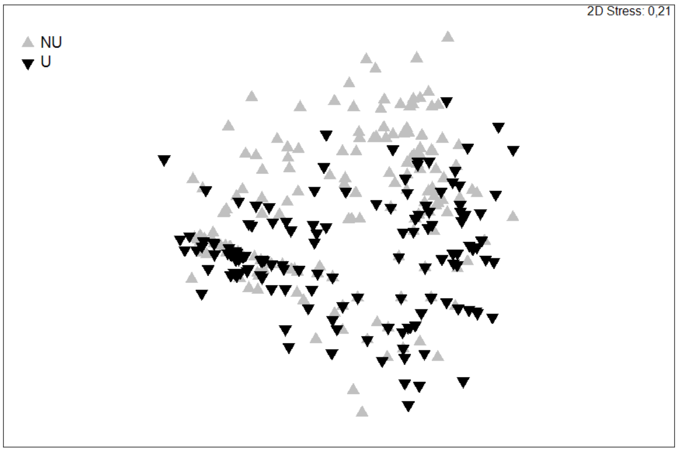


Figure 6. Non-metric multidimensional scaling ordination (nMDS) of the macrofauna assemblages in urbanized (U) and non-urbanized (NU) sectors in Grussaí Beach, southeast Brazilian coast.

Table 2. PERMANOVA and pairwise test related to macrofauna assemblages on non-urbanized and urbanized sectors of Grussaí Beach in summer and winter surveys (*p< 0.05), southeast Brazilian coast.

Factor	df	MS	F	*P*
Sector (urbanized x non-urbanized)	1	22941	15.920	0.001*
Time (Winter x Summer)	1	9850	6.836	0.001*
Intertidal level (upper, medium x lower)	2	105560	73.252	0.001*
Sector x time	1	3119	2.165	0.050*
Sector x intertidal level	2	5741	3.984	0.001*
Time x intertidal level	2	8499	5.898	0.001*
Sector x time x intertidal level	2	1818	1.262	0.240
Residuals	420	605220	1441.000	
Total	431	884360		
a) Pair-wise test (sector x level)	Groups		t	p(MC)
Winter	UxNU		3.399	0.001*
Summer	UxNU		2.625	0.001*
b) Pair-wise test (sector x intertidal level)			t	p(MC)
Upper	UxNU		1.442	0.08
Medium	UxNU		3.781	0.001*
Lower	UxNU		2.395	0.001*

3.4. Macrofauna of Manguinhos Beach

In total, 24 taxa were sampled in the U and NU sectors of Manguinhos Beach. Crustacea accounted for approximately 70% of the macrofauna. Polychaeta and Oligochaeta each represented 15%, followed by Mollusca (2%) and Nemertea (%), with the prevalence of Polychaeta, Mollusca and Nemertea in NU sector, and Crustacea and Oligochaeta in U sector (Fig. 7).

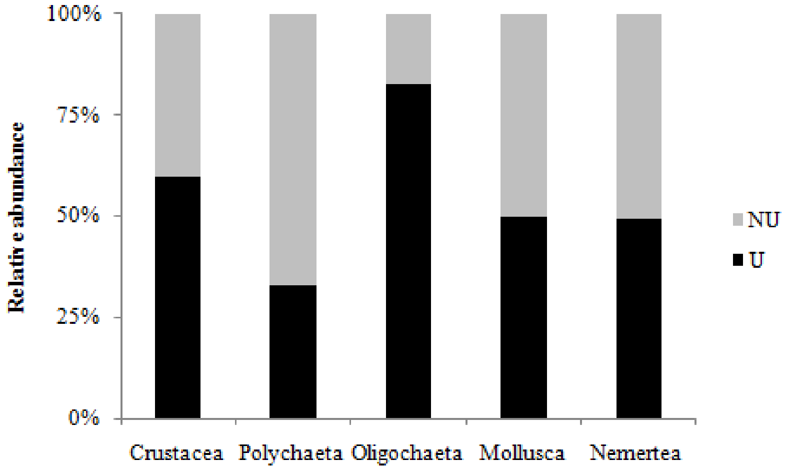


Figure 7. Relative abundance of the main taxonomic groups sampled in the urbanized (U) and non-urbanized (NU) sectors of Manguinhos Beach, southeast Brazilian coast.

Significant differences in species richness, density, and diversity values were recorded between surveys periods and intertidal levels, but not between sectors (Tab. 3). Significantly higher values on winter surveys of species density were due to the dominance of crustaceans *Talorchestia tucurauna*, *Emerita brasiliensis* and *Atlantorchestoidea brasiliensis*, and Oligochaeta (Fig. 8B, 8D, 8E, 8G) (Appendix 4).

Table 3. PERMANOVA and pairwise test related to species richness, density and diversity between non-urbanized and urbanized sectors of Manguinhos Beach in summer and winter surveys (*p< 0.05), southeast Brazilian coast.

Factor		Richness			Density			Diversity index		
	df	MS	F	*P*	MS	F	*P*	MS	F	*P*
Sector (urbanized x non-urbanized)	1	14	0.045	0.902	59	0.082	0.838	2	0.009	0.944
Time (Winter x Summer)	1	1137	3.589	0.053*	1873	2.601	0.116	1768	9.682	0.002*
Intertidal level (upper, medium x lower)	2	8220	25.952	0.001*	17102	23.751	0.001*	3110	17.031	0.001*
Sector x time	1	13	0.041	0.904	54	0.075	0.862	174	0.951	0.317
Sector x intertidal level	2	547	1.727	0.164	1182	1.641	0.192	161	0.882	0.424
Time x intertidal level	2	892	2.816	0.056	2243	3.116	0.044*	110	0.605	0.557
Sector x time x intertidal level	2	180	0.568	0.549	309	0.429	0.692	357	1.954	0.124
Residuals	420	317			720			183		
Total	431									

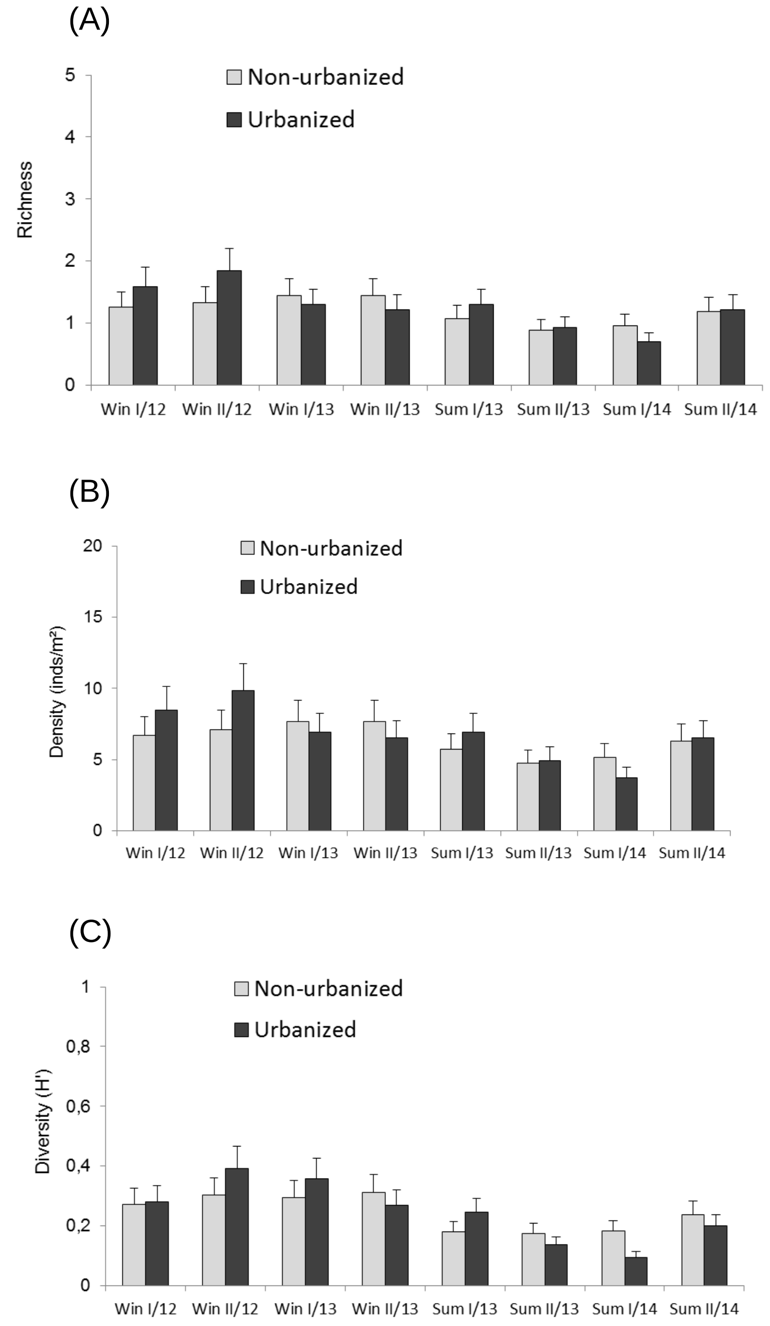


Figure 8. Temporal variation (mean ± SE) of species richness (A), density (B), and diversity index (C) values in non-urbanized (NU) and urbanized sectors (U) of Manguinhos Beach, southeast Brazilian coast.

The species association pattern of the macrofauna in Manguinhos Beach did not differ between NU and U sectors (Fig. 9, Tab. 4). However, the significant interaction between sectors and intertidal levels shows that the macrofauna of NU is different from U at the medium intertidal level (Tab. 4). The taxa that most contributed to this difference (dissimilarity index of 92%) were the polychete *Scolelepis* sp. (38%) and the crustacean *Emerita brasiliensis* (21%), which were more abundant in NU sector in all surveys (Appendix 4).

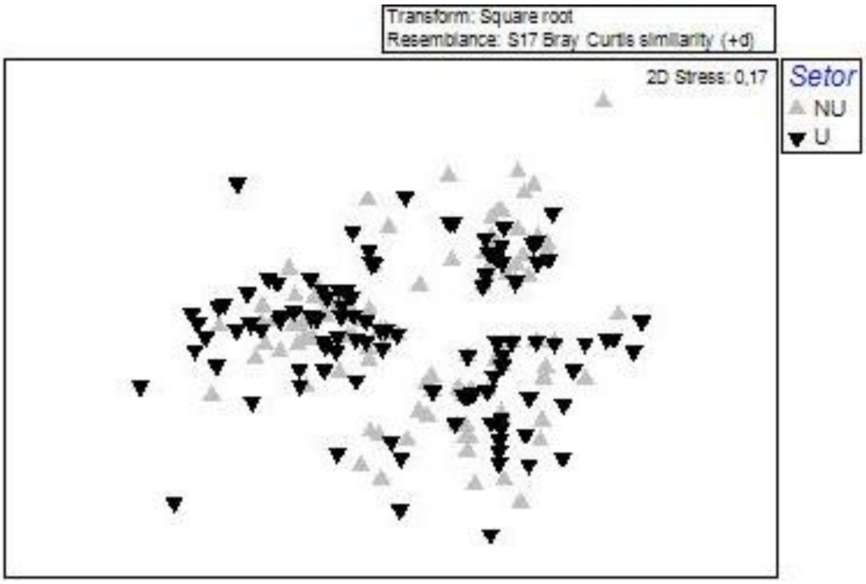


Figure 9. Non-metric multidimensional scaling ordination (nMDS) of the macrofauna assemblages in urbanized (U) and non-urbanized (NU) sectors in Manguinhos Beach, southeast Brazilian coast.

Table 4. PERMANOVA and pairwise test related macrofauna assemblages between non-urbanized and urbanized sectors of Manguinhos Beach in summer and winter surveys (*p< 0.05), southeast Brazilian coast.

Factor	df	MS	Pseudo-F	p
Sector (urbanized x non-urbanized)	1	1215	0.994	0.419
Time (Winter x Summer)	1	9052	7.404	0.001*
Intertidal level (upper, medium x lower)	2	70400	57.581	0.001*
Sector x time	1	1215	0.994	0.417
Sector x intertidal level	2	2192	1.793	0.034*
Time x intertidal level	2	4296	3.513	0.001*
Sector x time x intertidal level	2	1609	1.316	0.154
Residuals	420	1223		
Total	431			
a) Pair-wise test (sector x intertidal level)	Groups		t	p (MC)
Upper	Ux NU		1.083	0.313
Medium	Ux NU		1.805	0.013*
Lower	Ux NU		0.724	0.756

3.5. Generalized linear mixed models (GLMMs)

The intensity effect of human trampling on the most abundant macrofauna species evaluated using GLMMs revealed higher density values in NU sector, mainly in Grussaí Beach (Fig. 10). This difference is smaller in Manguinhos Beach. According to GLMM models, significant association was observed for *Hemipodia californiensis* and marginally significant for *Scolelepis* sp. (Tab. 5), and indicates the predictive power of trampling intensity to forecast the density of these species.

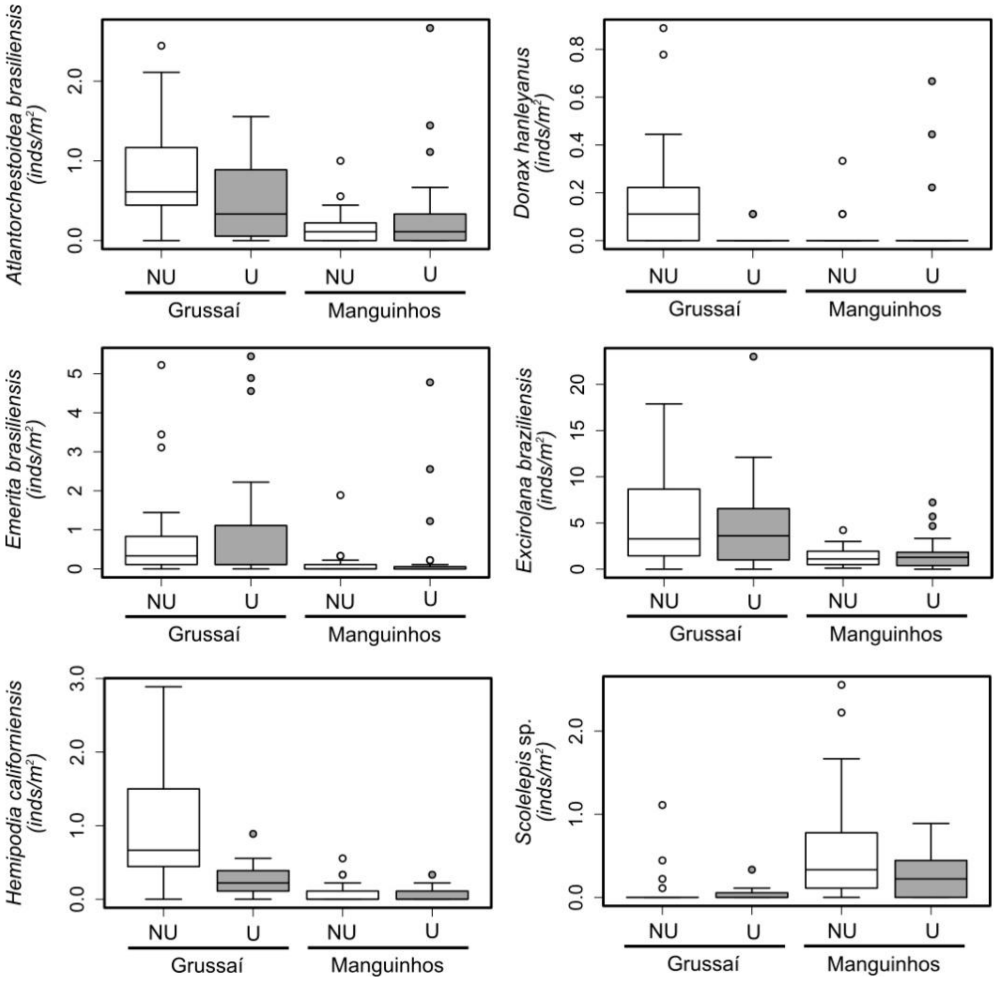


Figure 10. Box plot of the dominant macrofauna species in non-urbanized (NU) and urbanized (U) sectors of Grussaí and Manguinhos beaches, southeast Brazilian coast. Dots indicate outliers.

Table 5. Summary statistics of the Generalized Linear Mixed Models for macrofauna density related to trampling intensity in sandy beaches at north Rio de Janeiro state, Brazil. Models were fitted with negative binomial errors. β indicates 'slopes' for urbanized sectors (U) in comparison to non-urbanized ones (NU). Significant models: * ($p < 0.05$).

Species	**β (Urbanized)**	**SE**	**p-value**
Atlantorchestoidea brasiliensis	-0.20	0.30	0.50
Donax hanleyanus	0	0.87	1
Emerita brasiliensis	0.39	0.38	0.31
Excirolana brasiliensis	0.05	0.20	0.82
Hemipodia californiensis	-1.25	0.42	0.003*
Scolelepis sp.	-0.82	0.44	0.06

4. Discussion

Recreational activities are increasingly observed in sandy beaches, boosting the tourism industry around the world. Investment in urban infrastructure is essential to attract tourists to these beaches (Rolfe & Gregg, 2012). However, the lack of appropriate supervision strategies to these activities may affect the physical and biological stability of beach environments (McLachlan & Brown, 2006; Defeo *et al.*, 2009).

The results of the present study confirm this scenario of anthropic influence. The difference in trampling intensity between NU and U sectors was more evident in summer, mainly in Grussaí Beach. This difference was less marked in Manguinhos Beach, which is less urbanized in terms of infrastructure. There is a direct association between urbanization level and factors such as transportation options (De Ruyck *et al.*, 1998; McLachlan *et al.*, 2013). The U sector in Grussaí Beach includes several restaurants, parking lots, paved streets, in addition to walkways to the beach. In turn, NU sector has no infrastructure and public transport, and does not attract many visitors.

Although it is possible to assess the trampling effects, the results of such evaluations may not represent the natural conditions of the beaches. According to Ugolini *et al.* (2008) and Reyes-Martinez *et al.* (2015), the difficulty to compare actual impacts is explained by inadequate temporal and spatial scales. Therefore, one of the obstacles to evaluate the direct effects of anthropic impact on beach environments lies in the difficulty to differentiate the consequences of human presence from the influence of natural events in beaches (Schlacher & Thompson, 2012). In this sense, the use of two sectors in the same beach afforded to look into the effects of trampling alone, since U and NU sectors share some characteristics in common, like sand grain size, organic matter content in the sediment, and hydrodynamic. In addition, the evaluation of two beaches exposed to different trampling intensities also enabled assessing the effect of visitor number on macrofauna. In Grussaí, which is the most urbanized beach with up to 450 visitors/100m^2 on summer months, the differences in the benthic community were quite evident between U and NU, while in the less urbanized beach (Manguinhos) and around 50 visitors/100m^2, the macrofauna did not differ much between these sectors.

In general, higher values of richness, diversity, and density descriptors of macrofauna were observed in NU sector in Grussaí Beach in both winter and summer. Even in winter, when the beach is exposed to lower trampling intensity, these values were higher in NU sector, suggesting a chronic impact. This result suggests that the benthic community is less resilient to recover from the impact caused by tourists in summer. The intensive trampling pressure in urbanized areas may, in the long term, cause irreversible loss of biodiversity (Reyes-Martinez *et al.*, 2015). Studies have identified the negative effects of trampling on the benthic *taxa* of sandy beaches. For example, Veloso *et al.* (2008) observed reduced abundance of talitrid crustaceans throughout the year in an urbanized beach in Spain, despite the low number of visitors during winter. In a study carried out in Australia, Schlacher *et al*. (2008) did not record any macrofauna representative in the supralittoral of the beaches surveyed, which is the zone most affected by traffic. Vieira *et al.* (2012) also reported low benthic species richness and abundance in urbanized beaches in the state of Paraná, Brazil, due to the more intense recreational activities in summer.

Different patterns of species association were observed in NU and U sectors of Grussaí Beach, the most urbanized. The prevalence of *Excircolana braziliensis* in the U sector may be explained by food debris left by tourists on the beach, since this crustacean species has a detritivorous necrophagous habit (Souza & Gianuca, 1995). Also, the species is gregarious, distributing on the upper intertidal zone of sandy beaches (Dahl, 1952), which is the sector preferred by most visitors in Grussaí Beach. Another important aspect is that cirolanids have an opportunistic feeding habit, consuming and storing large amounts of food, apart from slow digestion (McLachlan & Brown, 2006). These crustaceans remain underground during the ebb tide, emerging only to feed, when waters rise again, mainly at night (Yanicelli *et al.*, 2001), when trampling intensity is low. Therefore, the higher density of this species in the U sector of Grussaí Beach may be associated with its ability to remain buried after feeding on rests of food left behind by visitors, which reduces its trampling vulnerability.

Other crustaceans, mainly the amphipods Talitridae are characterized by leaping organisms that actively exploit the surface of sands during the ebb tide, which increases their exposure to the trampling impacts (Fanini *et al.*, 2005, Ugolini *et al.*, 2008, Veloso *et al.*, 2009). The species *Atlantorchestoidea brasiliensis* was rather sensitive to anthropic effects in both beaches, as revealed by this crustacean' relatively higher abundance in winter, mainly in the NU sector of Grussaí Beach. The species also has some important characteristics that make it an appropriate bioindicator, namely the distribution in middle and upper regions of a beach, direct development, vertical distribution mainly in the top layer of the sediment, and short life cycle (Cardoso & Veloso, 1996). Interestingly, Veloso *et al.* (2008) observed low abundance of talitrids in urbanized beaches in Brazil and Spain used for recreation purposes, similarly to Vieira *et al.* (2012), in a study carried out in an urbanized beach in the state of Santa Catarina, Brazil. Also, two studies by Veloso *et al.* (2006, 2010) revealed that *A. brasiliensis* is not present in urbanized areas in beaches in RJ, Brazil, though high density of the species was reported in protected areas of the same shores.

The most abundant taxa in the NU sector of Grussaí (the polychete *Hemopodia californiensis* and Nemertea) and Manguinhos beaches (*Scolelepis* sp.) exhibit some characteristics that make them more vulnerable, like soft body (Amaral & Nallin, 2011) and absence of hard structures like shells and carapaces (Maccord & Amaral, 2005). The negative influence of recreational activities on the polychete *Euzunus furciferus* was recorded on the coast of Rio Grande do Sul state, Brazil, where the species was found to migrate vertically down into the deeper sediment layers (Vianna, 2008). It may be assumed that *H. californiensis* has the same strategy in scenarios of intense trampling, hiding itself deeper due to its intense burying behavior (Veloso & Neves, 2009). *Scolelepis* sp. was more sensitive to trampling, despite the lower trampling intensity in Manguinhos, contrasting with the results published by Vieira *et al.* (2012), which described the low sensitivity of *S. goodbodyi* due to its distribution in lower regions of the beach.

In addition to the direct effect of human trampling and garbage, the cleaning effect of beaches could also affect the intertidal macrofauna. The U sector of Grussaí Beach is cleaned daily during summer months through cleaning machines, which may influence the establishment of some species negatively while they are being driven on the sand. Faninin *et al.* (2005) also observed the high sensitivity of the talitrid *Talistrus saltador* to the effect of mechanical cleaning in Italian beaches. Another anthropic factor that commonly affects Grussaí Beach is the traffic of off-road vehicles, mainly in the supralittoral. This traffic may lead to loss of biodiversity, dune supression and sediment compaction, in addition to killing some animals, mainly of the benthic fauna, especially isopodes and talitrids (McLachlan & Brown, 2006). Therefore, apart from trampling, the influence of traffic on macrofauna should not be ruled out.

It should also be stressed that the dune vegetation in Grussaí Beach is more conserved in the NU sector, while it has essentially been destroyed by building developments in the U sector. As observed by Fanini *et al.* (2005), the benthic community in Italian beaches where plant cover is preserved retains its natural dynamic. Beach management plans should consider preservation of this vegetation, since the suppression might unbalance the trophic relationships in beach ecosystems (Andersen, 1995; McLachlan & Brown, 2006).

The hypothesis that human trampling triggers changes in structure and composition of benthic macrofauna, reducing species diversity, richness, and abundance of the community was confirmed to Grussai Beach. Manguinhos Beach, which is exposed to <1 person/m^2, shows that this trampling intensity is not enough to reduce the abundance of benthic organisms. These results highlight the importance of management strategies and conservation policies for this costal ecosystem, aiming to maintain the ecological functions of the macrofauna of sandy beaches. The vulnerability of some taxa, mainly *A. brasiliensis*, *H. californiensis*, *Scolelepis* sp., and Nemertea indicate that they might be potential indicators of anthropic impact, and can be used as fast and economically feasible tools to investigate environmental impact.

Research should focus on the knowledge about the effects of urbanization and its consequences on these invertebrates, since beach environments are becoming increasingly urbanized and exposed to several forms of impact besides trampling, like traffic (Lucrezi & Schlacher, 2010), urban occupation of coastal zones (Peterson *et al.*, 2000), suppression of dunes (Bessa *et al.*, 2013), garbage (Hong *et. al.*, 2014), cleaning procedures (Llewellyn & Shackley, 1996), fecal coliforms (Vieira *et al.*, 1999), and nitrogen pollutants (Barradas *et al.*, 2012). The investment in management and conservation strategies is essential as: i) the development of protected areas with restrictions to access and use, ii) the control of the number of visitors considering the influence of trampling, iii) the implementation of passages, iv) the use of less stressing cleaning methods, and v) the prohibition to traffic and buildings dunes (Veloso *et al.*, 2009). Urbanization affects the macrofauna, but also vertebrates like birds (Williams *et al.*, 2004; Tavares *et al.*, 2013; Tavares *et al.*, 2015) and fishes, that prey on this organisms (Pereira *et al.*, 2015). Therefore, the implementation of control measures for the access to beaches becomes imperative.

The results of the present study show that areas exposed to larger numbers of tourists are more susceptible to the trampling and visitors effects on macrofauna. So, control efforts should consider strategies to mitigate these effects as the decentralized occupation of the same beach. In this sense, the extent of impacts would not interfere negatively on the benthic community, as observed in Manguinhos Beach.

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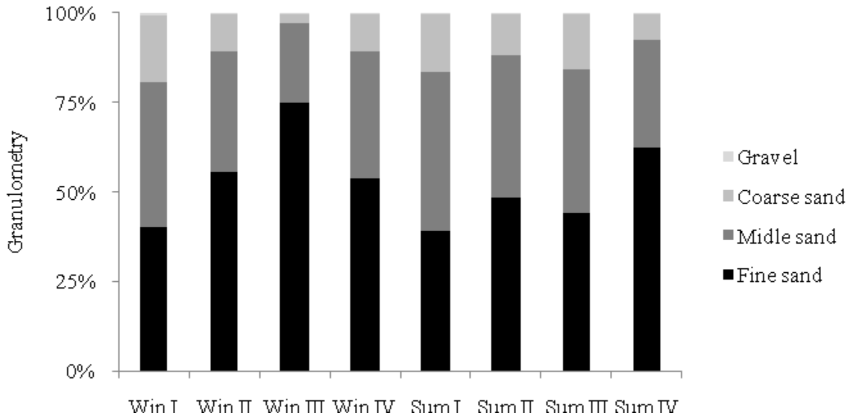
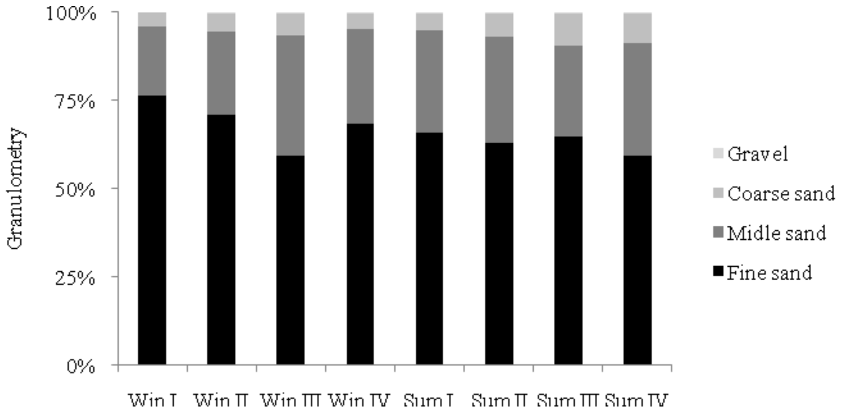
6. Appendix

Appendix 1. Grain size distribution of the sediment in the urbanized (U) and non-urbanized (NU) sectors of Grussaí beach (A and B) and Manguinhos beaches (C and D).

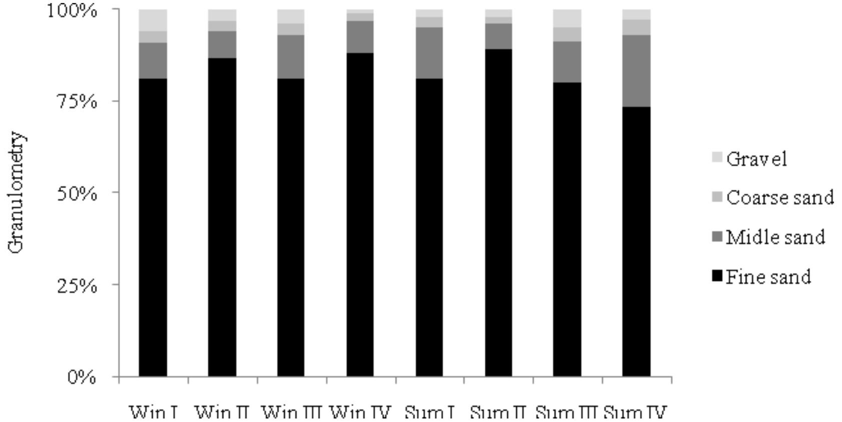
A (NU)



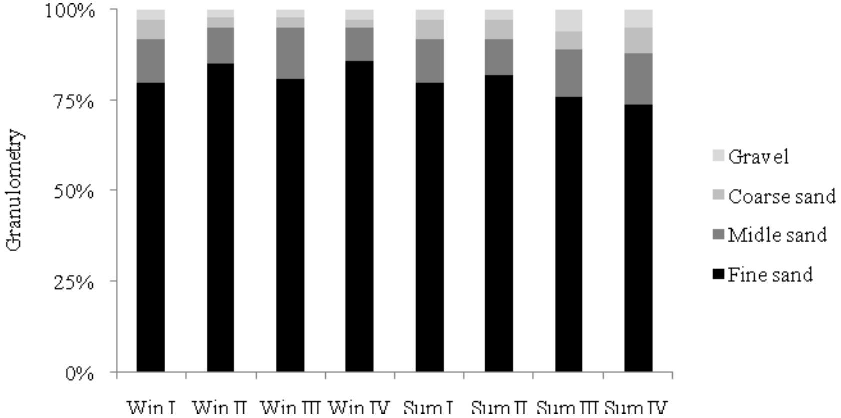
B (U)



C (NU)



D (U)



Appendix 2. Mean values (± SD) of the physical parameters in the urbanized (U) and non-urbanized (NU) sectors of Grussaí (A) and Manguinhos beaches (B). *p < 0.05.

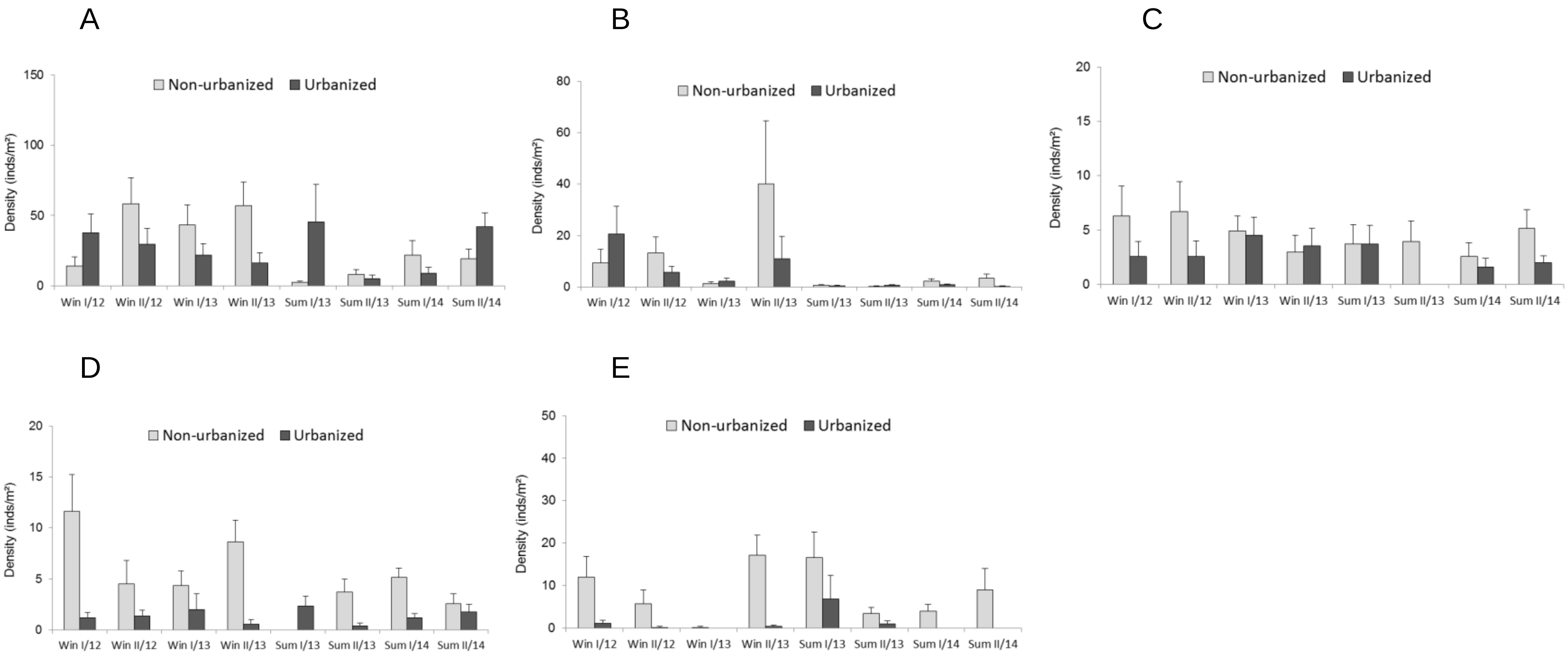
A

	winter I		winter II		winter III		winter IV		summer I		summer II		summer III		Summer IV		
Grussaí beach	U	NU	U	NU	U	NU	U	NU	U	NU	U	NU	U	NU	U	NU	
wave height (cm)	91.00 ±37.80	88.00 ±18.40	86.00 ±38.10	110.00 ±38.10	70.00 ± 9.40	98.00 ±14.80	67.00 ±20.6	88.00 ±19.90	92.00 ±30.80	145.00 ±38.10	72.00 ±9.20	92.00 ±19.90	106.00 ±71.70	116.00 ±36.40	67.00 ±20.60	76.00 ±15.80	* winter *vs* summer
wave period (s)	5.00 ±1.20	5.20 ±1.40	2.70 ±0.80	2.40 ±0.50	3.50 ±1.20	3.00 ±0.00	2.00 ±0.00	3.10 ±0.70	3.40 ±0.50	3.00 ±0.90	3.20 ±0.40	2.00 ±0.50	2.40 ±0.60	2.60 ±0.50	2.00 ±0.00	2.20 ±0.40	* winter *vs* summer
swash zone (m)	5.30 ±1.80	4.00 ±0.00	5.60 ±1.30	4.30 ±1.50	10.40 ±3.90	7.00 ±1.60	7.00 ±3.40	7.60 ±2.50	9.60 ±2.80	7.00 ±1.60	8.50 ±3.40	6.10 ±2.30	9.50 ±4.90	4.40 ±2.00	7.00 ±3.40	6.30 ±2.50	
swash time (s)	5.00 ±1.20	2.40 ±0.50	2.30 ±0.90	2.60 ±0.90	3.40 ±0.70	4.10 ±0.30	3.40 ±0.80	2.60 ±0.50	3.80 ±0.80	2.80 ±1.30	3.30 ±0.80	2.50 ±0.50	2.00 ±0.00	3.50 ±0.70	4.00 ±0.00	3.10 ±0.30	
organic matter (%)	0.06 ±0.06	0.01 ±0.02	0.78 ±0.04	0.01 ±0.00	0.05 ±0.03	0.03 ±0.02	0.04 ±0.03	0.04 ±0.03	0.05 ±0.03	0.04 ±0.03	0.05 ±0.08	0.05 ±0.05	0.02 ±0.01	0.01 ±0.00	0.05 ±0.03	0.02 ±0.02	

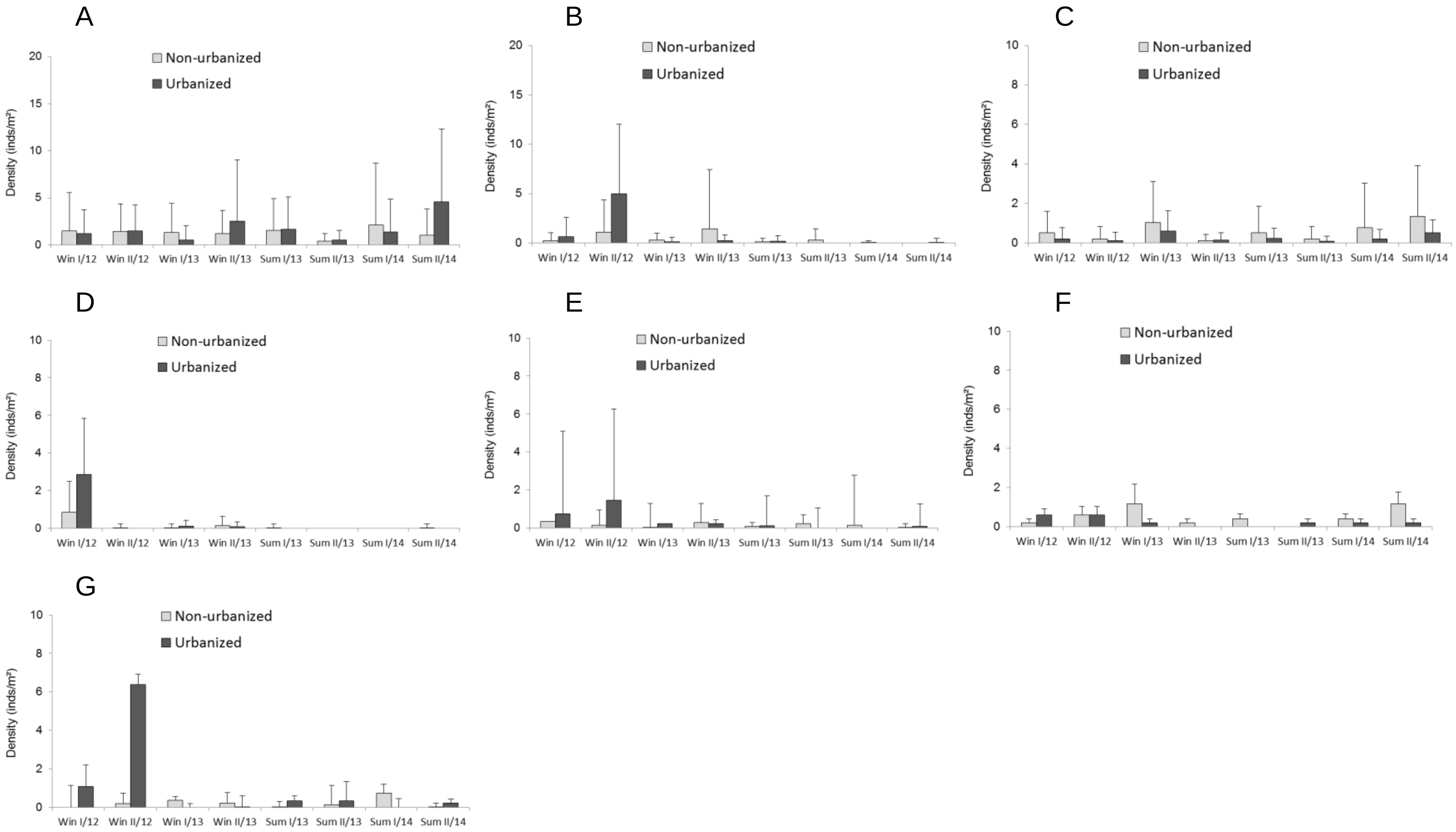
B

	winter I		winter II		winter III		winter IV		summer I		summer II		summer III		Summer IV		
Manguinhos beach	U	NU	U	NU	U	NU	U	NU	U	NU	U	NU	U	NU	U	NU	
wave height (cm)	36.00 ±6.50	40.00 ±15.50	40.00 ±14.10	55.00 ±18.70	27.00 ±4.80	42.00 ±9.20	29.00 ±5.70	44.00 ±9.70	17.00 ±7.9	45.00 ±21.2	17.00 ±7.90	44.00 ±7.00	26.00 ±2.50	50.00 ±16.30	20.00 ±4.10	52.00 ±1.2	
wave period (s)	2.20 ±0.80	5.00 ±0.00	2.70 ±0.50	2.70 ±0.50	2.20 ±0.40	2.00 ±0.00	2.00 ±0.00	1.50 ±0.50	2.20 ±0.40	1.70 ±0.50	2.20 ±0.40	1.00 ±0.00	3.70 ±0.80	2.00 ±0.50	3.50 ±0.50	2.00 ±0.00	* winter *vs* summer
swash zone (m)	4.77 ±0.70	4.30 ±0.60	4.80 ±1.00	8.70 ±2.90	4.80 ±0.70	9.60 ± 3.40	8.40 ±2.5	9.90 ±2.50	3.50 ±0.60	5.80 ±1.90	3.60 ±0.50	8.90 ±1.70	6.20 ±1.40	9.20 ±1.10	3.50 ±1.40	8.90 ±3.00	
swash time (s)	12.60 ±2.30	9.20 ±2.30	4.60 ±0.50	3.00 ±0.70	4.40 ±1.10	6.80 ±0.40	4.60 ±0.7	6.30 ±1.30	2.50 ±0.50	3.60 ±0.90	2.40 ±0.50	4.30 ±0.90	4.90 ±0.90	4.20 ±0.60	3.00 ±0.70	6.30 ±2.40	
organic matter (%)	0.20 ±0.17	0.01 ±0.00	0.57 ±0.07	0.02 ±0.01	0.58 ±1.32	0.02 ±0.00	0.02 ±0.08	0.06 ±0.14	0.14 ±0.04	0.02 ±0.01	0.59 ±1.39	0.04 ±0.07	0.16 ±0.05	0.01 ±0.00	0.16 ±0.04	0.01 ±0.01	

Appendix 3. Temporal variation of mean density values (± SD) of the most abundant taxa of *Excirolana braziliensis* (A), *Emerita brasiliensis* (B), *Atlantorchestoidea brasiliensis* (C), *Hemipodia californiensis* (D), and Nemertea (E) in the urbanized (U) and non-urbanized (NU) sectors of Grussaí Beach.



Appendix 4. Temporal variation of mean density values (± SD) of the most abundant taxa of *Excirolana braziliensis* (A), *Talorchestia tucurauna* (B), *Scolelepis* sp. (C), *Emerita brasiliensis* (D), *Atlantorchestoidea brasiliensis* (E), *Hemipodia californiensis* (F), and Oligochaeta (G) in the urbanized (U) and non-urbanized (NU) sectors of Manguinhos Beach.



Capítulo 3 (Publicado na Revista Marine Pollution Bulletin em Abril de 2016 – pdf em anexo)

Extreme storm wave influence on sandy beach macrofauna with distinct human pressures

Abstract

We evaluated the influence of storm waves on the intertidal community structure of urbanized and non-urbanized areas of a sandy beach on the northern coast of Rio de Janeiro, Brazil. The macrofauna was sampled before (PREV) and after two storm wave events (POEV I; POEV II) in 2013 and 2014. Significant differences in community structure between PREV and POEV I in the urbanized sector demonstrate higher macrofauna vulnerability, and the community recovery within 41 days on this scenario of less frequent events in 2013. On the other hand, significant differences in the macrofauna only in the urbanized sector between PREV and POEV II also highlight macrofauna vulnerability and community recovery failure within 42 days on this scenario of more frequent storm in 2014. Urbanization and wave height were the variables that most influenced species, indicating that high storm wave events and increasing urbanization synergism are a threat to the local macrofauna.

Keywords: macrofauna, extreme weather events, anthropogenic impact, community structure, sandy beaches.

1. Introduction

Coastal development inherent to economic progress has resulted in extensive changes, especially on sandy beaches, due to their tourist and recreational importance (McLachlan *et al*., 2013). Besides climate change, anthropogenic impacts threaten the maintenance of functions, goods and environmental services provided by these coastal ecosystems (Defeo *et al.*, 2009; Harley *et al*., 2006).

The increase in the frequency and intensity of extreme events is one of the consequences listed by climate change reports (IPCC, 2013). Storm waves are among the main extreme weather events on the Brazilian coast. The occurrence of cold fronts, storms, and comparatively higher waves generates direct impacts on beach hydrodynamics and sediment flows, leading to more intense waves and changes in sandy sediment fraction (Alves & Pezzuto, 2009). Thus, storm waves alter beach morphodynamics and, consequently, the local topographic profile (Brauko, 2009). Also, these events revolve sediment, and thus may increase organic matter available on drift line (Alves & Pezzuto, 2009).

Physical factors such as sand grain size, wind speed, and topography have been shown to affect material and energy cycling in sandy beaches on a spatial scale (McLachlan & Brown, 2006). Besides, the availability of organic matter as nutrient to macrofaunal organisms is crucial to understand their habitat association patterns in sandy beaches (Lastra *et al.*, 2006).

The intertidal macrofauna is adapted to severe hydrodynamic conditions (Veloso *et al*., 1997), however increased wave intensity in sandy beaches may alter the structure and composition of the community both directly (affecting survival of species) and indirectly (changing the environmental characteristics) (Brown, 1996; Posey *et al*., 1996; McLachlan & Brown, 2006).

The erosion processes that begin after storms might induce sediment defaunation, and it may take months, or even years, for environment recolonization to begin (Jaramillo *et al*., 1987). In exposed sandy beaches, massive mortality of benthic organisms may result from storm events due to erosive processes and alterations in the position of the swash zone (McLachlan, 1996). However, other studies that evaluated the effects of extreme events on beaches found no significant reduction in macrofauna abundance and richness (Saloman & Naughton, 1977; Hughes *et al*., 2009*;* Sola & Paiva, 2001; Gallucci & Neto, 2004; Cochôa *et al*., 2006; Alves & Pezzuto, 2009).

The influence of storm wave events is also described as favoring suspensivorous organisms, due to the resuspension of sediment material (Bock & Miller, 1995). Detrivorous also benefit in response to the increased availability of natural debris thrown into the beach by the waves (Alves & Pezzuto, 2009).

It should be considered that these studies were conducted at beaches without anthropogenic interference, and that urbanization might influence the community responses to natural stochastic events, since recovery after erosion processes is slower in urbanized coasts (Castelle *et al.*, 2008; Harris *et al.*, 2011; Witmer & Roelke, 2014). Therefore, the lack of knowledge about future scenarios in increasingly urbanized sandy beaches is evident.

Pre- and post-storm event studies have been carried out in distinct coastal ecosystems (see Underwood, 1999 on rocky shores; Larsen, 1985 on estuarine reef oysters; Whanpetch *et al.*, 2010 on seagrass communities and Lomovasky *et al.*, 2001 on a sublittoral bay). These investigations reported different species composition and interactions, low species abundance and diversity and poor recovery capacity.

Despite the long Brazilian coast, which is over 8,000 km long, few studies have evaluated the influence of extreme events on benthic communities in Brazilian beaches (Sola & Paiva, 2001; Galluci & Neto, 2004; Cochôa *et al.*, 2006; Brauko, 2008; Alves & Pezzuto, 2009). This lack of information becomes more relevant when we consider that Brazilian beach dynamic is often influenced by frontal systems, triggering high-energy events (Calliari & Klein, 1993) besides the rapid urbanization of the coast, which represents a critical issue in Brazil.

So, this study evaluated the effect of the interaction between natural extreme events (storm waves) and urbanization on the benthic intertidal macrofauna on the southeastern coast of Brazil based on the hypothesis that the urban beach community has less recovery capability to pre-event conditions when compared to non-urban beaches.

2. Material and Methods

2.1. Study area

Located at São Joãoda Barra, northern coast of Rio de Janeiro state (Brazil), Grussaí is an intermediate sandy beach about 10 km long and exposed to wave action. The microtidal beach has a wide coastal strip formed by areas of considerable human pressure (urbanized sector: U) and others with low visitation rates (non-urbanized sector: NU), 4 km away from each other (Fig. 1). The NU sector is characterized by dune vegetation and it is an environmentally protected area. Tourist numbers during the summer reach up to 150,000 people at São João da Barra, about four times as high as the official local population (34.583 inhabitants according to IBGE, 2015). Throughout the summer, most of the tourists remain in the urbanized sector, since it is about 5 km distant from the town and offers better infrastructure such as recreational activities, paved roads, gastronomic centers, hostels, accessibility walkways, and beach activities that include several sports. Trampling and vehicle traffic are the main human activities on urbanized sector. Seawalls, dikes, nourishment are absent and beach cleaning operations are conducted mainly on the supralittoral.

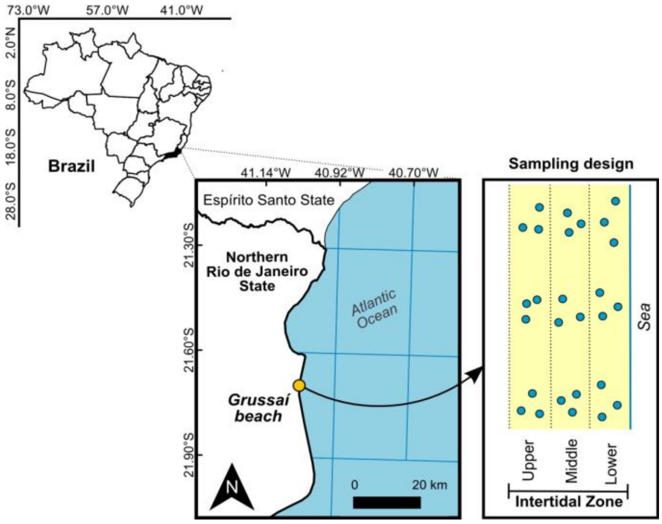


Figure 1. Map of the study area showing Grussaí beach, northern coast of Rio de Janeiro state and the sampling design.

According to the National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais - INPE), waves higher than 2 m characterize storm wave events in the study area. At São João da Barra, where Grussaí beach is located, 2.0-m to 3.0-m wave events occurred in three monitoring years, 2012-2014, most often from May to October (Fig. 2). Waves higher than 2.5 m were infrequent throughout the entire monitoring period (N=5).

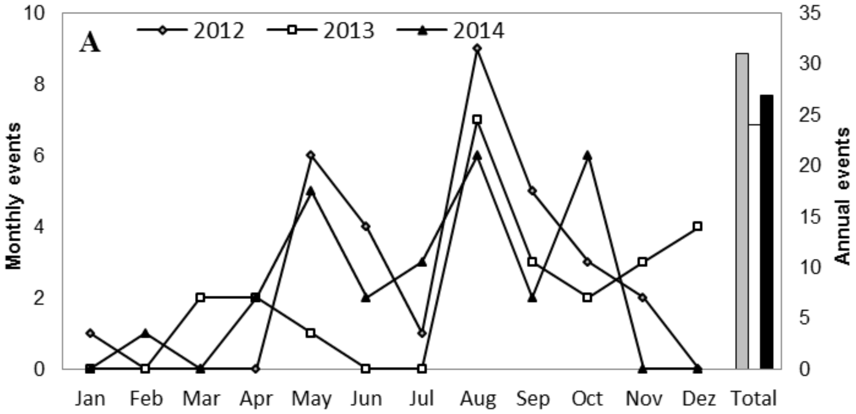


Figure 2. Monthly and annual number of storm waves events predicted for the years 2012, 2013, 2014 (www.cptec.inpe.br). Grey bar: 2012, white bar: 2013, black bar: 2014.

2.2. Sampling design

The before-after control impact (BACI) sampling strategy (Underwood, 1994) was used to characterize the macrofaunal structure before the disturbance (PREV) and to assess macrofauna ability to return to its status prior the disturbances on two time frames (post-event I, POEV I, and post-event II, POEV II) (Fig. 3).

The effect of extreme storm wave events of different intensities and frequencies was evaluated in each beach sector (NU and U). In 2013, events were more intense (2.5-m to 3.0-m waves) and less frequent (N=2events), while in 2014 events were less intense (2.0-m to 2.5-m waves) and more frequent (N=7events).

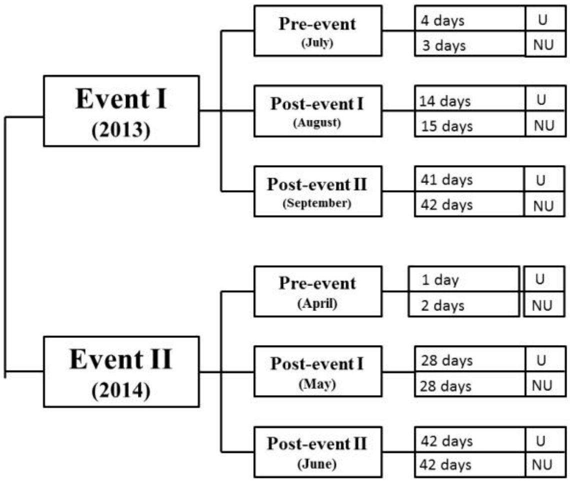


Figure 3. Schematic representation of the sampling strategy of the benthic intertidal macrofauna at both sectors (U and NU) of Grussaí beach**.**

Sediment samples were collected along three transects perpendicular to the coastline, set 50 m apart. Three equidistant sampling points were determined in each transect of the intertidal zone (upper, middle and lower mesolittoral). At each point, three samples approximately 2 m apart were collected, totaling 27 samples per sampling campaign in each sector (Fig. 1).

Macrofauna collection was performed with a corer (20 cm diameter and height) and sediment samples were sieved on a 500-µm mesh in the field (Holme & McIntyre, 1984) and fixed with 10% formaldehyde. In the laboratory, the sediment was screened and organisms were identified to the lowest taxonomic level (Abbott, 1954; Amaral & Nonato, 1996; Serejo, 2004; Amaral *et al.*, 2006) and preserved in 70% ethanol.

2.3. Environmental variables

Sediment samples used in the grain size analysis were collected at each intertidal level of each transect,totaling nine samples per campaign. Gravel (>2 mm), coarse sand (<2 mm and >0.5 mm), medium sand (<0.5 mm and >0.25 mm), fine sand (<0.5 mm and >0.063 mm), and silt/clay (<0.063 mm) proportions were determined by sieving (Suguio, 1973). Only fractions <0.5 mm were used in the laser diffraction particle analysis (SALD-3101, Shimadzu). Total organic matter content in nine samples of the sediment was also analyzed. The sediment was freeze-dried, homogenized (macerated), and weighed on an analytical balance (0.0001-g precision). The sediment was placed in an oven at 350 °C and weighed again after approximately 12 h (Goldin, 1987). Organic matter was calculated following the formula OM (%) = {(IW-FW)/IW}*100, where PI = Initial weight and PF = Final weight.

Mean wave period was estimated visually during a 5-min interval. Wave height estimates considered the distance between the top sea surface and the top of the wave, that is, the crest (Alves & Pezzuto, 2009). The swash zone includes the climate considered the swash zone distance stretch of sand between the waterline and the upper limit of the backshore. Spreading time was determined based on the time interval between the formation and the end of each swash (McArdle & McLachlan, 1992). The topographic beach profile was characterized in three transects according to the topographic leveling method during all sampling campaigns using a level ruler.

2.4. Data analysis

The effects of storm wave events on the structure of the benthic macrofauna were evaluated in each scenario (2013 and 2014) separately through comparative analyses between pre- and post-event sampling campaigns and between urbanized and non-urbanized areas, considering the species richness, density (individuals/m^2), and the Shannon-Weaver diversity index (H’). The differences were tested by a non-parametric variance analysis (Kruskal-Wallis), since the samples did not follow a normal distribution according to the Shapiro-Wilk normality test. When significant differences were detected, the *a posteriori* Dunn test was applied (Zar, 1984). These tests were performed using the BioEstat 5.0 statistical package. The MDS ordenation method and the Bray Curtis index as dissimilarity measure was applied to visualize the macrofauna association pattern before and after the events. The data were square rooted to balance the importance of rare and numerically dominant species

(Clarke & Warwick, 2001). In order to compare the pre- and post-event samples considering the different intertidal levels (lower, middle and upper) and the different sectors (U and NU), a PERMANOVA was carried out with 999 permutations. In case of significant differences ($p < 0.05$) a pair-wise test was performed to identify the pre- and post-event differences in each intertidal level (Clarke & Warwick, 2001). Multivariate analyses were performed using the statistical software PRIMER 6.0.

The most important variables affecting macrofauna abundance were assessed using Generalized Linear Models with negative binomial family as the best error distribution, according to graphical diagnostics (Zuur *et al.*, 2009). This method allowed analyzing non-normal data and over dispersion caused by zeros, affording inferences on how environmental variables influence species counts (Tavares *et al.*, 2015). Before starting the modeling steps, the data were explored in an attempt to detect and correct outliers, colinearity, and spatial and temporal correlations (Crawley, 2007; Zuur *et al.*, 2009).

Models were fitted step-by-step from a full model, including the following variables as fixed effects: wave height, coarse sand, medium sand, fine sand, and the beach sector (U or NU). Specifically, models were constructed for the five most representative macrofauna species included as response terms. Candidate models were ranked and selected according to the Akaike’s Information Criterion (AIC) (Burnham & Anderson,2002). As small differences in AIC scores (ΔAIC) indicate models with similar performances, model averaging was performed in the subset of models with ΔAICs smaller than 2 using the natural average method to avoid decreasing in effect sizes (Burnham & Anderson, 2002; Nakagawa & Frackleton, 2011; Grueber *et al.*, 2011). The inference about the most important variables affecting the macrofauna species was based on the model-averaged coefficients for significant terms and graphical inspection of response curves.

3. Results

3.1. Scenario 1 (2013): lesser frequency of storm wave events (N=2) and higher wave intensities (2.5 to 3.0 meters)

3.1.1. Environmental parameters

In the scenario of consecutive extreme events of lower frequency and higher intensity, wave periods and heights were significantly different during the storm event itself in the urbanized (U) and non-urbanized (NU) sectors. No significant temporal differences were observed for organic matter and the other parameters analyzed (Tab. 1).

Table 1. Mean ± standard deviation of hydrodynamic parameters and organic matter content of the sediment measured in the non-urbanized (NU) and urbanized (U) sectors in the pre and post-event sampling of 2013. WP: wave period; WH: wave height; SZ: swash zone; ST: swash time; **p <0.05*; ns: not significant; OM: organic matter. (PREV: pre-event; EVE: event; POEV I: post-event I; POEV II: post-event II). A = pre-event, B = event, C = post-event I, D = post-event II.

2013	**PREV**	**EVE**	**POEV I**	**POEV II**	**p**	**Dunn test**
NU	A	B	C	D		
WP	3.6 ±0.1	2.8 ±0.5	3.7 ±0.7	3.7 ±1.0	<0,01*	B≠A=C=D
WH	98.0 ±14.4	250.0 ±14.4	69.0 ±12.9	88.0 ±19.9	<0,01*	B≠A=C=D
SZ	7.0 ±1.6	7.9 ±3.8	5.7 ±2.1	7.6 ±2.5	ns	-
ST	4.1 ±0.3	2.6 ±0.7	2.9 ±0.7	2.6 ±0.5	ns	-
OM (%)	0.4 ±0.5	-	0.5 ±0.2	0.4 ±0.2	ns	-
U	A	B	C	D		
WP	3.5 ±1.2	2.9 ±0.4	5.3 ±0.6	3.3 ±0.5	<0,01*	B≠A=C=D
WH	70.0 ±9.4	260.0 ±42.0	61.1 ±24.4	78.0 ±16.9	<0,01*	B≠A=C=D
SZ	10.4 ±3.9	5.6 ±1.5	7.9 ±2.8	9.0 ±3.5	<0,05*	B≠A=C=D
ST	3.4 ±0.7	3.7 ±1.2	3.3 ±0.9	3.4 ±0.8	ns	-
OM (%)	0.4 ±0.2	-	0.4 ±0.3	0.8 ±0.6	ns	-

The topographic profile of the NU sector was characterized by more intense erosion in the middle and upper range of the intertidal zone (from 70 m onwards) with a shortening of the surf zone and consequently more direct wave breaking on the beach face during the event (Fig 4A). The U sector was characterized by a greater sediment deposition in the lower and middle intertidal zones (from 100 m onwards) after the storm waves (Figure 4B). The variation of the topographic profile between events was similar in both sectors, around 0.7 and 1.0 m in the NU and U sectors, respectively.The predominant size fractions were coarse sand and medium sand, followed by fine sand, with no significant differences between pre and post-events in the U and NU sectors.

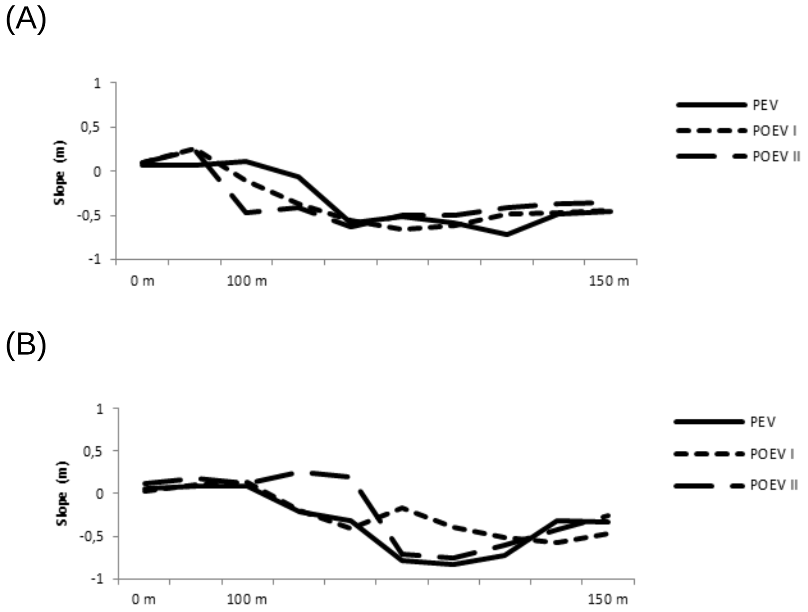


Figure 4. Topographic profile of Grussaí beach in the non-urbanized (A) and urbanized (B) sectors in 2013 considering the pre-event (PEV), post-event I (POEV I) and post-event II (POEV II) sampling periods. The distance 0 m corresponds to the beginning of the supralittoral zone.

3.1.2. Macrofauna

3.1.2.1. Taxonomic composition

A total of 11 taxa were sampled (NU=10; U=8), with crustaceans *Mysida* sp. and *Puelche* sp. exclusive to the NU sector. Crustaceans *Excirolana braziliensis*, *Emerita brasiliensis* and *Atlantorchestoidea brasiliensis*, the polychaetes *Hemipodia californiensis* and *Pisionidens indica* and Nemertea represented 95% of the community in the NU sector and 90% in the U sector. Among these, *E. braziliensis* was the predominant taxon, totaling about 50% of the macrofauna in both sectors.

The density of the most abundant species *E*. *braziliensis* and *A*. *brasiliensis* (U and NU) decreased after the storm wave events, though an increase mostly in density of *E. braziliensis* was observed in post-event 2. The density of other taxa after the events was generally higher, especially the species *Emerita brasiliensis* in the NU sector (Fig. 5).

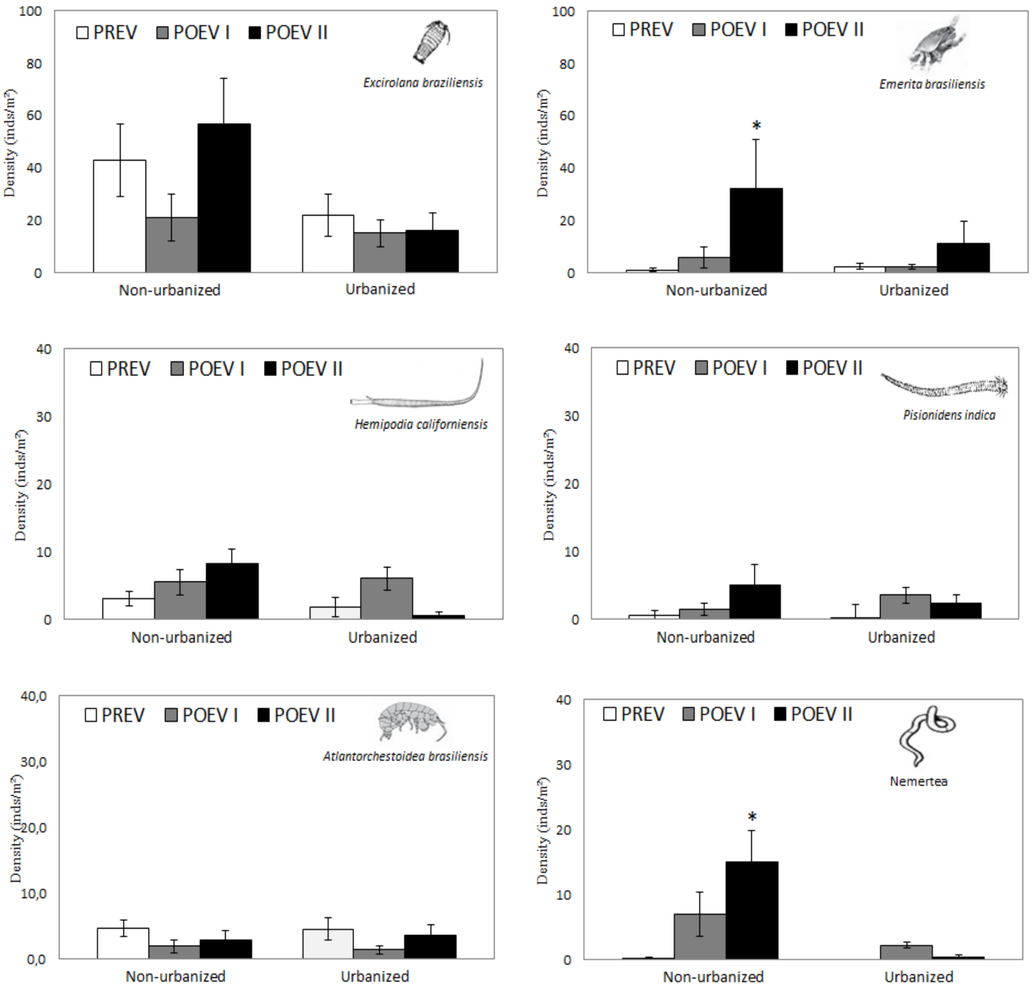


Figure 5. Average density values (SE) of the main macrofauna taxa in pre and post-event sampling periods at the urbanized and non-urbanized sectors at Grussaí beach (*p <0.05). Illustrated taxa: Pinotti *et al.* (2014), McLachlan& Brown (2006) and Ruppert & Barnes (1996).

3.1.2.2. Structure indicators

In this scenario of two consecutive storm wave events, the community structure indicators revealed a significant increase in mean richness, density and diversity values after the events in the NU sector (Fig. 6). It is noteworthy the higher values at the NU sector than on U.

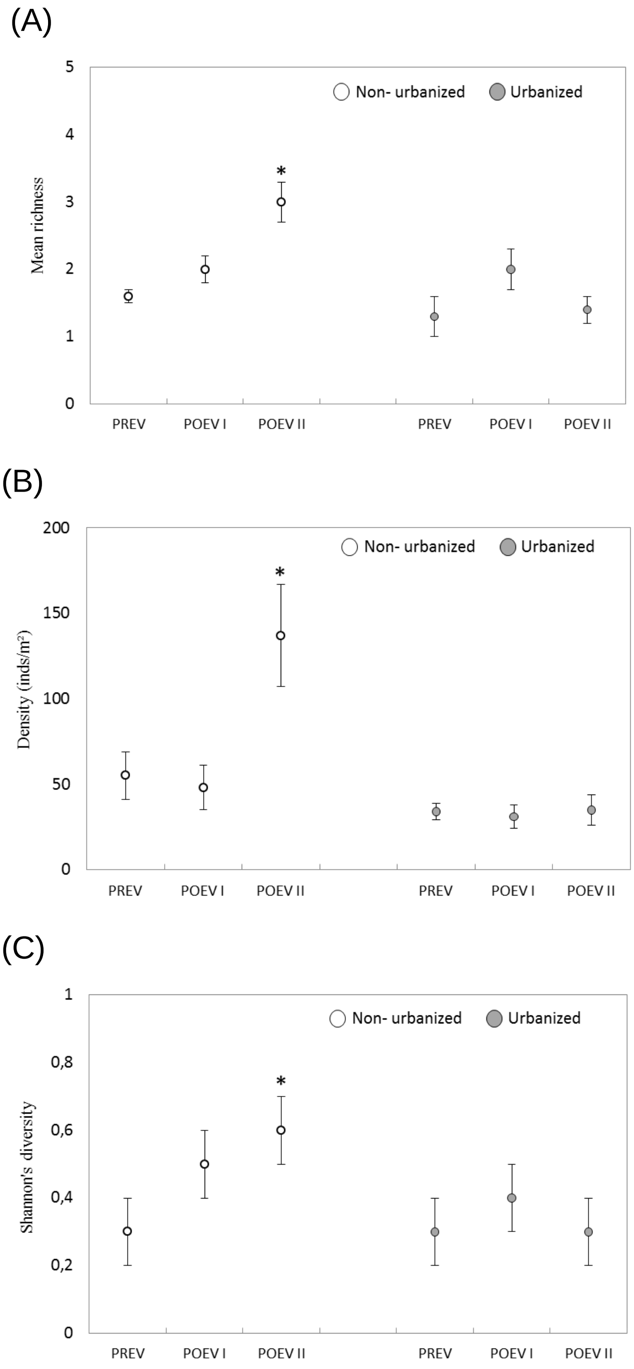


Figure 6. Mean values and standard error of the community structure indicators in the pre and post-event sampling periods in the urbanized and non-urbanized sectors at Grussaí beach. A: richness; B: density; C: Shannon diversity. PREV: pre-event; POEV I: post-event I; POEV II: post-event II; * $p < 0.05$.

3.1.2.3. Macrofauna association pattern

The MDS ordination regarding the NU and U sectors indicated the samples separation according to the tidal level, with the macrofauna of the superior mesolittoral more clustered, regardless the storm wave event (Fig. 7A and B).

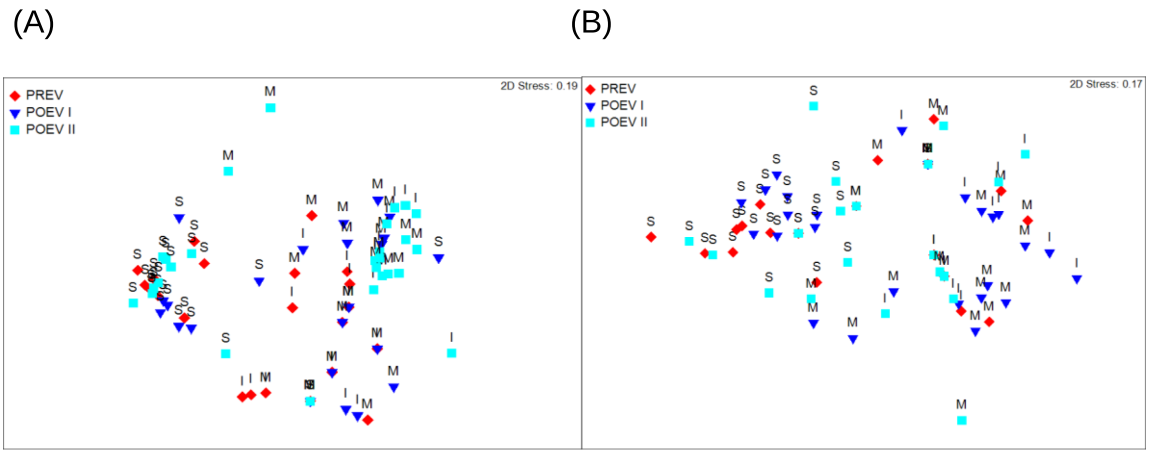


Figure 7. MDS ordination plots for the macrofauna abundance on the non-urbanized (A) and urbanized (B) sectors of Grussaí Beach (storm event scenario 2013). Filled symbols represent pre-event (PREV), post event I (POEV I) and post event II (POEV II). S=upper level, M=middle level, I=lower level of the intertidal zone.

The PERMANOVA confirmed the significant differences between the intertidal macrofauna levels and the interaction event/level in both sectors (Tab. 2). The *a posteriori* test pointed out the effect of the storm waves in the U sector considering the three intertidal levels. On the other hand, in the NU sector the macrofauna differences in the lower and middle levels occurred only in POEV II, i.e. independently of the events (Tab. 2).

Table 2. PERMANOVA results between levels of the intertidal zone (upper, middle and lower), events (pre-event, post-event I and post-event II) and the interaction between these factors in the 2013 scenario *p<0.05: significant differences; p(MC): p value with the Monte Carlo test.

PERMANOVA	Non-urbanized			Non-urbanized		
Factor	F	p (MC)	Perms	F	p (MC)	Perms
Event	1.580	0.226	950	1.303	0.298	951
Intertidal level	27.513	0.001*	998	27.435	0.001*	999
Event x intertidal level	3.219	0.002*	997	2.274	0.009*	999
Pair-wise test	Non-urbanized			Urbanized		
Lower level	Pre-event = post-event I ≠ post-event II			Pre-event ≠ post-event I		
Medium level	Pre-event = post-event I ≠ post-event II			Pre-event ≠ post-event I		
Upper level	No significant difference			Pre-event ≠ post-event I		

3.2. Scenario 2 (2014): higher frequency of storm wave events (N=7) and lesser wave intensity (2.0 – 2.5 m)

3.2.1. Environmental parameters

In the scenario of higher frequency and lower intensity of consecutive extreme events, wave height and period differed significantly during the storm event itself in both U and NU sectors. None of the other hydrodynamic parameters, such as swash zone e swash time varied significantly (Tab. 3). The content of organic matter in the sediment showed no significant temporal differences, but there was an increase in post-events values.

Table 3. Mean ± standard deviation of hydrodynamic parameters and organic matter content of the sediment in the non-urbanized (NU) and urbanized (U) sectors in pre and post-events of 2014. WP: wave period; WH: wave height; SZ: swash zone; ST: swash time; *p<0.05; ns: not significant; OM: organic matter; A: pre-event (PREV), B: event (EVE), C: post-event I (POEV I) and D: post-event II (POEV II). A = pre-event, B = event, C = post-event I, D = post-event II.

2014	**PREV**	**EVE**	**POEV I**	**POEV II**	**p**	**Dunn test**
NU	A	B	C	D		
WP	4.1 ±1.0	2.8 ±0.8	3.6 ±0.3	5.1 ±0.8	<0,03*	B≠A=C=D
WH	115.6 ±36.4	200.0 ±33.3	102.2 ±30.3	76.0 ±15.0	<0,01*	B≠A=C=D
SZ	4.4 ±2.0	6.0 ±1.6	7.2 ±1.9	6.3 ±2.5	ns	-
ST	3.6 ±0.7	2.0 ±0.9	2.1 ±0.6	3.1 ±0.3	ns	-
OM (%)	0.6 ±0.4	-	1.1 ±1.0	1.3 ±1.2	ns	-
U	A	B	C	D	<0,01*	A=B≠C=D
WP	3.7 ±0.7	2.8 ±0.6	5.3 ±0.6	5.5 ±0.0	<0,01*	B≠A=C=D
WH	105.5 ±71.6	200.0 ±8.9	118.0 ±28.2	66.7 ±20.6	<0,05*	-
SZ	8.8 ±4.5	6.8 ±1.2	8.5 ±2.1	7.0 ±3.3	ns	-
ST	2.0 ±0.0	2.8 ±0.4	2.8 ±0.4	4.0 ±0.0	ns	-
OM (%)	0.4 ±0.3	-	0.5 ±0.4	0.4 ±0.1	ns	-

The topographic profile at both sectors was influenced by the storm waves. At the NU sector, the erosion was most intense after the events from 50 m onwards, as revealed by the pits in the intertidal area (Fig. 8A). At the U sector the depositional sediment processes were more intense from 100 meters onwards (Fig. 8B). It is also worthnoting the formation of arches by erosion towards the waterline. The oscillation of the topographic profile between events was similar in both sectors, around 1.0 and 1.3 m at the NU and U sectors, respectively.The predominant size fractions were coarse and medium sands, followed by fine sand with no significant temporal (PREV-POEVI-POEVII) and spatial (U-NU) differences.

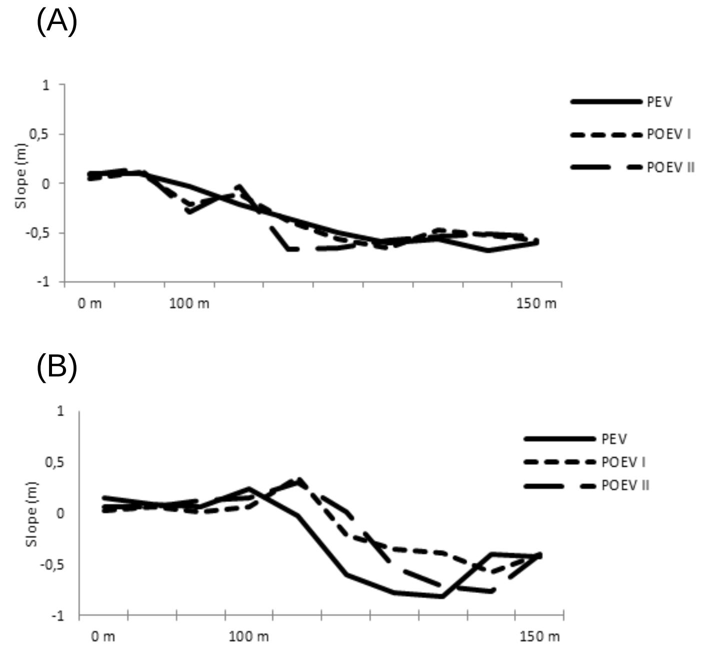


Figure 8. Topographic profile of Grussaí beach in the non-urbanized (A) and urbanized (B) sectors in 2014 considering the pre-event (PREV), post-event I (POEV I) and post-event II (POEV II). The distance 0 corresponds to the beginning of supralittoral.

3.2.2. Macrofauna

3.2.2.1. Taxonomic composition

A total of 15 taxa were sampled (NU=11, U=10). Oligochaeta, *Donax* sp., and Nemertea were found exclusively in the NU sector, while *Scolelepis* sp. occurred only in the U sector. The crustaceans *Excirolana braziliensis*, *Emerita brasiliensis* and *Atlantorchestoidea brasiliensis*, the polychaetes *Hemipodia californiensis* and *Pisionidens indica* and Nemertea represented 90% of the community in both sectors. The crustacean *E. braziliensis* was the dominant taxon, totaling 52% of the community at the U sector and 64% at the NU sector.

After the storm wave sequence in 2014, the density of the main representative taxon *E. braziliensis* (NU and U) and *A. brasiliensis* (NU) increased, while the density of polychaetes *H. californiensis* and *P. indica* and of Nemertea decreased after the events, at both sectors. Increasing density values in post-event II occurred only at NU (Fig. 9).

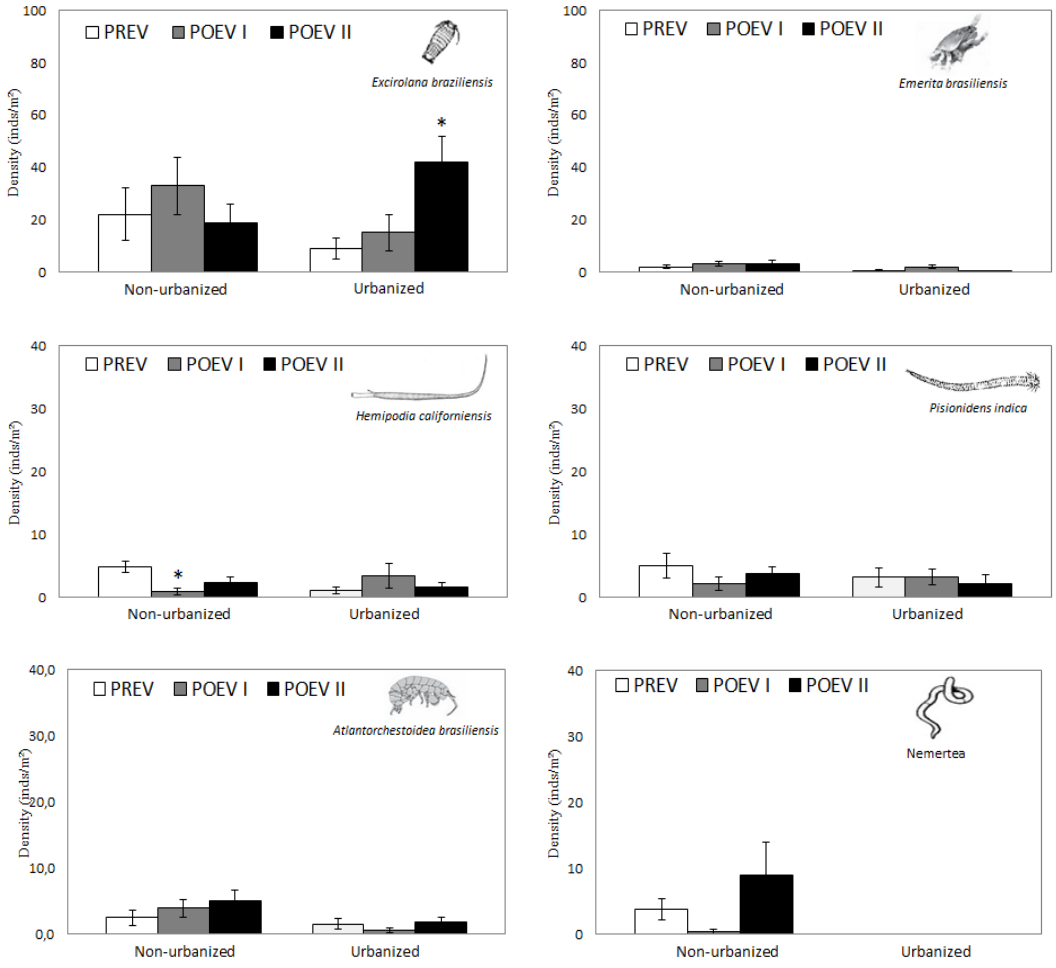


Figure 9. Mean density values (SD) of the main macrofauna representatives in pre- and post-event sampling periods in 2014 at the urbanized and non-urbanized sectors at Grussaí beach. Illustrated taxa: Pinotti *et al.* (2014), McLachlan & Brown, 2006 and Ruppert & Barnes, (1996).

3.2.2.2. Structure indicators

In this scenario of seven consecutive storm wave events, mean species richness and diversity generally showed a decreasing trend in both sectors (Fig. 10A and C). Greater density values were observed in the U sector (Fig. 10B). It should be highlighted that the values at the NU sector were higher than at the U sector.

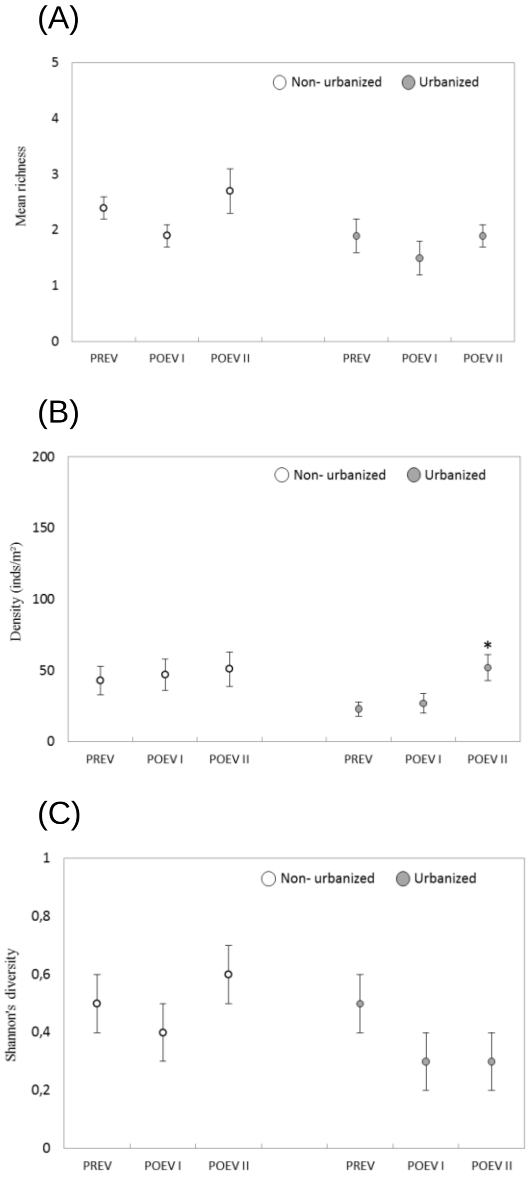


Figure 10. Mean values and standard error of the community structure indicators in the pre- and post-event sampling period, 2014, in the urbanized and non-urbanized sectors at Grussaí beach. A: mean richness; B: mean density; C: Shannon diversity; PREV: pre-event; POEV I: post-event I; POEV II: post-event II; * $p < 0.05$.

3.2.2.3. Macrofauna association pattern

The MDS ordination regarding the NU sector indicated the scattering of samples according to tidal level, with the macrofauna of the middle and lower mesolittoral clustering together, regardless of the storm wave effect (Fig. 11A, Tab. 4). At the urbanized sector (U), the macrofauna was related to the sampling event and tidal levels, with middle and higher mesolittoral samples clustering in both post-events (Fig. 11B). The PERMANOVA confirmed the significant differences in the macrofauna between the intertidal levels (NU and U sectors) and the interaction event/level only in the U sector (Tab. 4). The *a posteriori* test shows the effect of higher storm wave frequencies in the middle and upper levels of the intertidal zone at the U sector, and the significant differences of the macrofauna community even 42 days after the storm events (Tab. 4).

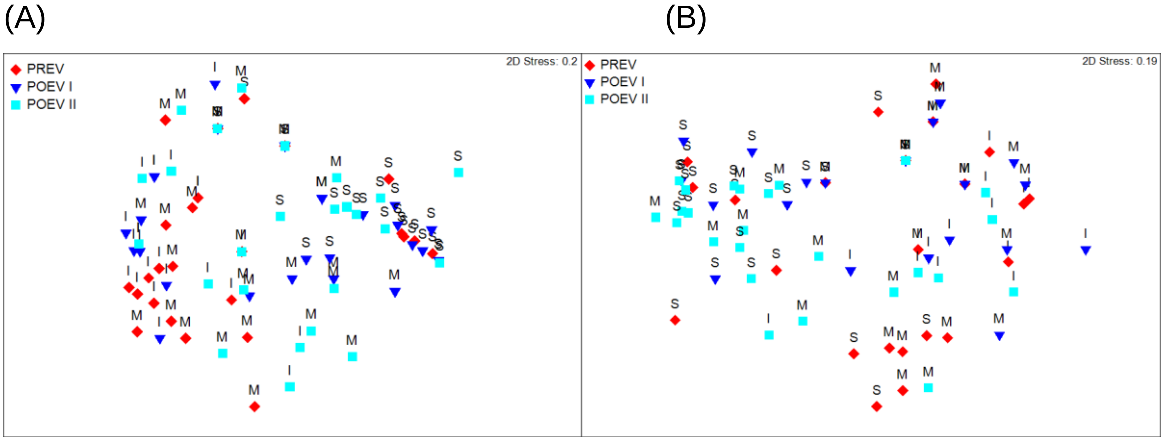


Figure 11. MDS ordination plots for the macrofauna abundance of the non-urbanized (A) and urbanized (B) sectors of Grussaí Beach (storm event scenarios of 2014). Filled symbols represent pre-event (PREV), post event I (POEV I) and post event II (POEV II). S = upper level, M = middle level, I = lower level of the intertidal zone.

Table 4. PERMANOVA results between intertidal levels (upper, middle and lower), events (pre-event, post-event I and post-event II) and the interaction between these factors in the 2014 scenario. *p<0.05: significant differences; p(MC): p value with the Monte Carlo test.

PERMANOVA	Non-urbanized			Urbanized		
Factor	F	p (MC)	Perms	F	p (MC)	Perms
Event	1.503	0.203	950	2.894	0.046*	957
Intertidal level	17.516	0.001*	999	17.525	0.001*	999
Event x intertidal level	1.533	0.069	997	2.183	0.022*	997
Pair-wise test	Non-urbanized			Urbanized		
Lower level	No significant difference			No significant difference		
Medium level	No significant difference			Pre-event = post-event I ≠ post-event I		
Upper level	No significant difference			Pre-event ≠ post-event II		

3.3. Generalized Linear Models Analyses

According to the Generalized Linear Models (GLM), urbanization and wave height were the variables that most influenced the representative species in both scenarios (2013 and 2014), except for the polychaete *P. indica* (Table 5). The mean coefficients of the models indicate a decreasing abundance of the crustaceans *E. braziliensis* and *A. brasiliensis* and of the polychaete *H. californiensis* with higher wave height, especially in the U sector (Fig. 12). At the NU sector, an increasing abundance of the polychaetes *H. californiensis* and *P. indica* was observed during higher wave height periods (Fig. 12).

Table 5. Model-averaged parameters of the Negative Binomial Generalized Linear Mixed Models for macrofauna as functions of environmental variables at Grussaí beach. Significant terms ($p < 0.05$) are marked in bold. Ab = *Atlantorchestoidea brasiliensis*, Exbr = *Excirolana braziliensis*, Hc = *Hemipodia californiensis*, Pi = *Pisionidens indica*, Embr = *Emerita brasiliensis*.

Species	Model-averaged parameters	Estimates	p-value
Ab	Urbanized site	-0.34	0.19
	Wave height	**-0.009**	**0.04**
	Coarse sand	-0.01	0.08
	Fine sand	**-0.04**	**0.009**
EXbr	**Urbanized site**	**-0.23**	**0.03**
	Wave height / Urbanized site	**-0.004**	**0.02**
	Wave height	-0.008	0.14
Hc	**Urbanized site**	**-0.74**	**0.002**
	Fine sand	-0.01	0.57
	Coarse sand	-0.03	0.17
	Medium sand	-0.03	0.11
	Wave height	0.002	0.72
	Wave height / Urbanized site	**-0.007**	**0.004**
Pi	Wave height	0.005	0.41
	Coarse sand	0.01	0.185
	Wave height / Urbanized site	0	0.95
	Urbanized site	0.06	0.85
	Medium sand	-0.002	0.9
EMbr	Wave height	-0.002	0.72
	Wave height / Urbanized site	**-0.006**	**0.03**
	Urbanized site	**-0.52**	**0.04**
	Coarse sand	0.006	0.36

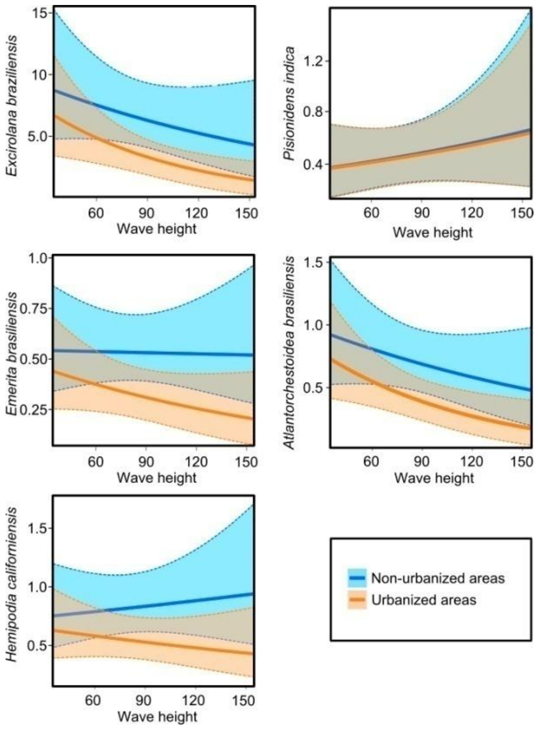


Figure 12. The expected counts of macrofauna species as functions of environmental variables atGrussaí beach with the Negative Binomial Generalized Linear Models. Shaded areas delimited by dashed lines indicate 95% confidence bands.

4. Discussion

Predictive scenarios of global climate change have shown an increase in the intensity and frequency of different natural disturbances such as hurricanes, storms and cold fronts, making imperative to understand the medium- and long-term effects of these extreme events on coastal ecosystems, which are highly vulnerable areas to such extreme events (Jaramillo *et al.*, 2012). The magnitude of decline and subsequent recovery of abundance and diversity of macrobenthic animals maybe favored on vegetated areas, suggesting that temporal changes in these parameters are not solely related to the magnitude of the disturbance (Whanpetch *et al.*, 2010).

The benthic macrofauna on the northern coast of Rio de Janeiro state responded differently to both scenarios and degrees of urbanization evaluated, considering species abundance, richness and diversity patterns. Human activities in sandy beaches may influence the responses of benthic communities to high-energy events, since system recovery after erosion may be slower in urbanized beaches (Castelle *et al.*, 2008). The changes triggered by storm waves promoted similar changes in the hydrodynamic conditions in the urbanized (U) and non-urbanized (NU) sectors were similar, inducing greater wave action on the beach face and confirming the forecasts of wave heights above 2 m off the beach (www.cptec.inpe.br).

Beach morphology was consequently affected, as evidenced by the displacement observed on the drift line towards the upper regions of the intertidal zone, and by changes in the topographic profile, which were characterized by sediment depositional processes in some areas, particularly in the middle and upper ranges of the intertidal zone in the urbanized sector. The displacement of the intertidal zone resulted from rising sea levels, which are characteristic of storm surges that manage to reach greater distances from the waterline (Alves & Pezzuto, 2009). Such morphological changes in beaches resulting from high-energy events were also reported by other authors (Agaard *et al.,* 2005; Sedrati & Anthony, 2007; Houser & Greenwood, 2007). However, it is important to characterize the history of the storm wave frequency and intensity in the region studied. Similar intensity events (<2.5 m wave heights) were frequent in the past three years, according to the Weather Forecasting and Climate Studies Center (www.cptec.inpe.br), indicating that events of this magnitude are common at this time frame.

In scenario 1, characterized by comparatively lower frequency of events and higher intensity waves, significantly higher values of species richness, density, and diversity were observed 42 days after the event only in the NU sector. Similarly, the density of representative species increased, suggesting that urbanized areas are more susceptible to such storm wave events. Harris *et al.* (2011) evaluated the effects of storms in South African beaches and found that those under lesser influence of human activities showed greater macrofauna resilience after events. Witmer & Roelke (2014) evaluated the effects of a hurricane in beaches in Texas (USA) and observed that motor vehicle traffic prevented macrofauna recovery after the event.

Macrofauna temporal changes have been related to seasonal variations in species reproductive activities (Veloso *et al.*, 1997, Neves *et al.*, 2008). Seasonality is not remarkable in Rio de Janeiro state, and species usually reproduce throughout the year (Veloso *et al.*, 1997, 2003; Caetano *et al.*, 2006). However, severe changes in hydrodynamic conditions may affect the dispersal of larvae and recruits of macrofauna species (Wielking & Kröncke, 2001). Also, we observed that the dominant species *Emerita brasiliensis* was characterized mainly by juveniles after storm events, probably as a recruitment response to the intensification of hydrodynamics. *E. brasiliensis* has a continuous reproduction pattern during the year in the tropical and subtropical beaches (Defeo & Cardoso, 2002); however, recruitment peaks are common from April to September on Brazilian beaches (Eutrópio *et al.*, 2006), when storm waves are more frequent and reach greater height on the northern coast of Rio de Janeiro state (see Fig. 2). Higher wave heights on scenario 1 might have further contributed to launching advanced stages of *E. brasiliensis* larvae to the beach face. Saloman & Naughton (1977) also observed the increase in the abundance of *Emerita talpoida* recruits after storm waves on a beach in Florida, USA. The variation in the number of Anomura larval stages is also common. This may indicate that such a disturbance can reduce the time required for the development of these larvae. In fact, some species of macrofauna of indirect development benefit from the increase in hydrodynamics (Harris *et al*., 2011).

In scenario 2, of higher frequency and lower height of consecutive storm waves, significant differences in community indicators comparing pre- and post-events were not observed in the NU sector. The U sector was more susceptible to such extreme events, with lower species richness and diversity values and a significant increase in macrofauna density 42 days after the events. Although some studies show that the waves may have a positive effect on the composition and abundance of benthic macrofauna (Posey *et al*., 1996; Alves & Pezzuto, 2009), but severe mortality of some benthic taxa, erosive effects and changes in the swash zone positions have also been recorded (McLachlan, 1996; Gallucci & Netto, 2004).

The effects of storm waves on the macrofauna community depend on local species composition, the proximity of source populations, and the intensity of human pressure (Jaramillo *et al.*, 2012). In the present study, the increase in richness values in the NU sector was possibly due to passive organism transport from neighboring habitats, besides migratory activities after the events. Also, passive transport by wave action and swashing might be responsible for the increase in species density with limited mobility capability, which are distributed in the lower intertidal and subtidal fringe, such as the polychaetes *Hemipodia californiensis*, *Pisionidens indica*, and Nemertea, as suggested by Saloman & Naughton (1977) and Hughes *et al.* (2009). Colonization of the U sector by the species above after the event may have been hampered by human activities, which are very common in this area. Chronic disturbance mainly of anthropogenic origin reduces resilience and affects the maintenance of intertidal communities of sandy beaches after natural disturbance (Harris *et al*., 2011; Witmer & Roelke, 2014).

In both scenarios, significant differences in the macrofauna association pattern before and after the events were observed mainly in the U sector, emphasizing the greater sensitivity of this disturbed area to higher wave energy events. The increase in the density of *E. braziliensis* in the middle and upper intertidal levels corroborates the results obtained by Alves & Pezzuto (2009), which found an increase in the abundance of this species in a Brazilian beach four days after a moderate event for the region considered (waves ≤ 2.5 m). In the U sector, the increasing density could be attributed to the accumulation of anthropogenic debris after the sequence of storm wave events, resulting in higher food availability for this detritivorous crustacean (Souza *&* Gianuca, 1995). Therefore, the positive effects of storm waves may be indirect, with increased energy waves resulting in an input of nutrients and higher deposition of particulate material in the intertidal zone (McKenzie *et al*., 2011).

In addition to the intensity and frequency of storm waves, it is important to consider the sampling period after the event(s). It is possible that the time frame (POEV I: 15-30 days, POEV II: 41-42 days post-event) were wide to evaluate immediate storm wave effects. However, as the aim of the study was to compare the macrofauna recovery on urbanized and non-urbanized areas, the sampling time interval after the events considered the period the beach returned to its pre-event conditions regarding particle size and topographic features in a pilot study. According to Alves & Pezzuto (2009), sandy beaches naturally exposed to intense hydrodynamics, especially in morphodynamically reflective and intermediary environments are susceptible to higher wave heights and intense geomorphological changes. Thus, the resilience capacity of the macrofauna should be evaluated after the restoration of the geomorphological conditions.

It is expected that intertidal macrofauna at beaches with intermediate profiles, like Grussaí, and therefore subjected to intense wave action on the beach face are not negatively influenced by wave action. However, it is worth emphasizing that this ecosystem can be particularly vulnerable to storm wave events, due to the continuous sediment resuspension caused by intense turbulence (Harris *et. al*., 2011). Such impacts can reach more than 20 cm deep from the sedimentary layer, directly influencing the biological communities that are mainly concentrated in the top 50 cm of sediment (McLachlan *et al*., 1981; Gómez-Pujol *et al*., 2011).

Table 6 shows the main results of several studies evaluating the effects of extreme events on macrofauna in sandy beaches. The results show that urbanized environments are more susceptible to these events. Also, the increase in macrofauna richness and diversity observed in the present study, especially in scenario 1, as well as the results obtained by several authors (see Table 6) indicate the importance of natural disturbances in the benthic intertidal dynamics of sandy beaches. Harris *et al.* (2011) suggest that the impacts on these communities can be transient or persistent, depending on wave intensity and frequency. Thus, the higher the event intensity, the more persistent the impact and the lower the resilience, confirming the results of the linear models in the present study, which showed greater trends towards the reduction of macrofauna abundance with higher mean wave heights, mainly on disturbed areas.

Table 6. List of studies that evaluated the effects of extreme weather events on benthic communities of sandy beaches.

Authors	Country	Event	Intensity	Days after each event	Major results
Crocker (1968)	USA	Hurricane	High	Two days (Event I); 16 and 30 days (Event II)	Reduction on anphipods abundance
Saloman & Naughton (1977)	USA	Hurricane	High	One, two, three, six, nine, 14 and 28 days	Increased richness and recruitment of *Emerita talpoida*
Hughes *et al.* (2009)	USA	Hurricane	High	Six days	Increased richness, diversity and opportunistic species abundance
Witmer & Roelke (2014)	USA	Hurricane	High	Monthly samplings	Higher resilience of the macrofauna at non-urbanized beach
Jaramilo *et al.* (2012)	Chile	Tsunami	High	ca. 30 days	Restoration of intertidal habitat followed by rapid colonization of mobile species on armored beaches
Harris *et al.* (2011)	South Africa	Storm waves	High	47 days (Event I); 15 days (Event II)	Higher resilience of the macrofauna at non-urbanized beach
Cochôa *et al.* (2006)	Brazil	Cold front	Low/Moderate	One day	Changes on zonation pattern
Alves & Pezzuto (2009)	Brazil	Cold front	Moderate	Two and four days (Event I); Two days (Event II)	Increasing on detritivorous species (*Excirolana braziliensis*) density on reflective beach
Present study	Brazil	Storm waves	Low/Moderate	15 and 42 days (Event I); 28 and 42 days (Event II)	Event I: Increasing on community numerical indicators at non-urbanized site Event II: Increasing on detritivorous species (*Excirolana braziliensis*) density at urbanized site

Besides sandy beaches, other marine ecosystems can be influenced by extreme events like storm waves like coral reefs, rocky shores, mangroves, and sea grass beds, (Underwood, 1999; Faraco & Lana, 2006; Whanpetch *et al.*, 2010; Lomovasky *et al.*, 2011). Indeed, their benthic communities are not exposed to constant wave action, therefore they are more susceptible. In sandy beaches, even in those adapted to environmental severity, the synergistic effects of urbanization and storm waves may influence benthic organisms negatively.

In conclusion, the present study demonstrates the greater beach vulnerability to storm wave events in more urbanized areas. The recovery of the environment and macrofauna is affected by intensity and frequency of impacts. So, extreme weather events as storm waves and cold fronts may exponentially enhance the disturbance effect, which will be inversely proportional to macrofauna resilience, endangering the maintenance of biological communities. It is noteworthy that conservation plans normally fail to address sandy beaches properly (Harris *et al.*, 2014). Therefore, management interventions are crucial to mitigate the negative effects of urbanization and extreme climate changes on the biodiversity of these ecosystems (Schlacher *et al.*, 2008) with some specific actions as (i) the effective control of recreational use, (ii) reduction of pollution originating from the occupation of coastal areas, and (iii) the establishment of effective littoral-active zones to reduce the negative effects of climate change and human pressures (Defeo *et al.*, 2009; Harris *et al.*, 2014). Finally, long-term monitoring is necessary to improve the prediction of impact of urbanization and extreme events on sandy beach biodiversity, as well as to evaluate the effectiveness of management measures.

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Capítulo 4

Effect of extreme weather events and urbanization on population density of the ghost crab *Ocypode quadrata*: a biomonitoring strategy

Abstract

The bioindicator potential of the ghost crab *Ocypode quadrata* was evaluated considering anthropic impact (trampling) and extreme climate events (storm waves and wind) based on population density and burrow characteristics. The effect of storm waves was assessed before and after climate events in urbanized and non-urbanized sectors of two beaches in southeast Brazil. Significant differences were observed in this species' population density values between urbanization levels. Generalized linear mixed models showed that the number of *O. quadrata* burrows in urbanized sectors was lower after storm waves, compared to non-urbanized sectors. Although the effect of storm waves by itself was not observed in the beaches, the interaction between storm waves and urbanization influenced the number of *O. quadrata* burrows, and suggest that *O. quadrata* populations are more vulnerable to the effect of storm waves in urbanized beaches. Also, increasing wind speeds when considered together with urbanization affected *O. quadrata* burrow frequency more significantly. Our results demonstrate the negative ecological impacts in beaches exposed to intense recreational activities. *Ocypode quadrata* seems to be an important bioindicator to evaluate the effect of climate change and urbanization on sandy beaches in the medium and long terms.

Keywords: Anthropic impact, bioindicator, climate change, ghost crab, sandy beach.

1. Introduction

The crab *Ocypode quadrata* also known as ghost crab occurs along the whole coast of the country and it is the only species of the *Ocypode* genus found in Brazilian shores (Turra *et al.*, 2005). These animals are exclusive to the sandy beaches of the West Atlantic coast (Melo, 1996), where they play an important role not only in the energy transfer across the trophic levels of coastal ecosystems, but also as consumers of organic debris in the environment (Branco *et al.*, 2010).

Ocypode quadrata is more often found on the higher beach grounds, inhabiting burrows at the supralittoral fringe that are easily identified. Warren (1990) attested the positive correlation between the number of burrows and the abundance of these animals on beaches. Also, Wolcott & Wolcott (1984) demonstrated that the burrow diameter indicates the size of the animal. Therefore, assessing burrow usage by *O. quadrata* represents a simple and fast method to evaluate this species' population density (Barros, 2001).

In a scenario of increasing anthropic pressure on coastal environments, sandy beaches are some of the ecosystems most used by humans (Schlacher *et al.*, 2006). With the increasing number of visitors, they are exposed not only to more intense trampling, but also to high levels of organic pollution and traffic of motor vehicles. Studies have shown that *O. quadrata* is negatively affected by these human-made disturbances, besides the deleterious effect of beach cleaning methods (Wolcott & Wolcott, 1984; Barros, 2001; Turra *et al.*, 2005; Blankensteyn, 2006; Schlacher *et al.*, 2007; Hobbs *et al.*, 2008). Some studies have demonstrated that crabs of the *Ocypode* genus may be used as bioindicators of environmental impact, showing this species' potential in short-term monitoring studies (Barros, 2001; Blankensteyn, 2006; Neves & Benvenuti, 2006).

In addition to anthropic influence factors, climate change and rising sea levels due to global warming increase the vulnerability of benthic populations in sandy beaches. According to Brown *et al.* (2014), the main threat to species in coastal environments is loss of habitat, mostly when rising sea levels are accompanied by more intense and numerous thunderstorms, storm waves and cold fronts.

Storm wave events follow an increasing trend in frequency and intensity (IPCC, 2013), which are the main extreme climate events on the Brazilian coast. These events result from increasing wind speed and changes in wind direction and rising sea levels, typical of cold fronts and tropical cyclones (Rodrigues *et al.*, 2003; Kobiyana *et al.*, 2006). Studies have shown that these events affect benthic communities, reducing richness, abundance, and diversity (Jaramillo et al., 1987; Solomon *et al.*, 2007; Harris *et al.*, 2011). However, few studies have addressed this problem, concerning the effects of these climate events on *O. quadrata* populations. In an interesting investigation on this topic Hobbs *et al.* (2008) documented this species' increased vulnerability in environments affected by human activities, in addition to the problems brought about by the greater occurrence of hurricanes in the US.

In this context, few sustainable management strategies for coastal regions have been implemented, especially on the use of the biota as indicator of anthropic stressors and extreme events. As in other sandy beaches worldwide, many Brazilian beaches are exposed to intense tourist pressure. More specifically, on the northern coast of Rio de Janeiro state, the main anthropic action is associated with the intense tourism activities in summer, which may affect the population density of *O. quadrata* due to human trampling and garbage. In addition, both the supralittoral and mesolittoral zones are exposed to more intense motor vehicle traffic. Therefore, activities focused on monitoring should be promoted to gather information about ecological indicators related to intense anthropic pressure and extreme events.

The objective of the present study was to investigate the bioindicator potential of *O. quadrata* for anthropic impact and extreme climate events, considering two hypotheses: (i) the species is more abundant in area less exposed to anthropic action, and (ii) the species' vulnerability increases with the intensity of extreme events, especially in more urbanized areas.

2. Materials and methods

2.1.Study area

This study was carried out in two sandy beaches of distinct morphodynamics on the northern coast of Rio de Janeiro state, Brazil (Fig. 1). Manguinhos Beach (21º28'14" S, 41º6'34" W) is classified as dissipative, with mild slope, long surf zone, and fine to medium sand particles. Grussaí is an intermediate beach (21º41'46" S, 41º2'39" W), comparatively more hydrodynamic, presenting sharp slope and mainly medium and coarse sand particles. Both beaches have been exposed to a variety of human interventions, though Grussaí Beach has seen more intense anthropic impact due to tourism and leisure activities.

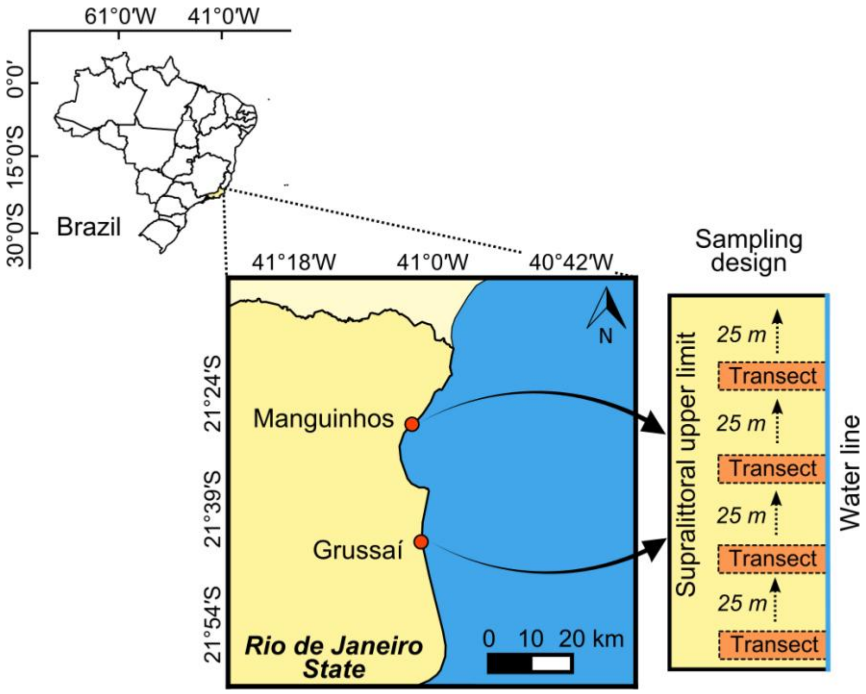

Figure 1. Study area in northern Rio de Janeiro state, Brazil with diagram showing the sampling design of *Ocypode quadrata* collections.

2.2. Sampling design and data analysis

The surveys were carried out in areas exposed to intense trampling (urbanized sector, U) and little anthropic pressure (non-urbanized, NU) in both beaches.

A long supralittoral fringe is the main feature in the urbanized sector of Grussaí Beach, measuring approximately 100 m in length and with a comparatively small dune vegetation limited by several buildings. The non-urbanized sector is characterized by a 50- to 80-m-long supralittoral fringe covered with preserved sand dune vegetation. In Manguinhos Beach, both urbanized and non-urbanized sectors are characterized by a rather narrow supralittoral fringe, measuring under 5 m, beyond which lies a patch of sand dune vegetation physiognomy. This vegetation area is contained by houses and narrow roads mainly in the urbanized sector.

Anthropic effects were assessed based on the intensity of trampling, according to Veloso *et al.* (2006), which consider the number of people in a 30-min period between 9:00 am and 3:00 pm, when both beaches are exposed to the largest number of visitors. The same area used to evaluate *O. quadrata* burrows (the beginning of the intertidal zone and the end of the supralittoral fringe) was used to analyze the intensity of trampling in both beaches. The influence of winds on the burrows of *O. quadrata* was based on wind speed measured on sampling days with an anemometer (AD-250, Instrutherm).

Extreme storm waves were monitored in the urbanized and non-urbanized sectors of Grussaí Beach (N = 3) and Manguinhos (N = 2) in the years 2013 and 2014. According to the Brazilian weather authority, National Institute of Spacial Research (INPE), storm waves in the study area are characterized by waves over 2.0 m in height. The before-after control impact (BACI) sampling strategy (Underwood, 1994) was used to characterize the population density of *O. quadrata* before and after storm waves recorded during the study period. One sampling was carried out 3 days before each event (PREV) and two were conducted 15 and 30 days after (POEV I and POEV II, respectively). The aim was to evaluate the capacity of the local population of *O. quadrata* to return to the condition prior to the climate disturbance, at two distinct moments.

Burrows exhibiting activity signs by *O. quadrata* were counted and measured along nine parallel transects of 2 m width at 25-m intervals and perpendicular to the coastline, starting at the water line and proceeding to the end of the supralittoral zone (Fig. 1). Differences in abundance and size of burrows between the urbanized and non-urbanized sectors of the two beaches were tested using the analysis of variance (ANOVA) and the Tukey test as *post hoc* (Zar, 1984).

To investigate the effects of winds, trampling, and storm waves on the abundance of *O. quadrata* we performed regression analyses using the generalized linear mixed models (GLMMS) (Bolker *et al.*, 2009). This statistical method allowed us to account for non-normal data (count data), zero inflation caused by excess zeroes in the data, and problems like random effects, including pseudoreplication across sites (Zuur *et al.*, 2009).

The number of used burrows in the beach was set as response variable to wind speed (numerical), storm waves progress (ordinal) and trampling intensity (nominal). The beaches were set as random factors, to account for within-site variance. Models were fitted using the Negative Binomial family as the best error distribution and the Adaptive Gauss-Hermite quadrature in order to optimize the evaluation of the log-likelihood (nAGQ=10).

We selected the most effective models on predicting the variation in the number of crab burrows using the Akaike’s Information Criterion corrected to small samples (AICc) (Burnham & Anderson, 2002). Models with small differences did not differ significantly in terms of performance, although the best ones show the lowest

AICc scores. Therefore, we used model-averaged (Burnham & Anderson, 2002) differing in two AICc from the first model (Tavares *et al.*, 2015). Before our regression analyses we explored data checking for outliers, collinearity and the best error distribution (Zuur *et al.*, 2010). We assessed model assumptions by the graphical inspection of model residuals using the package ggplot2 for R. All analyses were performed using 3.0.2 (R Core Team, 2013). We used the pages 'ade4' for model fit, 'MuMIn' for calculating AICc values and perform model-averaging.

3. Results

3.1. Environmental parameter – wind

Wind speed varied between 5 - 36 km/h in Grussaí Beach and 5 - 25 km/h in Manguinhos Beach, without statistically significant differences between urbanized and non-urbanized sectors (Table 1).

Table 1. Wind speed (km/h) in the urbanized and non-urbanized sectors in Grussaí (N=9 surveys) and Manguinhos (N=6 surveys) beaches.

		Grussaí - U	Grussaí - NU	Manguinhos - U	Manguinhos - NU
Storn even	Samplin	W (km/h)	W (km/h)	W (km/h)	W (km/h)
1	I	10	7	16	6
	II	8	6	7	8
	III	25	25	14	5
2	I	20	9	13	20
	II	6	9	10	5
	III	32	7	25	25
3	I	6	15		
	II	5	11		
	III	7	36		

3.2. Anthropic effect – trampling

The number of visitors to both beaches was significantly higher ($p < 0.05$) in the urbanized sector than in the non-urbanized sector in summer (Table 2). In winter, the number of visitors fell drastically in both sectors and beaches, compared to the summer period (Table 2).

Table 2. Number of visitors recorded in the urbanized and non-urbanized sectors of the two beaches in summer and winter of 2013.

	Grussaí Beach		Manguinhos Beach	
	Urbanize	Non-urbanized	Urbanize	Non-urbanized
Summer I	3,750	66	364	24
Summer II	2,120	18	172	5
Winter I	11	0	3	0
Winter II	9	0	4	0

3.3. Anthropic effect – burrow abundance and size of Ocypode quadrata

Mean number of active burrows was significantly higher ($p < 0.05$) in Grussaí Beach (N=6.6) compared to Manguinhos Beach (N=4.0). In both beaches, mean number of burrows was higher in the non-urbanized sector (N = 9.4 and 5.0 burrows in Grussaí and Manguinhos beaches, respectively) than in the urbanized sector (N = 1.7 and 1.6 burrows, respectively) (Fig. 2).

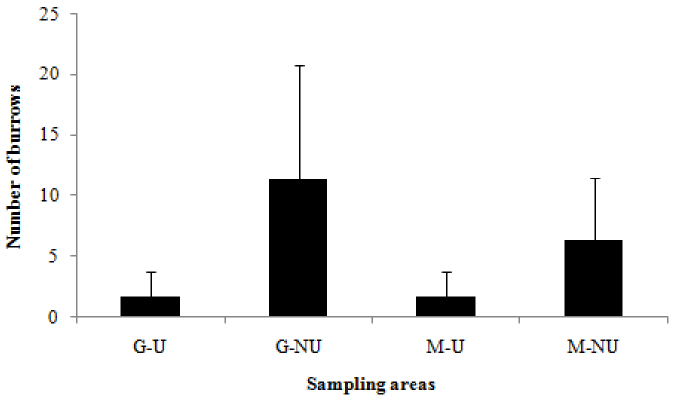

Figure 2. Number of *Ocypode quadrata* burrows (mean ± SD) in the urbanized (U) and non-urbanized (NU) sectors of Grussaí (G) and Manguinhos (M) beaches.

Mean diameter of burrows in the urbanized (2.3 cm) and non-urbanized (3.2 cm) sectors of Grussaí Beach didn´t differ significantly. In Manguinhos Beach, mean burrow diameters were 3.7 cm in the urbanized sector and 2.9 cm in the non-urbanized sector(Fig. 3).

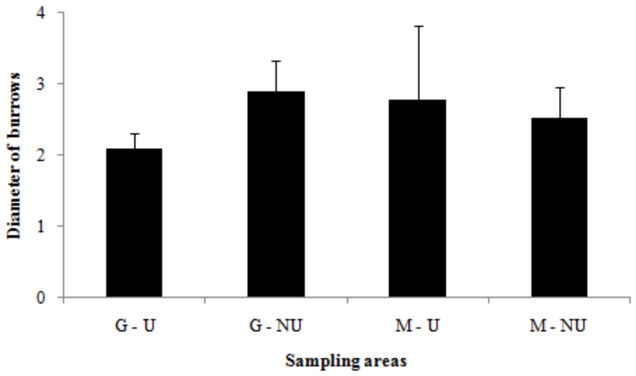

Figure 3. Mean diameter of *Ocypode quadrata* burrows in the urbanized (U) and non-urbanized (NU) sectors of Grussaí (G) and Manguinhos (M) beaches.

3.4. Extreme weather effects (storm waves and winds)

In the urbanized sector of Grussaí Beach, the number of burrows increased soon after the three storm wave events, returning to previous values after 30 days (Fig. 4A). In the non-urbanized sector, a significant decrease in burrow occurrence was observed after the first event (Fig. 4B). The lowest numbers of burrows were observed on windy days, mainly when wind speed was over 15 km/h in both the urbanized and non-urbanized sector (Table 1).

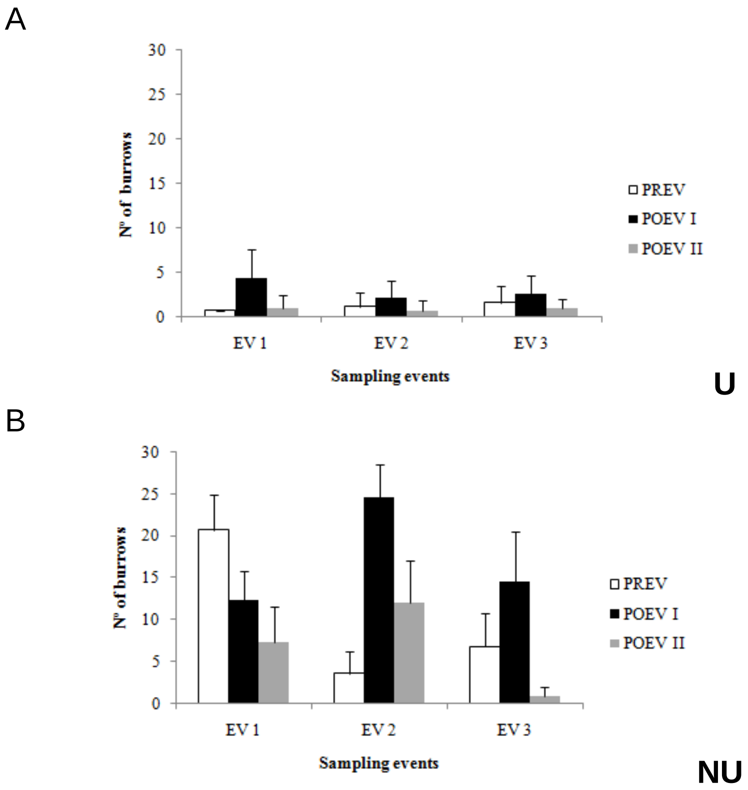

Figure 4. Number of active burrows (mean ± SD) of *Ocypode quadrata* in Grussaí Beach after three storm waves events (EV1, EV2, EV3) in the urbanized (A) and non-urbanized sectors (B). (PREV: before the event, POEV1: post-event 1, POEV2: post-event 2)

In the urbanized sector of Manguinhos Beach, the number of burrows increased after the storm waves (EV1 and EV2, Fig. 5A), while in the non-urbanized area, the number of burrows was significantly lower after the two events recorded (Fig. 5B). It should be highlighted that lower abundance of *O. quadrata* burrows was also recorded on windy days, when wind speed was above 15 km/h (Table 2).

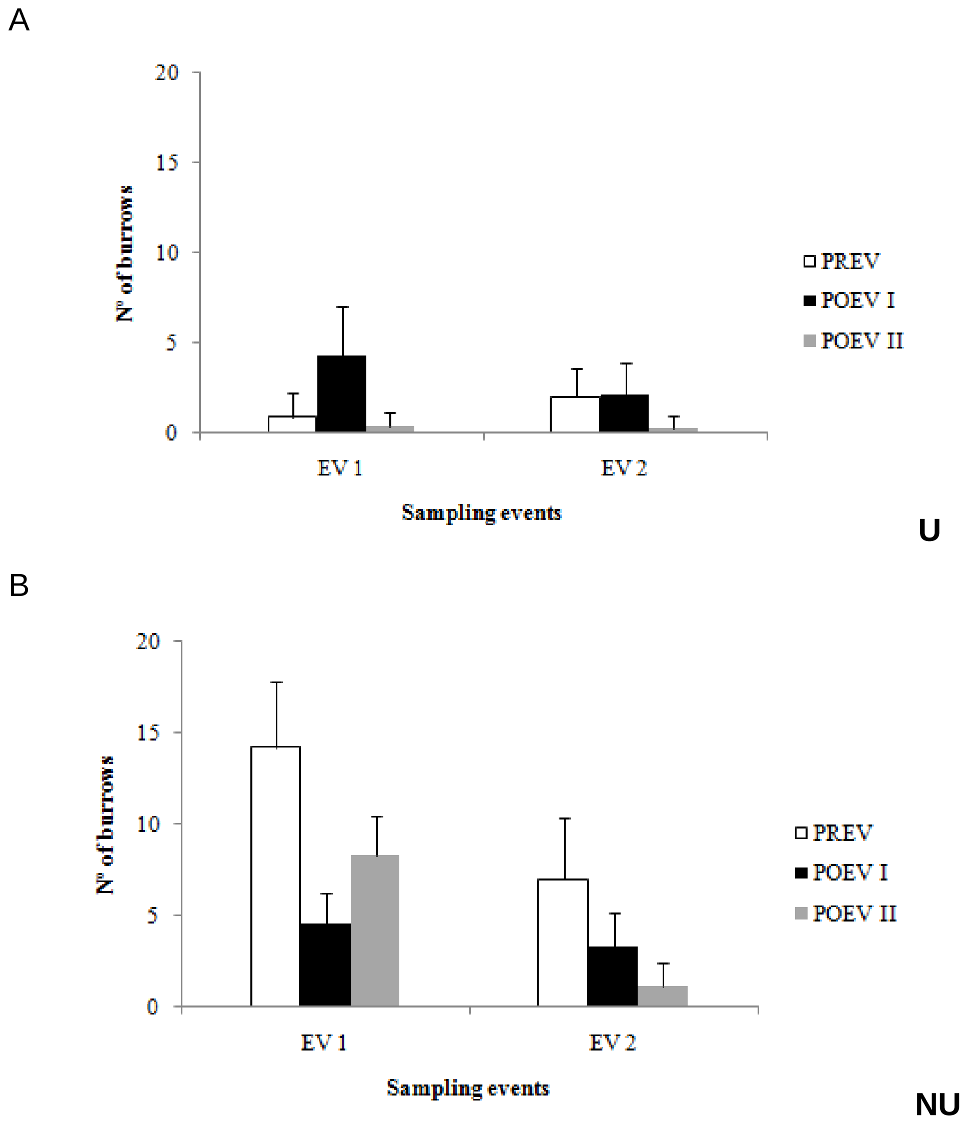

Figure 5. Number of active burrows (mean ± SD) of *Ocypode quadrata* in Manguinhos Beach after two storm waves events (EV1, EV2, EV3) in the urbanized (A) and non-urbanized sectors (B). (PREV: before the event, POEV1: post-event 1, POEV2: post-event 2).

3.5. Generalized linear models

The generalized linear models (GLMs) included the variables urbanization, wave height, and wind intensity, which had an important role in the population density of *O. quadrata* (Table 3). The results indicate that beaches more exposed to trampling have lower numbers of burrows after storm waves, compared with beaches less exposed to this factor (Fig. 6). However, the results also show that a storm wave by itself did not influence the burrow number and diameter; rather, there was a combined effect of weather events and urbanization on *O. quadrata* burrowing patterns. This means that urbanized beaches seem to be more vulnerable to the effect of storm wave considering the occurrence of *O. quadrata* burrows (Fig. 6). Also, wind speed by itself did not influence the burrow patterns, but the combined effect of wind and urbanization reduces significantly the number of burrows used by this crab (Table 4).

Table 3. Ranking of the negative binomial Generalized Linear Mixed Models for estimate the abundance of *Ocypode quadrata* relative to predictive variables in sandy beaches of northern Rio de Janeiro, Brazil. The best selected models are highlighted in bold. AICc: Akaike's Information Criterion corrected to small samples, delta AIC: Differences in AIC scores.

Predictive variables	**AICc**	**AIC**
Storm waves/Trampling degree	**51.6**	**0**
Wind speed/Trampling degree	**55.7**	**4.1**
Wind speed/Trampling + Storm waves	58.6	7
Storm waves/Trampling degree +Wind speed	59.7	8.1
Storm waves/Trampling degree + Storm waves*winds	62.2	10.7
Wind speed* Storm waves	62.6	11
Storm waves/Trampling degree + Wind speed/Trampling degree	63.1	11.6
Storm waves + Wind speed + Trampling degree	63.5	11.9
Storm waves*Trampling degree + Wind speed	65.1	13.5
Storm waves + Temperature + Wind speed + Trampling degree	65.5	14
Storm waves*Trampling degree + Wind speed*Trampling degree	67.1	15.5

Table 4. Model-averaged parameters estimates for the best Generalized Linear Mixed Models predicting the abundance of *Ocypode quadrata* as functions of storm waves, trampling degree and wind speed in sandy beaches of northern Rio de Janeiro, Brazil. [U] = Urbanized beaches.

Variables	**Parameters estimate**	**CI lower**	**CI upper**	**P value**
Storm waves	-0.09	-0.84	0.65	0.81
Storm waves/Trampling degree [U]	-0.77	-1.25	-0.30	0.001*
Wind speed	-0.06	-0.13	0.02	0.13
Wind speed/Trampling degree [U]	-0.10	-0.17	-0.04	0.001*

* Significant variables

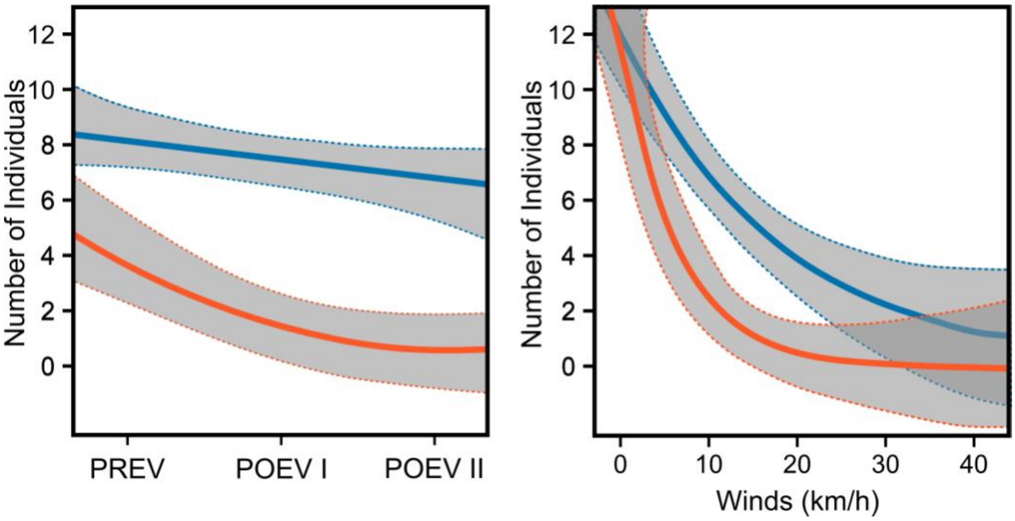

Figure 6. Response curves for the number of individuals of *Ocypode quadrata* related to storm wave events and wind speed, according to the best Negative Binomial Generalized Linear Mixed Models. Shaded areas delimited by dashed lines indicated 95% confidence intervals. Orange and blue lines indicate urbanized and non-urbanized sectors, respectively.

4. Discussion

Benthic invertebrates have been used as bioindicator of anthropic impacts such as motor vehicles, trampling and urban growth in coastal ecosystems (Walker & Schlacher, 2011; Marschall *et al.*, 2014; Reyes-Martinez *et al.*, 2015). The results of the present study substantiate the hypothesis that *O. quadrata* is negatively affected by anthropic pressure. The number of burrows was significantly high in the non-urbanized sectors of both beaches surveyed, underlining the relevance of this species as bioindicator of anthropic factors such as trampling, and confirming previously published results (Neves & Bemvenuti, 2006; Schlacher *et al.*, 2007; Lucrezi *et al.*, 2009).

In addition to high abundance and wide geographic distribution, *O. quadrata* is very easy to sample and to classify taxonomically, making it one of the species that has been most often used as bioindicator of anthropic impact in sandy beaches (Barros, 2001; Schlacher *et al.*, 2015). According to Schlacher *et al.* (2015), 80% of the studies published have reported the drop in the number of *O. quadrata* burrows in environments impacted by anthropic activities, mainly trampling and traffic, confirming the results of the present study.

Despite the approximately 7,000-km-long Brazilian coastline, only two studies were carried out in the country to evaluate the effect of trampling of sands on the populations of *O. quadrata* (Blankensteyn, 2006; Neves & Benvenuti, 2006). Both studies were carried out in southern Brazil, and pointed to the negative impact of trampling on ghost crab populations. Lucrezi *et al.* (2008) argued that trampling may interfere in this species' population density by reducing the stability of sand near the burrow openings, in addition to interfering in feeding habits due to food waste left by humans on the beach, affecting the diet, distribution, and abundance of *O. quadrata*.

Burrow counts are considered a logistically efficient method to evaluate population density of *O. quadrata* in sandy beaches (Warren, 1990). Barros (2001) sustained that the presence of open burrows indicates a behavioral trait of the species, since in urbanized sectors *O. quadrata* seals up the burrow entry as a protection strategy. However, this trait was not observed in the present study, since burrows were open and showed occupation signs in the urbanized sector of both beaches detected in summer, when trampling pressure is high, and also in winter, when the number of visitors decrease. Burrow counting is an efficient method to estimate the population dynamic of *O. quadrata*, making monitoring more feasible and facilitating this species' bioindicator potential (Oliveira *et al.*, 2016).

In both beaches investigated, the presence of visitors is more evident in the upper intertidal zone. This is also the preferred area by *O. quadrata*, which means that the species is more exposed to anthropic pressure. Such preference has been associated with the build-up of organic waste, caused by the movement of tides. In addition, this species' juveniles normally require further access to the water than adults, which explains the smaller burrows in this zone (Wolcott, 1976). However, the distribution of *O. quadrata* is affected by tides and waves, since prolonged immersion may lead to osmotic stress and the consequent death of individuals (Vinagre *et al.*, 2007).

Though studies have reached discrepant conclusions about anthropic effects on mean diameter of *O. quadrata* burrows, it is generally accepted that their diameter tend to diminish with increasing human presence (Schlacher *et al.*, 2015). Also in the present study a mean decrease of 1 cm in burrow diameter was observed from the non-urbanized to urbanized sectors of Grussaí Beach.

According to Lucrezi *et al.* (2010), traffic has negative effects on the population density of *O. quadrata*, since these individuals tend to dig deeper in the sand, as a protection strategy. This in turn represents greater energy expenditure in terms of metabolism, affecting reproduction investment. Besides the higher energy demand inherent to this protection strategy, *O. quadrata* individuals are forced to spend more time foraging outside burrows, where they are more exposed to predators and motor vehicles (Schlacher *et al.*, 2007). Trampling might worsen this scenario, prompting individuals to dig even deeper burrows that increase the energy output.

The actual reasons of this decreasing number of active burrows used by *O. quadrata* individuals remain relatively unknown, with the exception of off-road vehicles, which may crush animals directly (Lucrezi *et al.*, 2010). Nevertheless, Lucrezi *et al.* (2008) pointed to the role of habitat loss or change, alterations in trophic balance and in metabolic expenditure, apart from reproduction and behaviour aspects and the direct crushing of individuals by trampling and light pollution as aspects that may explain the decrease in *O. quadrata* populations in sandy beaches.

Although anthropic influence on communities of benthic invertebrates in sandy beaches has been the object of some research, little has been discovered about the effects of climate change on these populations and, more importantly, about the consequences of any given synergy between climate change and human activities. Considering coastal ecosystems specifically, sandy beaches are rather dynamic environments that may respond promptly to climate extreme events, like those caused by climate change (Bernard *et al.*, 2015), mainly rising sea levels (IPCC, 2013) and higher storm frequency (Emanuel, 2013). These factors may affect beach morphology, resulting in greater erosion (Johnson *et al.*, 2015) and, as a result, alterations in the structure of biological populations and communities.

The characterization of the effects of climate change in the short term faces certain obstacles, such as sample size. Therefore, in order to evaluate the influence of extreme climate events such as winds and storm waves on biological communities in sandy beaches, specific tools such as predictive models have to be conceived. Broadly speaking, such models are useful tools in strategies for the management and mitigation of environmental impact. In the present study, the GLMMS showed that, in both beaches, the urbanized sectors presented lower numbers of *O. quadrata* burrows after storm waves, compared to the non-urbanized sectors. The effect of storm waves in itself was not observed in beaches, but it was noticed in the interaction between the factors storm waves and urbanization. This means that urbanized beaches seem to be more susceptible to the negative effect of storm waves on the abundance of *O. quadrata*. It should be stressed that, despite the higher number of *O. quadrata* burrows observed after storm waves, the GLMMS pointed to a general decreasing trend in burrow occurrence, mainly in the urbanized sectors of both beaches, proving the importance of these models in the development of medium- and long-term predictive scenarios.

Similarly, GLMMS also showed that wind speed alone does not significantly affect *O. quadrata* abundance. However, when considered synergistically with the role of urbanization, the influence of wind was shown to be even stronger than that of storm waves, with higher wind speeds prompting a considerable drop in *O. quadrata* abundance.

Some studies have suggested that stronger winds may actually have a positive effect on the population density of *O. quadrata*. It is believed that windy conditions release larger amounts of organic matter on beaches, increasing the offer of food resources (Wolcott, 1978; Lucrezi *et al.*, 2008). However, no study has looked into the direct influence of wind on the species. We noticed the negative effect of wind speeds over 15 km/h on *O. quadrata* populations in the beaches surveyed. The lowest numbers of burrows were recorded on the windiest days, irrespective of beach or urbanization level. However, it should be remembered that the upper intertidal zone is the preferred area by this species, which is relatively wet and the sand is rather compact. These characteristics prevent burrows from being sealed up by sand blown by the wind (personal communication). According to Pombo (2015) abandoned burrows may remain open for about a week when sand is dry and compact, and those in drier areas of the beach (as the supralittoral zone) are more susceptible to disappear.

The dispersion of these individuals to nearby areas covered with some vegetation as dunes, as a protection strategy was observed during the surveys, as reported in other studies (Leber, 1982; Hobbs *et al.*, 2008). Therefore, under windy conditions, this behaviour may have negative impact on this species’ population, since the vegetation in many urbanized beaches is reduced by anthropic activities. Barros (2001) attributed the decreasing abundance of *Ocypode cordinama* to the loss of habitat in Australian beaches, characterized by a supralitoral zone contained by concrete walls.

Alberto & Fontoura (1999) and Blankensteyn (2006) suggest that *O. quadrata* uses the supralittoral zone and dunes as refuge during storm waves. The last author adds that ocean conditions normally do not affect the population structure of this species, and argues that space in the intertidal and supralittoral zones plays an essential role in the maintenance of *O. quadrata* population density. Therefore, habitat loss caused by anthropic activities and the effects of winds and storm wave's altogether may be considered negative elements on *O. quadrata* density. Lucrezi *et al.* (2010) observed that the abundance of crab species of the *Ocypode* genus did not recover after a storm in an urbanized beach in Australia. Similarly, Hobbs *et al.* (2008) reported that *O. quadrata* population density is more severely affected in beaches exposed to anthropic influence and storm waves than in areas where these extreme climate events do occur but with no human presence.

In a scenario of extreme climate events, erosion may obliterate the burrows of *O. quadrata*, prompting the species to temporarily migrate to more protected areas on dunes. In this case, the return of these individuals to the zones they inhabited before storms may have been hampered especially in more urbanized sectors due to the associated anthropic pressures such as trampling, traffic, and dune disappearance, where the effect of storm waves and winds were more evident.

The present study demonstrates the greater vulnerability of sandy beaches to intense climate events, both in terms of wave and wind intensity, mainly in urbanized beaches, as revealed by the significant decrease in the number of *O. quadrata* burrows. Despite the large area covered by sandy beaches around the world, urbanization has steadily grown in these environments, increasing their susceptibility to climate change, especially in densely populated coastal towns. Therefore, in light of the vulnerability of *O. quadrata* to anthropic pressure and extreme climate events, which highlights this species' bioindicator potential, it should be the object of medium- and long-term monitoring strategies.

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3. Discussão Geral

As influências humanas e de eventos resultantes de mudanças climáticas em praias arenosas seguem uma tendência de aumento em frequência e intensidade, tornando imprescindível o entendimento de como esse ecossistema irá responder a tais pressões. Neste sentido, os capítulos inseridos nesta tese abordam desde aspectos básicos de estrutura e composição de comunidades bênticas em praias arenosas, destacando os principais mecanismos que controlam as variações espaço-temporais da macrofauna como também avaliam os efeitos de eventos extremos (ressacas) na macrofauna e na população do crustáceo *Ocypode quadrata* (conhecido como marinha-farinha, caranguejo-fantasma ou espera-maré) e em praias com diferentes pressões antrópicas.

O efeito do morfodinamismo foi evidente nas praias estudadas, com maior densidade e diversidade na praia intermediária (Grussaí) e maior riqueza na dissipativa (Manguinhos). As diferenças temporais foram atribuídas, sobretudo a variações de temperatura do sedimento e pluviosidade, com decréscimo nos indicadores de comunidade em cenários de maiores intensidades destas variáveis. Além desses fatores, as ressacas foram importantes estruturadores da macrofauna, conforme já verificado na região por Machado *et al.* (2016).

Para distinguir os efeitos do pisoteio de influências naturais e antrópicas foram utilizados dois setores no mesmo arco praial, um caracterizado como urbanizado e outro não urbanizado. Ambos apresentam características ambientais como granulometria, teor de matéria orgânica do sedimento e hidrodinamismo similares. Além disso, duas praias com intensidades diferentes de pisoteio foram utilizadas para verificarmos sua influência na macrofauna. Na praia mais turística (Grussaí) as diferenças na comunidade foram bastante evidentes entre setores urbanizado e não urbanizado no verão e inverno, demonstrando o efeito crônico do pisoteio mesmo no período de menor impacto humano, enquanto na praia menos urbanizada (Manguinhos), a macrofauna foi similar nos dois setores. Os resultados corroboraram os estudos de Veloso *et al*. (2008), Schlacher *et al.* (2008) e Vieira *et al.* (2012), que em ambientes com maior pressão antrópica de pisoteio, os organismos são mais vulneráveis. Os menores valores nos descritores de comunidade verificados no setor urbanizado na praia de Grussaí enfatizam a necessidade da elaboração de políticas de manejo e conservação desse ecossistema, tais como o investimento em lixeiras apropriadas para coleta seletiva, fiscalização e multas para veículos que transitam na praia e, primordialmente, atividades voltadas para educação ambiental, destacando as influências negativas de determinadas atividades e comportamentos humanos no ambiente praial.

O potencial bioindicador do caranguejo *Ocypode quadrata* frente a impactos antrópicos de pisoteio e de eventos extremos (ressacas e ventos) também foi avaliado a partir da contagem de tocas, que é uma estratégia eficiente para a amostragem da população de *O. quadrata* (Warren, 1990; Oliveira *et al.*, 2016). O número de tocas de *O. quadrata* foi significativamente superior no setor não urbanizado nas praias de Grussaí e Manguinhos, reforçando o potencial bioindicador da espécie frente a pressões antrópicas, como pisoteio, o que corrobora com outros estudos (Neves & Bemvenuti, 2006, Schlacher *et al.*, 2007, Lucrezi *et al.*, 2009). Fatores como perda ou modificações de habitats, alterações no equilíbrio trófico, alterações nos custos metabólicos, reprodução, comportamento, esmagamento direto a partir do pisoteio e poluição luminosa, além do tráfego de veículos são as principais causas que levam ao declínio populacional desse caranguejo (Lucrezi *et al.*, 2009; 2010).

Apesar do amplo conhecimento acerca do potencial bioindicador de *O. quadrata* frente a efeitos antrópicos, pouco se conhece sobre as os efeitos de mudanças climáticas sobre essa espécie e, principalmente, sobre os efeitos sinérgicos dessas mudanças com atividades humanas (Schlacher *et al.*, 2015). Os resultados indicaram que praias com maior pressão de pisoteio apresentaram menor abundância de tocas de *O. quadrata* após a ocorrência de ressacas em relação a praia menos turísticas. O mesmo resultado foi encontrado para intensidade de vento, que em sinergia com os efeitos da urbanização promoveu o decréscimo na abundância de tocas à medida que aumenta a intensidade eólica.

O caranguejo *O. quadrata* se mostrou uma importante ferramenta para se avaliar, a médio e longo prazo, impactos decorrentes de mudanças climáticas associados à urbanização em praias arenosas, portanto, recomenda-se o monitoramento a médio e longo prazo de populações dessa espécie, devido seu potencial bioindicador.

Além da avaliação dos efeitos da urbanização e eventos extremos sobre *O. quadrata*, também foram consideradas a influência dessas variáveis sobre a comunidade bêntica do entremarés em Grussaí, em função da maior pressão antrópica. Mesmo com as condições hidrodinâmicas similares nos setores urbanizado e não urbanizado e confirmando as previsões fornecidas pelo CPTEC/INPE, de ondas acima de dois metros, a macrofauna bêntica respondeu de forma distinta aos eventos de ressacas de acordo com o grau de urbanização das praias. O setor urbanizado foi mais susceptível aos efeitos das ressacas na macrofauna, principalmente em condições de maior frequência de ressacas, cenário em que a macrofauna foi incapaz de se recuperar à condição pré-ressaca até 45 dias após a ocorrência de tais eventos extremos. Os resultados indicaram que a urbanização e a altura de ondas foram as variáveis que mais influenciaram as espécies, principalmente no setor urbanizado, mostrando que os efeitos de eventos de ressacas aliado ao incremento da urbanização são uma ameaça à macrofauna do entremarés. Assim, tais organismos também demonstraram sua potencialidade como bioindicadores.

Praias com maiores influências antrópicas mostraram maior vulnerabilidade na manutenção da macrofauna frente as diversas interferências abordadas neste estudo, tais como o pisoteio, eventos extremos de ressacas e ventos com velocidade acima de 15 km/h. Portanto, intervenções de manejo são cruciais para mitigar os efeitos negativos da urbanização e mudanças climáticas na biodiversidade desses ecossistemas. Para isso, múltiplas alternativas devem ser aplicadas, como controle efetivo do uso recreativo, redução de fontes de poluição com origem em ocupações humanas costeiras e formas efetivas de zoneamento para frear os efeitos negativos das pressões urbanas e das mudanças climáticas. Por fim, monitoramentos de longo prazo são necessários para aprimorar o potencial preditivo do impacto da urbanização e eventos extremos na biodiversidade em praias arenosas, bem como para avaliar a eficácia das medidas de manejo.

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Extreme storm wave influence on sandy beach macrofauna with distinct human pressures

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ABSTRACT

We evaluated the influence of storm waves on the intertidal community structure of urbanized and non-urbanized areas of a sandy beach on the northern coast of Rio de Janeiro, Brazil. The macrofauna was sampled before (PREV) and after two storm wave events (POEV I; POEV II) in 2013 and 2014. Significant differences in community structure between PREV and POEV I in the urbanized sector demonstrate higher macrofauna vulnerability, and the community recovery within 41 days on this scenario of less frequent events in 2013. On the other hand, significant differences in the macrofauna only in the urbanized sector between PREV and POEV II also highlight macrofauna vulnerability and community recovery failure within 42 days on this scenario of more frequent storm in 2014. Urbanization and wave height were the variables that most influenced species, indicating that high storm wave events and increasing urbanization synergism are a threat to the macrofauna.

1. Introduction

Coastal development inherent to economic progress has resulted in extensive changes, especially on sandy beaches, due to their tourist and recreational importance (McLachlan et al., 2013). Besides climate change, anthropogenic impacts threaten the maintenance of functions, goods and environmental services provided by these coastal ecosystems (Defeo et al., 2009; Harley et al., 2006).

The increase in the frequency and intensity of extreme events is one of the consequences listed by climate change reports (IPCC, 2013). Storm waves are among the main extreme weather events on the Brazilian coast. The occurrence of cold fronts, storms, and comparatively higher waves generates direct impacts on beach hydrodynamics and sediment flows, leading to more intense waves and changes in sandy sediment fraction (Alves and Pezzuto, 2009). Thus, storm waves alter beach morphodynamics and, consequently, the local topographic profile (Brauko, 2008). Also, these events revolve sediment, and thus may increase organic matter available on drift line (Alves and Pezzuto, 2009).

Physical factors such as sand grain size, wind speed, and topography have been shown to affect material and energy cycling in sandy beaches on a spatial scale (McLachlan and Brown, 2006). Besides, the availability of organic matter as nutrient to macrofaunal organisms is crucial to understand their habitat association patterns in sandy beaches (Lastra et al., 2006).

The intertidal macrofauna is adapted to severe hydrodynamic conditions (Veloso et al., 1997), however increased wave intensity in sandy beaches may alter the structure and composition of the community both directly (affecting survival of species) and indirectly (changing the environmental characteristics) (Brown, 1996; Posey et al., 1996; McLachlan and Brown, 2006).

The erosion processes that begin after storms might induce sediment defaunation, and it may take months, or even years, for environment recolonization to begin (Jaramillo, 1987). In exposed sandy beaches, massive mortality of benthic organisms may result from storm events due to erosive processes and alterations in the position of the swash zone (McLachlan, 1996). However, other studies that evaluated the effects of extreme events on beaches found no significant reduction in macrofauna abundance and richness (Saloman and Naughton, 1977; Hughes et al., 2009; Sola and Paiva, 2001; Gallucci and Netto, 2004; Cochôa et al., 2006; Alves and Pezzuto, 2009).

The influence of storm wave events is also described as favoring suspensivorous organisms, due to the resuspension of sediment material (Bock and Miller, 1995). Detritivorous also take advantage in response to the increased of natural debris thrown into the beach by the waves (Alves and Pezzuto, 2009).

It should be considered that these studies were conducted at beaches without anthropogenic interference, and that urbanization might influence the community responses to natural stochastic events, since recovery after erosion processes is slower in urbanized coasts (Castelle et al., 2008; Harris et al., 2011; Witmer and Roelke, 2014). Therefore, the lack of knowledge about future scenarios in increasingly urbanized sandy beaches is evident.

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