UNIVERSIDADE FEDERAL RURAL DE PERNAMBUCO
PRÓ-REITORIA DE PESQUISA E PÓS-GRADUAÇÃO
PROGRAMA DE PÓS-GRADUAÇÃO EM RECURSOS PESQUEIROS E AQUICULTURA

ESTRUTURA TRÓFICA DA ICTIOFAUNA ESTUARINA E MARINHA DO COMPLEXO ITAPISSUMA/ITAMARACÁ, NORTE DE PERNAMBUCO, BRASIL

Valdimere Ferreira

Tese apresentada ao Programa de Pós-Graduação em Recursos Pesqueiros e Aquicultura da Universidade Federal Rural de Pernambuco como exigência para obtenção do título de Doutora.

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Tese julgada adequada para obtenção do título de doutora em Recursos Pesqueiros e Aquicultura. Defendida e aprovada em 27/02/2018 pela seguinte Banca Examinadora.

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Dedicatória

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Resumo

Os ambientes estuarino e costeiro do Complexo Itapissuma/Itamaracá (IIC), Pernambuco, Brasil, destacam-se como áreas de relevante importância biológica, pesqueira e social. Dada a complexidade e a importância do IIC, este trabalho tem o objetivo de investigar a estrutura trófica da ictiofauna e a conectividade entre os ambientes estuarino e costeiro, através das guildas ambientais e tróficas, dos isótopos estáveis de carbono ($\delta^{13}C$) e nitrogênio ($\delta^{15}N$) e do modelo Ecopath. Os dados foram coletados entre 2013 e 2015 nas regiões estuarina e costeira do IIC. Foram coletadas 141 espécies de 34 famílias sendo 66 espécies (47%) exclusivas no estuário, 50 espécies (35%) na costa e 25 (18%) em ambos os ambientes. No estuário, as espécies marinhas foram dominantes em riqueza e biomassa e as espécies estuarinas em abundância. Migrantes marinhas apresentaram maior riqueza, abundância e biomassa nas águas costeiras. Zoobentívoros dominaram em riqueza e os detritívoros em abundância e biomassa no estuário. Na costa, zoobentívoros apresentaram maior riqueza e abundância e os piscívoros tiveram maior biomassa. Foram obtidos os $\delta^{13}C$ e $\delta^{15}N$ de 9 fontes basais, 8 invertebrados e 16 espécies de peixes. No estuário, $\delta^{13}C$ de peixe e $\delta^{15}N$ de invertebrados e na costa, o $\delta^{13}C$ de POM (Matéria Orgânica Particulada), SOM (Matéria orgânica no Sedimento) e $\delta^{15}N$ de POM, SOM e peixe foram mais enriquecidos ($p < 0,05$). Espécies de peixes capturadas no estuário e na costa, indicaram uma baixa sobreposição de nicho isotópico (20,36%) entre os ambientes. O Ecopath foi baseado em 32 grupos funcionais (3 produtores primários, 6 invertebrados, 22 peixes e 1 detrito). Invertebrados, *Lutjanus* spp. e *Gobionelus oceanicus* foram altamente consumidos ou exportados no IIC. A maioria da biomassa de peixes dominou em níveis tróficos baixos e os consumidores primários foram as principais fontes de detritos. Os predadores alimentam-se predominantemente de presas dos baixos níveis tróficos, principalmente grupos bentônicos. *Centropomus* spp., *Caranx* spp. e *Sphyraena* spp. tiveram um alto impacto na teia trófica e o aumento da pescaria impacta negativamente *Centropomus* spp. e, positivamente, *Sphyraena* spp.. O nível trófico estimado por Ecopath e o $\delta^{15}N$ no IIC foram altamente correlacionados ($R = 0,77$). O IIC tem alta capacidade de resiliência e suporta uma rede trófica complexa dependente das áreas estuarinas e costeiras formada, principalmente por espécies migrantes e zoobentívoras.

Palavras-chave: conectividade, guildas ecológicas, isótopos de carbono e nitrogênio, interações tróficas, modelagem ecossistêmica.

Abstract

The estuarine and coastal environments of the Itapissuma/Itamaracá Complex (IIC), Pernambuco, Brazil, are areas of relevant biological, fishing and social importance. This work has the objective of investigating the trophic structure of the ichthyofauna and the connectivity between the estuarine and coastal environments through the environmental and trophic guilds, the stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) and the Ecopath model. Data were collected between 2013 and 2015 in the estuarine and coastal environments of IIC. A total of 140 species from 34 families were collected, 65 species (47%) were exclusive in the estuary, 50 species (35%) in the coast and 25 (18%) in both environments. In the estuary, marine species were dominant in richness and biomass and estuarine species in abundance. Marine migrants presented greater richness, abundance and biomass in coastal waters. Zoobentívores dominated in richness and detritivores in abundance and biomass in the estuary. In the coast, zoobentívores presented greater richness and abundance and the piscivores had greater biomass. $\delta^{13}C$ and $\delta^{15}N$ were obtained from 9 basal sources, 8 invertebrates and 16 fish. In the estuary, $\delta^{13}C$ of fish and $\delta^{15}N$ of invertebrates and in the coast, $\delta^{13}C$ of POM, SOM and $\delta^{15}N$ of POM, SOM and fish were more enriched ($p < 0.05$). Species of fish caught in the estuary and coast indicated a low overlap of isotope niche (20.36%) between environments. Ecopath was based on 32 functional groups (3 primary producers, 6 invertebrates, 22 fish and 1 detritus). Invertebrates, *Lutjanus* spp. and *Gobionelus oceanicus* were highly consumed or exported in the IIC. Most fish biomass dominated at low trophic levels and primary consumers were the major sources of detritus. Predators feed predominantly on prey of low trophic levels, mainly benthic groups. *Centropomus* spp., *Caranx* spp. and *Sphyraena* spp. had a high impact on the trophic web and the increase of fishery negatively impacts *Centropomus* spp. and, positively, *Sphyraena* spp. The trophic level estimated by Ecopath and $\delta^{15}N$ in IIC were highly correlated ($R = 0.77$). The IIC has high resilience capacity and complex trophic network dependent on the estuarine and coastal areas formed mainly by migrant and zoobentivorous species.

Key words: connectivity, ecological guilds, carbon and nitrogen isotopes, trophic interactions, ecosystem modeling.

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1. Introdução

1.1 - Ecologia

O homem tem se interessado pela ecologia desde os primórdios da história, pois precisava conhecer o ambiente em que vivia e, entende-se que conhecer o ambiente é indispensável para a qualidade de vida da humanidade (ODUM, 1971). Ecologia, conceitualmente, pode ser definida como a ciência que investiga as relações dos organismos ou grupo de organismos com o meio em que vivem. Embora o termo "ecologia" tenha sido proposto em 1869 por Ernest Haeckel, vários estudiosos já contribuíam para o tema, entre eles, Anton van Leeuwenhoek, no século XVIII, estudando as cadeias alimentares (ODUM, 1971). Em 1915, o biólogo Johannes Petersen criou o primeiro diagrama da cadeia alimentar conhecido para uma comunidade marinha (EGERTON, 2007) iniciando assim os estudos na ecologia trófica de ambientes costeiros (FIGURA 1). Algumas perguntas são altamente relevantes na ecologia trófica, entre elas, "Como está estruturada a cadeia trófica?" e "Como esta estrutura influencia a dinâmica da população e os processos ecossistêmicos?". Para buscar estas respostas, deve-se considerar: a cadeia trófica como uma unidade operacional, os componentes da cadeia trófica, a natureza dos links e as variações espaço-temporais. E em busca dessas respostas, diferentes ferramentas podem ser aplicadas, combinadas ou não, entre elas as guildas ecológicas, isótopos estáveis e modelagem ecossistêmica.

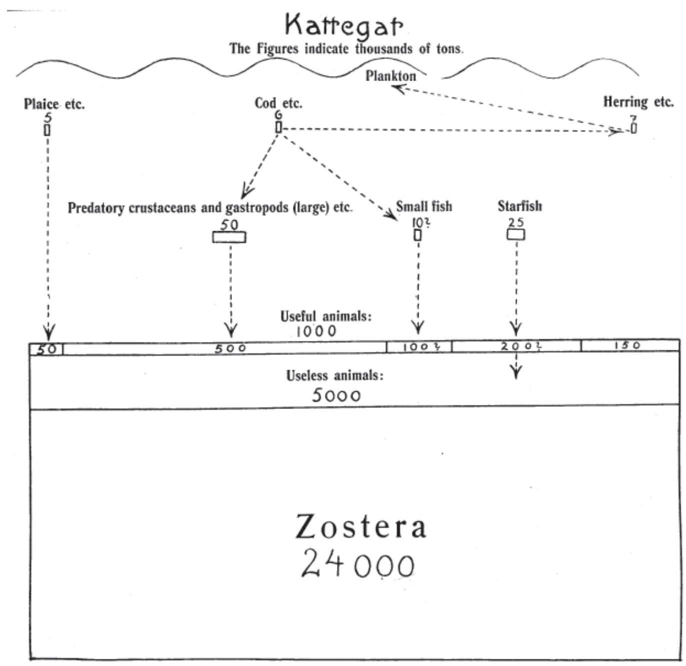

Figura 1. Cadeia trófica desenhada por Johannes Petersen em 1915. Os números indicam a produção de cada grupo em toneladas. Extraído de EGERTON, 2007.

1.2 - Guildas ecológicas

As guildas ecológicas são ferramentas eficientes para investigar a estrutura e uso do habitat nos ecossistemas e podem ser definidas como um grupo de espécies que exploram o mesmo recurso ambiental de forma similar (ROOT, 1967). Estudos com guildas geram informações sobre o funcionamento, estrutura hierárquica e conectividade e simplificam o entendimento dos ecossistemas complexos (GARRISON e LINK 2000; ANGEL e OJEDA, 2001; FRANCO et al., 2008; NICOLAS et al., 2010). Os resultados obtidos através das guildas permitem melhor inferência, pois um padrão observado dentro de uma guilda pode implicar funções ecológicas, como alimentação ou reprodução, gerando evidências mais conclusivas do que tendências dentro de uma única espécie (KWAK e PETERSON, 2007). Através das guildas ecológicas, pode-se investigar a composição e distribuição espacial e temporal da ictiofauna (AKIN, 2005). As guildas são baseadas em relações tróficas (GERKING, 1994; ELLIOTT et al., 2007), reprodução (BALON, 1981; ELLIOTT et al., 2007) ou habitat (ELLIOTT et al., 2007).

A composição da ictiofauna varia de acordo com as mudanças que ocorrem nos ambientes (RAY, 2005) e, no caso dos ambientes costeiros, as guildas contribuem na compreensão do uso dos estuários pela ictiofauna, suas interações e conectividade com áreas adjacentes (zona costeira e continental) (ABLE, 2005; ELLIOTT et al, 2007). As guildas ecológicas também permitem investigar os efeitos das perturbações antrópicas nos ecossistemas. Espécies de mesma guilda respondem de forma similar à degradação do habitat pela sedimentação (BERKMAN e RABENI, 1987); alterações advindas da pesca provocam mudanças na estrutura levando à dominância de algumas guildas em detrimento de outras (AUSTER e LINK, 2009); e após mudanças hidrológicas, os grupos dominantes que eram pelágicos, detritívoros e espécies mais toleráveis às variações de salinidade são substituídos por espécies demersais, bentônicas, piscívoras e marinhas (BAPTISTA et al., 2015).

1.3 - Isótopos estáveis

“Você é o que você come” (DeNIRO e EPSTEIN, 1976). Esta afirmação, recorrente nos estudos tróficos, enfatiza a importância da dieta para o consumidor e a necessidade de compreender as relações entre fontes e consumidores nos ecossistemas.

O uso de isótopos estáveis em estudos ambientais considera que a composição isotópica varia de forma previsível, conforme o elemento se move através dos diversos compartimentos de um ecossistema (MARTINELLI et al., 2009). Os isótopos estáveis emergiram como uns dos principais meios para analisar a estrutura das redes alimentares (LAYMAN et al., 2007), pois as principais fontes de energia para a cadeia trófica podem ser identificadas através das análises isotópicas de alguns elementos (H, O, S), destacando-se o carbono e o nitrogênio (POST, 2002; FRY, 2006). A composição isotópica de carbono (DeNIRO e EPSTEIN, 1978) e nitrogênio (DeNIRO e EPSTEIN, 1981) observada no consumidor reflete a composição isotópica da dieta e, assim, permite inferências sobre as fontes assimiladas e a posição trófica. O fracionamento dos isótopos de carbono é muito baixo entre fonte e consumidor (~1‰), assim, podendo indicar vias de alimentação (VANDER ZANDER e RASMUSSEN, 2001; POST, 2002). Os valores dos isótopos de nitrogênio tornam-se enriquecidos em sucessivos níveis tróficos (~3,4‰), permitindo estimar a posição trófica do consumidor (CABANA e RASMUSSEN, 1996; VANDER ZANDEN e RASMUSSEN, 1999; POST, 2002). A composição isotópica de um elemento é a razão entre o isótopo raro, considerado o mais pesado (^{13}C, ^{15}N) e o isótopo mais abundante, o mais leve (^{12}C, ^{14}N) expressa pela relação:

$$\delta = [(R_{amostra}/R_{padrão} - 1)]*1000,$$

Onde $R = {}^{H}F/{}^{L}F$; e F = Abundância fracional do isótopo pesado (^{H}F) ou leve (^{L}F)

Diferentes contribuições científicas, através da aplicação dos isótopos estáveis de carbono ($^{13}C/^{12}C$) e nitrogênio ($^{15}N/^{14}N$) nas investigações das teias alimentares e fluxo de energia em diferentes ecossistemas aquáticos, são atualmente disponíveis na literatura (FAYE et al., 2011; ABRANTES et al., 2013; CONNOLLY e WALTHAM, 2015). As informações obtidas permitem observar mudanças temporais e espaciais (CLAUDINO et al., 2013; BERGAMINO e RICHOUX, 2014; SOARES et al., 2014), identificar perturbações na cadeia trófica (MIDDELBURG, 2014; LETOURNEUR et al., 2017) e contribuir para o monitoramento dos ecossistemas (TRUEMAN e MOORE, 2007). Através dos isótopos é possível também estimar o nicho trófico das espécies (CHEREL et al., 2011; O'FARRELL et al., 2017) e investigar a conectividade trófica nos ecossistemas (GAJDZIK et al., 2014; CLAUDINO et al., 2015; VINAGRE et al., 2016).

1.4 - Modelagem ecossistêmica

Os modelos ecossistêmicos descrevem as interações tróficas dentro dos ecossistemas e são a base para o estudo dos padrões gerais de propriedades ecológicas (HEYMANS et al., 2011). Modelos são extremamente úteis como resumo da situação a ser modelada e através das simplificações, revelam os processos ocorrentes no ecossistema (ODUM, 1971; ANGELINI, 2017). Quando se analisa os ecossistemas através de modelagem matemática emergem perspectivas bem diferentes e interessantes sobre a estrutura e dinâmica da rede trófica (LAYMAN et al., 2015). O funcionamento dos ecossistemas foi discutido por ODUM (1969) através de atributos e métricas que descrevem os estágios de sucessão dos ecossistemas (TABELA 1). Estas informações foram base para o desenvolvimento do modelo Ecopath (POLOVINA, 1984) que mais tarde foi aperfeiçoado por PAULY et al. (1987) e CHRISTENSEN e PAULY (1992).

O Ecopath é um modelo trófico que analisa os processos bióticos como produção, consumo e suas eficiências nos fluxos de níveis tróficos e tem como premissa que os componentes devem estar em condições de equilíbrio no sistema (ANGELINI, 2017). É um modelo estático, porém o software dispõe de ferramentas que permitem uma modelagem dinâmica - Ecosim e espacial dos dados – Ecospace (CHRISTENSEN e WALTERS, 2004). O modelo é um dos vários métodos que existem para analisar um conjunto complexo de informações (ANGELINI e TUBINO, 2017) e os atributos gerados pelo Ecopath tem sido amplamente discutidos em todo o mundo. São diversos os objetivos dos trabalhos desenvolvidos com o Ecopath, entre eles podem-se citar: comparações espaciais (VILLANUEVA, 2015) e temporais (RAKSHIT et al., 2017) da estrutura e funcionamento dos ecossistemas; avaliação dos efeitos do processos de eutrofização no ambiente (PATRÍCIO e MARQUES, 2006); contribuição do conhecimento local de pescadores na modelagem científica (BEVILACQUA et al. 2016) e avaliação do efeito da pesca no ecossistema (FREIRE et al., 2007; HALOUANI, et al., 2016; CORRALES et al., 2017).

Tabela 1 - Atributos e categorias indicando o estágio de desenvolvimento dos ecossistemas, observados por ODUM (1969).

	Atributos do ecossistema	Fases do desenvolvimento	Fases maduras
	Energia da comunidade		
1	Produção bruta/respiração da comunidade(P/R)	Maior ou menor que 1	Próximo a 1
2	Produção bruta/biomassa da comunidade(P/B)	Alta	Baixa
3	Biomassa/fluxo de energia (B/E)	Baixa	Alta
4	Produção líquida da comunidade	Alta	Baixa
5	Cadeia alimentar	Linear (pastoreio)	Rede (detritos)
	Estrutura da comunidade		
6	Matéria orgânica	Pouca	Próximo a 1
7	Nutrientes inorgânicos	Extrabiótica	Intrabiótica
8	Diversidade em espécies-variedade	Baixa	Alta
9	Diversidade em espécies-equidade	Baixa	Alta
10	Diversidade bioquímica	Baixa	Alta
11	Estratificação e heterogeneidade espacial (diversidade de padrão)	Pouco organizada	Bem organizada
	Biologia		
12	Especialização de nicho	Ampla	Restrita
13	Tamanho do organismo	Pequeno	Grande
14	Ciclos de vida	Curto, simples	Longo, complexo
	Ciclo de nutrientes		
15	Ciclos minerais	Aberto	Fechado
16	Fluxo de nutrientes entre organismo e comunidade	Rápido	Lento
17	Importância dos detritos na regeneração dos nutrientes	Sem importância	Importante
	Pressão da seleção		
18	Forma de crescimento	Rápido: r	Lento: k
19	Produção	Quantitativo	Qualitativo
	Homeostasia geral		
20	Simbiose interna	Não desenvolvida	Desenvolvida
21	Conservação de nutrientes	Sem qualidade	Com qualidade
22	Estabilidade (resistência às perturbações externas)	Sem qualidade	Com qualidade
23	Entropia	Alta	Baixa
24	Informação	Baixa	Alta

1.5 - Complexo Itapissuma/Itamaracá

Os ambientes estuarino e costeiro do Complexo Itapissuma/Itamaracá (IIC), localizado no litoral norte de Pernambuco, nordeste do Brasil, destacam-se como áreas de relevante importância biológica, pesqueira (IBAMA, 2009; CPRH, 2010) e social, e integram a Área de Proteção Ambiental do Canal de Santa Cruz - APA de Santa Cruz. Criada em 2008, a APA de Santa Cruz tem, entre os seus objetivos, a proteção do IIC, considerado de relevante importância ambiental de forma a conservar a sua qualidade, diversidade biológica e seus recursos pesqueiros (CPRH, 2010). No IIC, os pescadores tem um conhecimento acurado sobre a biodiversidade, as relações ecológicas e a importância dos recursos naturais para a produção pesqueira, cuja base econômica familiar advém desses recursos (CARNEIRO et al., 2008) que representam uma importante fonte protéica para a população local (LINO, 2003).

Além da importância para o homem, as áreas estuarina e costeira do IIC são utilizadas para o desenvolvimento (VASCONCELOS e OLIVEIRA, 1999; SANTANA, 2009) e alimentação de muitas espécies da ictiofauna (ALMEIDA et al., 1997; VASCONCELOS FILHO et al., 2003, 2009, 2010; LIRA, 2008; ARAUJO et al., 2013, LIRA et al., 2017). Um modelo conceitual indicando as interações abióticas e bióticas dos componentes no estuário e na costa, evidenciou a conectividade e dependência entre esses ambientes do IIC (FIGURA 2) (ESKINAZI-LEÇA et al., 1999).

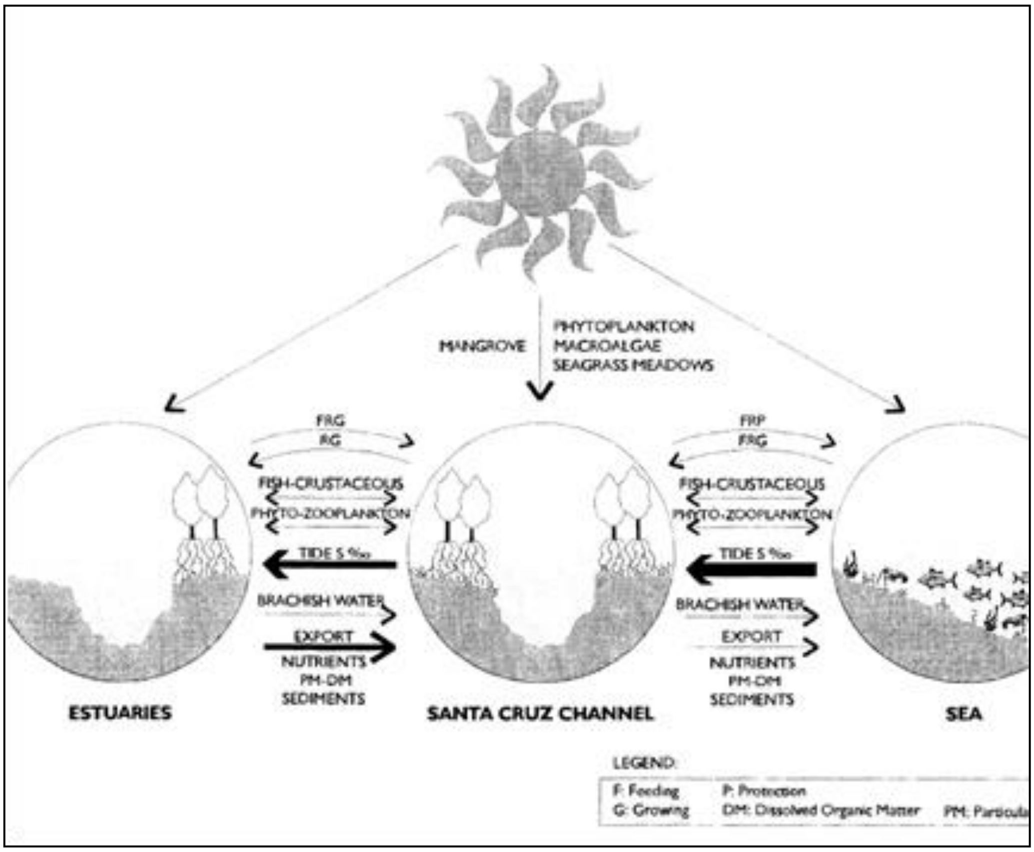

Figura 2: Modelo conceitual desenvolvido para o Complexo Itapissuma/Itamaracá, Pernambuco, Brasil. Extraído de ESKINAZI-LEÇA et al. (1999).

Dada a complexidade e a importância do IIC, as pesquisas devem, sempre que possível, considerar os elos existentes entre o estuário e a costa. Conhecer a estrutura e as interações ocorrentes nos ecossistemas possibilita recomendações mais abrangentes sobre o manejo dos recursos.

2 - Objetivos

Dada a importância biológica, pesqueira e social do Complexo Itapissuma/Itamaracá, o objetivo desta pesquisa é investigar e descrever a estrutura trófica da ictiofauna nas áreas estuarina (Canal de Santa Cruz) e costeira (Mar de Dentro). Considerando que existe uma conectividade trófica, o que influencia a estrutura da cadeia, múltiplas ferramentas foram utilizadas para atender o objetivo da Tese, tratado em três capítulos: guildas ecológicas, isótopos estáveis e modelagem ecossistêmica.

No capítulo 1, intitulado "**Guildas ecológicas da ictiofauna e evidência de conectividade entre ambientes costeiros no Nordeste do Brasil"** a composição e estrutura da ictiofauna estuarina e costeira foram descritas através de guildas ambientais e tróficas. A conectividade entre os ambientes estuarino e costeiro e as variações espaciais e temporais foram investigadas considerando a riqueza, abundância e biomassa das guildas.

No capítulo 2, intitulado "**Cadeia trófica de um ecossistema costeiro no Nordeste do Brasil, investigado por isótopos estáveis"**, a estrutura da cadeia trófica do estuário e da costa foi investigada através dos isótopos estáveis de carbono e nitrogênio. A escolha das espécies analisadas foi baseada nas informações geradas pelo capítulo 1 e também por outros estudos feitos no complexo. A variação espacial e temporal isotópica das fontes basais, invertebrados e peixes da cadeia trófica e a conectividade trófica da ictiofauna entre os ambientes estuarino e costeiro foram analisadas e testadas.

No capítulo 3, intitulado "**Modelo de balanceamento de massa para avaliar a cadeia trófica em um estuário tropical, Nordeste do Brasil**" foi aplicado o modelo Ecopath para o canal de Santa Cruz, considerada como a área estuarina neste estudo. O objetivo da modelagem foi avaliar a importância dos grupos funcionais no ecossistema, investigar as relações tróficas entre esses grupos, e descrever os fluxos de energia e biomassa que sustentam a cadeia trófica. Além disso, o nível trófico de algumas espécies estimado pelo Ecopath foi correlacionado com os resultados isotópicos obtidos no capítulo 2.

3 - Artigo Científico 1

Artigo científico redigido segundo as normas da revista Journal of Fish Biology. Online ISSN: 1095-8649.

Ecological guilds of the fish fauna and evidence of connectivity between coastal environments in Northeastern Brazil

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Ecological guilds have been widely applied for the understanding of the structure and functioning of aquatic ecosystems with a focus on the connectivity between environments and their use as a feeding, breeding or development ground. This study aims to describe the composition and the spatio-temporal changes in the structure of the fish fauna and to investigate, through ecological guilds, the connectivity between the estuary and the coast of Itapissuma/Itamaracá Complex (IIC), a tropical estuary in Northeastern Brazil. Fish specimens were collected during the dry and rainy seasons in 2013 and 2014. A total of 141 species of 34 families were recorded in the IIC. Almost half of the species (66 species, 47%) were exclusive to the estuary and 50 species (35%) to the coast; 25 (18%) were common to both environments. Marine species (stragglers and migrants) were dominant in both richness (the number of species) and biomass (the total weight) in the estuary as they explore the environment during part of their life cycle, whereas estuarine species dominated considering abundance. Marine stragglers displayed a higher richness, abundance and biomass in the coastal waters. The estuarine environment was dominated by zoobentivores in terms of richness, while detritivores prevailed in abundance (the total number) and biomass. Zoobentivores had highest richness and abundance in coastal waters while piscivores showed the highest biomass. Considering the icthyofauna, the IIC supports a rich fauna with a diverse trophic structure. The complex is a relevant feeding and developement area for migratory species and the high percentage of marine species confirms the connectivity and dependence between estuarine and coastal area of the IIC.

Key words: fish; functional attribute; habitat; Pernambuco, spatial-temporal distribution; tropical estuary.

INTRODUCTION

The ichthyofauna can be described and classified through the functional attributes of organisms (Nagelkerken & van der Velde, 2004; Akin *et al.*, 2005), mainly based on the trophic level, reproductive strategy or the use of the environment (Elliott *et al.*, 2007; Franco *et al.*, 2008). The functional attributes organize the species in guilds, defined as group of species that exploit the same class of environmental resources in a similar way (Root, 1967). The guild approach allows a better understanding of the ecology and role of the biota in the ecosystem (Blondel, 2003; Elliott *et al.*, 2007; Jaafour *et al.*, 2015). It may contribute for the identification of overexploited resources through changes in the composition of the food web (Garrison & Link, 2000) and of the energy flows in the system (Harrison & Whitfield, 2008; Carassou *et al.*, 2016). It also helps for the understanding of the effects of climatic changes on the structure and composition of the fish fauna (Gillanders *et al.*, 2011b; Ko *et al.*, 2014; Feyrer *et al.*, 2015).

Environmental and trophic guilds have been widely applied for understanding the structure and functioning of aquatic ecosystems with a focus on the connectivity between environments and their use as a feeding, breeding or development grounds (Elliott *et al.*, 2007; Passos *et al.*, 2013). The understanding of species-specific patterns of connectivity is vital for spatially defined management. For example, the size, location, number, and spacing of Marine Protected Areas and terrestrial conservation parks should ideally be dictated by dispersal and connectivity of key species (Gillanders *et al.*, 2011a). Environmental guilds reflect migratory patterns and physiological adaptations of species that explore the area throughout their life cycle or part of it (Elliott *et al.*, 2007). Trophic guilds are useful in the comprehension of the feeding habits of a species (Elliott *et al.*, 2007), its ecological relationships and the energy flows (Paiva *et al.*, 2008; Rasher *et al.*, 2013; Dantas *et al.*, 2012), which may reflect the possible strategies to avoid competition or to optimize the consume of available resources (Angel & Ojeda, 2001).

Estuaries are important transitional environments for the movement of the ichthyofauna between the continental basins and the ocean (Pihl *et al.*, 2002; Ray, 2005). As an ecotone, estuaries link marine and freshwater ecosystems (Gray & Elliott, 2009), and persistent environmental fluctuations place considerable physiological demands on the species inhabiting the area (Elliott & Quintino, 2007). Many species are dependent of estuarine environments; several marine species are considered visitors and explore estuarine habitats during their ontogenetic development, evidencing the relationship between coastal environments (Able, 2005). Therefore, defining the relationships between species and their functional roles within communities is critical for understanding the dynamics of the ecosystem, fundamental for the implementation of ecosystem-based fisheries management (Whipple *et al.*, 2000; Tyrrell *et al.*, 2011; Buchheister & Latour, 2015).

The Brazilian coast hosts large estuarine complexes and along the 187 km of the coast of Pernambuco, several areas are considered of relevant environmental importance (CPRH, 2010). Among these areas the Itapissuma/Itamaracá Complex (IIC), inserted in the Santa Cruz Environmental Preservation Area (APA Santa Cruz), is considered highly productive (Macêdo *et al.*, 2000), hosting the largest fishery port in the state. In IIC, fishery is a very important socio-economical activity, generating income and protein for the local community and region (CPRH, 2010). Conversely, this ecosystem is exposed to multiple pressures from industrial pollution, domestic sewage discharge, urban expansion, land reclamation and fisheries (Medeiros *et al.*, 2001). Also, the IIC has a large variety of connecting habitats favouring the development of the ichtyofauna (Vasconcelos Filho *et al.*, 2009; Santana *et al.*, 2013). This variety of habitats, along with the complexity of interactions within the fish community and the migratory nature of many species, hampers the assessment of the area overall condition (Vasconcelos Filho *et al.*, 2003).

This study aims to describe the spatial and temporal composition of the fish fauna in the IIC through ecological guilds in order to assess the connectivity patterns between a tropical estuarine complex and its adjacent costal area in northeastern Brazil.

MATERIALS AND METHODS

STUDY AREA

The Itapissuma/Itamaracá Complex (IIC), located in Pernambuco, Northeastern Brazil, is composed by the Santa Cruz Channel and the adjacent sea, locally named as "Inner Sea" (Fig. 1). The Santa Cruz channel, which corresponds to the estuarine area in this study, is 22 km long and width ranging from 0.6 to 1.5 km. Depth varies from 2 to 5 m in the central part of the channel, reaching 10 m in the north and south bars that connect the channel to the sea (Vasconcelos Filho & Oliveira, 1999). The channel bottom consists of quartz sand banks and dark, reductive and dense mud patches. The muddy banks are dominated by *Rhyzophora mangle*, *Laguncularia racemosa*, *Avicennia* sp. and *Conocarpus erectus* and meadows of the marine phanerogam, *Halodule wrigtii* (Neumann-Leitão & Schwamborn, 2000). Surface water temperature varies between 25°

and 31ºC and salinity between 18 and 34 (Macêdo *et al.*, 1998). The Inner Sea, corresponding to the coastal area hereafter, with depth of 2 to 5 m, is characterized by a reef barrier parallel to the coast, placed 4 km from the beach (Kempf, 1970), which functions as a barrier between nearshore and shelf waters (Mabesoone, 1964). The substrate is formed by terrigenous sediments from the mouth of the Jaguaribe River and the Channel of Santa Cruz, and carbonates from the reef barrier (Almeida & Manso, 2011), partially covered by large banks of phanerogams (Kempf, 1970). The carbonaceous material is the result of the decomposition of rocks and quartz, sand, mollusc shells, foraminifera and calcareous algal fragments (Guerra *et al.*, 2005). In the Inner Sea, water temperature varies between 27 and 30.8°C (Manso *et al.*, 1992) and the annual average salinity is 34.7 (Bonifácio, 1990).

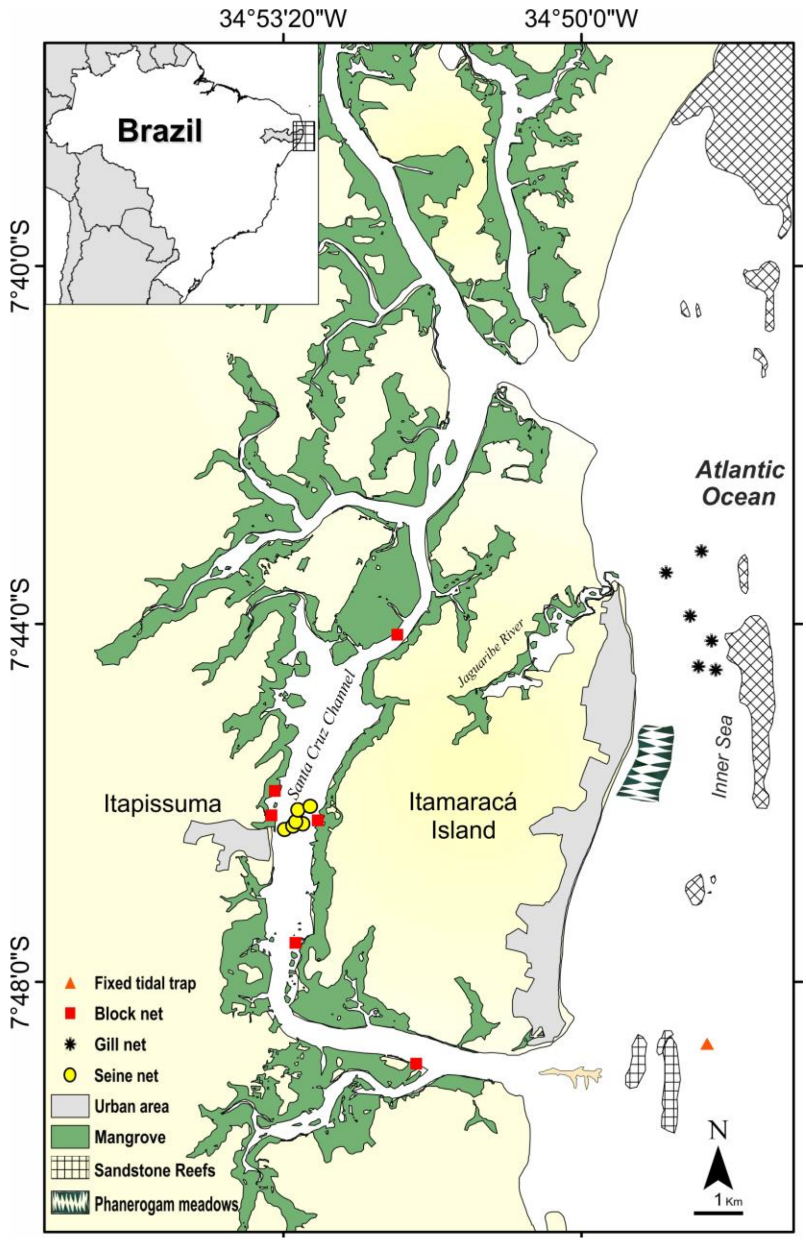

FIG. 1. The study area of Itapissuma/Itamaracá Complex, Pernambuco, Brazil and location of fish sampling points.

DATA COLLECTION

Fish specimens were collected during dry (January, February, March, November) and rainy seasons (May, July, August) in 2013 and 2014 in the Santa Cruz Channel and the Inner Sea. In order to minimize biases due to gear selectivity, different fishing gears were combined for accessing and sampling different habitats and maximize the collection of fish individuals (Table S1, Supporting information). In the estuary, quarterly, four sets of 25 minutes each were carried out with a seine net, and sets of block net of six hours each were also deployed. The seine net was 67.5 m long, with a mesh size of 10 mm. The block net was 348 m long, with a mesh size of 60, 70 and 80 mm. In the coast, samples were obtained quarterly with gillnet (3 sets of two hours each) and with fixed tidal trap (6 fishing days). The gill net had mesh sizes of 50, 70 and 80 mm, and was 690 m long, and the fixed tidal trap had 27 m of diameter and mesh size of 70 mm.

In the field, the fish fauna was conserved in thermal boxes with ice and, in the laboratory, samples were frozen. Fish were identified based on Figueiredo & Menezes (1980), Menezes & Figueiredo (1980, 1985), Nóbrega *et al*. (2009) and Garcia Júnior *et al*. (2010).

DATA ANALYSIS

Firstly, we computed a species accumulation curve with non-parametric Bootstrap method (Smith & van Belle, 1984) to assess whether the fish community was exhaustively sampled (Gotelli & Colwell, 2001). This method assumes that all species occur randomly, without taking into account species abundance, i.e., the method does not distinguish rare and abundant species (Smith & van Belle, 1984; Magurran, 1988). The index and standard deviations of the estimates were obtained through the analytical equation of Colwell *et al*. (2004) using the EstimateS software v. 9 9.1.0 (Colwell, 2013).

The composition of the fish fauna was reported in terms of absolute species richness (S), and for each species, in frequency of occurrence (% FO) and relative abundance in number (% N) and biomass (% B). Species were considered to be abundant according to the Garcia & Vieira (2001) classification when % N was greater than 100/S, where S = the number of species recorded in the area. A species was defined as frequent when its % FO value for a given area was greater than 50 %. The combination of these parameters enabled the classification of the different species into four categories: AF - abundant and frequent (% N > 100/S and % FO ≥ 50%); AI - abundant, but infrequent (% N > 100/S and % FO < 50 %); LAF - Less abundant but frequent (% N < 100/S and % FO ≥ 50 %), and LAI - less abundant and infrequent (%N < 100/S and % FO < 50 %).

Each species was assigned to an Estuarine Use Functional Group: marine stragglers (MS), marine migrants (MM) and estuarine species (ES), according to the classification proposed by Elliott *et al.* (2007). This classification is based on the type, frequency and period of use of the estuarine environment, and the abundance of the species in the estuary. In addition, each species was assigned to a trophic functional group (based on local information about feeding preferences and strategies, according to the categories proposed by Elliott *et al.* 2007). The trophic functional groups were: zooplanktivore (ZP), detritivore (DV), piscivore (PV), zoobenthivore (ZB), herbivore (HV) and omnivore (OV). Information on trophic guilds were obtained in studies carried out in the IIC, the scientific literature or, when not available, based on the WoRMS database (2017) and FishBase project (Froese & Pauly, 2007) (Table S2, Supporting information). For each environment (estuary and coast) and season (dry and rainy), the environmental and trophic guilds were reported in terms of richness (% S), abundance (% N) and biomass (% B).

We computed a multivariate analyses to investigate the spatial and temporal variations in the structure of the fish community, considering the abundance of trophic and environmental guild in the environments and seasons. The data were standardized using the mean percentage of abundance between the fishing gear for the each environment (estuary and coast) and season (dry and rainy). To analyse the guilds composition, a Principal Coordinate Analysis (PCO), based on Bray–Curtis distances, was applied. The differences of the contribution of guilds between environments and seasons was tested by permutational multivariate analysis (PERMANOVA) (Anderson, 2001). PERMANOVA was performed with a Bray-Curtis distance matrix built on square-root-transformed data. Multivariate analyses were performed with R software (R Core Team, 2016).

RESULTS

FISH ASSEMBLAGE

A total of 140 species (135 Actinopterygii and 5 Elasmobranchii) of 34 families were recorded in the Itapissuma/Itamaracá Complex (IIC) (Table I). For both coastal and estuarine areas, the species accumulation curve did not stabilise towards asymptotic values (Fig. S1, Supporting information). However, a large portion of the estimated richness was effectively sampled: 88 species (88% of the estimated richness) were observed in the estuary and 75 species (85% of the estimated richness) in the coast. A total of 25 species (18%) were common to both estuary and coast, 65 species (47%) were exclusive to the estuary and 50 species (35%) only occurred in the coast (Table I).

In the estuary, Engraulidae (9 species), Gerreidae (9 species) and Gobiidae (8 species) stood out in richness (S). The Gobiidae family had the highest abundance (%N) in the dry (7694 individuals, 62 %) and rainy (3776 individuals, 58 %) seasons. In terms of biomass, Mugilidae dominated during the dry season (114.34 kg, 51.74%) and Gobiidae during the rainy season (22.20 kg, 28 %). The gobiid *Gobionelus stomatus* Starks, 1913 showed the highest abundance in both seasons (dry – 6582 individuals, 53% and rainy – 3532 individuals, 54%), while for biomass, *Mugil curema* Valenciennes, 1836 (114.39 kg, 52%) and *Cetengraulis edentulus* (Spix & Agassiz, 1829) (18 kg, 22.42%) stood out during the dry and the rainy seasons, respectively (Table I).

In the coast, Carangidae stood out in richness (14 species), abundance (288 individuals - 49% and 166 individuals – 50%, during the dry and rainy seasons, respectively) and biomass (115 kg - 57% and 203 kg - 74% in the dry and rainy seasons, respectively). In terms of species, *Selene brownii* (Cuvier, 1816) was dominant with the highest abundance during the dry season (138 individuals; 23%) and *Selene vomer* (Linnaeus, 1758) throughout the rainy season (45 individuals, 14%), while *Trichiurus lepturus* Linnaeus, 1758 (26 kg, 13%) and *Caranx hippos* (Linnaeus, 1766) (151.59 kg, 55%) dominated in terms of biomass during the dry and the rainy seasons, respectively (Table I).

Less abundant and infrequent species (LAI) stood out in the estuary (85%) and in the coast (77%) (Table I). *Eucinostomus argenteus* Baird & Girard, 1855, *Eucinostomus gula* (Quoy & Gaimard, 1824), *Ctenogobius smaragdus* (Valenciennes, 1837), *Ctenogobius stigmaticus* (Poey, 1860), *Gobionellus oceanicus* (Pallas, 1770), *G. stomatus* and *Sphoeroides testudineus* (Linnaeus, 1758) were considered as abundant and frequent in the estuary, and *S. vomer* in the coastal area.

ENVIRONMENTAL USE STRUCTURE

Richness, abundance and biomass of the environmental guilds did not vary by season but differences were observed between the estuary and coast. In the estuary, marine stragglers and marine migrants dominated in richness during the dry (33 species, 43%) and rainy seasons (23 species, 41%), respectively. Estuarine species showed the highest abundance in the dry (8150 individuals, 66%) and rainy (4099 individuals, 64%) seasons, however in terms of biomass, marine migrants dominated throughout the year (Fig. 2). In the coast, marine stragglers were dominant in richness (38 species, 70% and 31 species, 65%), abundance (458 individuals, 78% and 259 individuals, 79%) and biomass (147 kg, 76% and 238 kg, 90% - in the dry and rainy seasons, respectively) (Fig. 2).

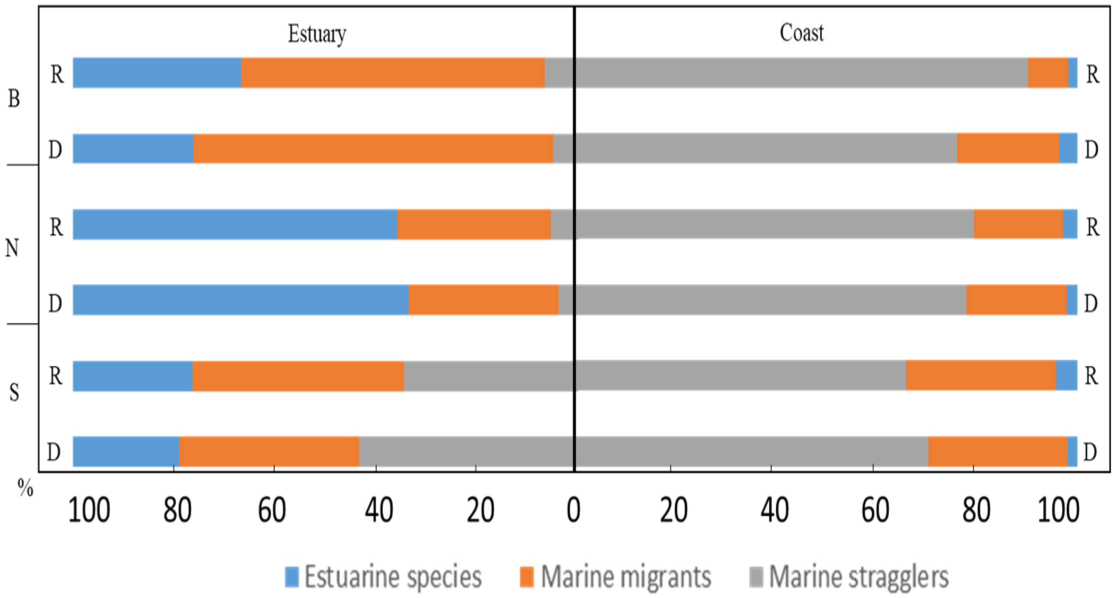

FIG. 2. Percentage participation (%) of richness (S), abundance (N) and biomass (B) of environmentals guilds by season (D, dry; R, rainy) and location in the Itapissuma/Itamaracá Complex, northeastern Brazil.

TABLE I. Composition of the ichthyofauna captured in the Itapissuma/Itamaracá Complex. D-Dry; R-Rainy; EUFG-Estuarine Use Functional Groups; ES-Estuarine Species; MM-Marine Migrants; MS-Marine Stragglers; FMFG-Feeding Mode Functional Groups; HV-Herbivore; DV-Detritivore; OV-Omnivore; PV-Piscivore; ZB-Zoobenthivore; ZP-Zooplanktivore; E-Estuary; C-Coast; N-abundance; B- biomass; FO - Ocorrence Frequency. IR- Relative Importance: 1-Abundant and Frequent; 2-Abundant and Infrequent; 4-Less Abundant and Infrequent; (*) Species present in all the studied environments. Sea = Season. **value < 0.01.

		Sea	**EUFG**	**FMFG**	**N (%)**		**B (%)**		**FO (%)**		**IR**	
	Species				E	C	E	C	E	C	E	C
Carcharhinidae	*Rhizoprionodon porosus* (Poey, 1861)	D	MS	PV		0.11		0.06		1.9		4
	Rhizoprionodon lalandii (Valenciennes, 1839)	D	MS	PV		0.11		0.04		1.9		4
Dasyatidae	*Dasyatis guttatus* (Bloch & Schneider, 1801) *	D/R	MS	ZB	0.01	0.11	0.07	2.57	3.4	1.9	4	4
	Dasyatis marianae Gomes, Rosa & Gadig, 2000	D/R	MS	ZB		0.22		0.14		3.8		4
	Dasyatis sp.	D				0.11		0.52		1.9		4
Elopidae	*Elops saurus* (Linnaeus, 1766)	D	MS	PV	0.01		0.07		3.4		4	
Muraenidae	*Gymnothorax funebris* Ranzani, 1839	R	MS	ZB		0.43		1.53		5.8		4
	Gymnothorax ocellatus Agassiz, 1831*	D/R	MS	ZB	0.01	0.33	0.04	0.55	3.4	1.9	4	4
	Muraenidae sp.	R				0.33		1.98		1.9		4
Engraulidae	*Anchoa lyolepis* (Evermann & Marsh, 1900)	D	MS	ZP	0.02				3.4		4	
	Anchoa marinii Hildebrand, 1943	D	MS	ZP	0.04		0.01		3.4		4	
	Anchoa sp.	R			0.06		0.01		3.4		4	
	Anchoa spinifer (Valenciennes, 1848)	D	MM	PV	0.21		0.04		17.2		4	

	Anchoa tricolor (Spix & Agassiz, 1829)	D/R	MM	ZB	0.12		0.03		10.3		4	
	Anchovia clupeoides (Swainson, 1839)	D	MM	ZP	0.91		1.06		3.4		4	
	Cetengraulis edentulus (Cuvier, 1829)	D/R	MM	ZP	4.63		6.55		41.4		2	
	Engraulis anchoita Hubbs & Marini, 1935	R	MS	ZP	0.25		0.1		3.4		4	
	Lycengraulis grossidens (Spix & Agassiz, 1829)	D/R	ES	PV	0.2		0.05		13.8		4	
Clupeidae	*Harengula clupeola* (Cuvier, 1829)	D/R	MS	ZP	0.24		0.44		6.9		4	
	Opisthonema oglinum (Lesueur, 1818)*	D/R	MS	ZP	0.21	1.84	0.10	0.22	17.2	15.4	4	2
	Rhinosardinia bahiensis (Steindachner, 1879)	D/R	ES	ZP	0.07		0.02		17.2		4	
	Sardinella brasiliensis (Steindachner, 1879)	D/R	MS	ZP	0.06		0.05		6.9		4	
Chaetodontidae	*Chaetodon ocellatus* Bloch, 1787	D	MS	ZB	0.01				3.4		4	
Ariidae	*Ariidae* sp.	D				0.22		0.27		1.9		4
	Aspistor luniscutis (Valenciennes, 1840)	D/R	MS	OV		5.31		2.15		15.4		2
	Aspistor quadriscutis (Valenciennes, 1840)	D/R	MS	ZB		0.87		0.4		9.6		4
	Aspistor sp.	R				0.33		0.13		1.9		4
	Bagre marinus (Mitchill, 1815)	D/R	MM	ZB		1.52		0.92		9.6		2
	Cathorops agassizii (Eigenmann & Eigenmann, 1888)	R	ES	ZB	0.01		0.04		3.4		4	
	Cathorops spixii (Agassiz, 1829)	R	ES	ZB		0.43		0.11		3.8		4
	Sciades herzbergii (Bloch, 1794)	D/R	ES	ZB	0.07		1.11		10.3		4	
	Sciades proops (Valenciennes, 1840)	D/R	ES	ZB		1.84		2.29		7.7		2

Synodontidae	*Synodus foetens* (Linnaeus, 1766)	D/R	MS	PV	0.02		0.02		6.9		4	
Batrachoididae	*Batrachoides surinamensis* (Bloch & Schneider, 1801)	D/R	MS	ZB	0.04		0.21		13.8		4	
	Thalassophryne nattereri Steindachner, 1876	D/R	MS	ZB	0.08		0.17		20.7		4	
Mugilidae	*Mugil curema* Valenciennes, 1836 *	D/R	MM	DV	10.4	0.65	41.8	0.4	17.2	9.6	2	4
Atherinopsidae	*Atherinella brasiliensis* (Quoy & Gaimard, 1825)	D/R	ES	OV	0.01		**		6.9		4	
Belonidae	*Tylosurus acus acus* (Lacepède, 1803)	D	MS	PV	0.02		0.03		10.3		4	
Hemiramphidae	*Hemiramphus brasiliensis* (Linnaeus, 1758)	R	MS	HV	0.10		0.06		13.8		4	
	Hyporhamphus unifasciatus (Ranzani, 1841)	D/R	MM	OV	0.10		0.07		20.7		4	
Syngnathidae	*Syngnathus* sp.	D			0.01		**		3.4		4	
Triglidae	*Prionotus punctatus* (Bloch, 1793)	D	MS	ZB	0.01		**		3.4		4	
Centropomidae	*Centropomus parallelus* Poey, 1860	D/R	MM	PV	0.46		1.25		20.7		4	
	Centropomus pectinatus Poey, 1860	D/R	MM	PV	0.03		0.09		6.9		4	
	Centropomus sp.	D				0.11		0.5		1.9		4
	Centropomus undecimalis (Bloch, 1792)*	D/R	MM	PV	0.26	0.76	2.41	2.26	17.2	11.5	4	4
Serranidae	*Epinephelus adscensionis* (Osbeck, 1765) *	D/R	MS	ZB	0.01	0.11	**	0.01	3.4	1.9	4	4
	Epinephelus marginatus (Lowe, 1834)	R	MS	OP	0.01		0.18		3.4		4	
	Mycteroperca bonaci (Poey, 1860) *	D	MS	PV	0.01	0.11	**	0.02	3.4	1.9	4	4
Carangidae	*Carangoides bartholomaei* (Cuvier, 1833)	D/R	MS	PV		3.9		1.51		19.2		2
	Caranx crysos (Mitchill, 1815) *	D	MS	PV	0.01	0.11	**	0.03	3.4	1.9	4	4
	Caranx hippos (Linnaeus, 1766)*	D/R	MS	PV	0.4	6.39	0.24	40.5	17.2	32.7	4	2

	Caranx latus Agassiz, 1831*	D/R	MS	ZB	0.21	0.98	0.33	3.63	17.2	9.6	4	4
	Caranx ruber (Bloch, 1793)	D	MM	ZB		3.25		0.54		1.9		2
	Chloroscombrus chrysurus (Linnaeus, 1766)*	D/R	MS	ZB	0.15	0.54	0.01	0.07	13.8	9.6	4	4
	Oligoplites palometa (Cuvier, 1832) *	D/R	MM	PV	0.01	1.3	**	1.14	3.4	17.3	4	4
	Oligoplites saliens (Bloch, 1793)	D	MM	PV	0.01		0.01		3.4		4	
	Oligoplites saurus (Bloch & Schneider, 1801)*	D/R	MM	PV	0.02	0.87	0.01	0.25	10.3	11.5	4	4
	Selene brownii (Cuvier, 1816)	D/R	MS	ZB		19.5		6.18		48.1		2
	Selene spixii (Castelnau, 1855)	R	MS	ZB		0.76		0.41		3.8		4
	Selene vômer (Linnaeus, 1758)	D/R	MS	PV		8.99		5.36		57.7		1
	Trachinotus carolinus (Linnaeus, 1766)	D/R	MM	ZB		0.98		3.03		11.5		4
	Trachinotus falcatus (Linnaeus, 1758)	D/R	MS	ZB		0.98		3.6		13.5		4
	Trachinotus goodei Jordan & Evermann, 1896	D/R	MS	ZB		0.76		0.53		7.7		4
Lutjanidae	*Lutjanus alexandrei* Moura & Lindeman, 2007	D/R	MS	ZB	0.28		0.85		17.2		4	
	Lutjanus analis (Cuvier, 1828)*	D/R	MS	ZB	0.41	1.08	0.13	0.45	41.4	13.5	4	4
	Lutjanus jocu (Bloch & Schneider, 1801) *	D/R	MS	ZB	0.24	0.22	0.19	0.05	31	1.9	4	4
	Lutjanus synagris (Linnaeus, 1758)	D/R	MS	ZB	0.33		0.03		17.2		4	
Gerreidae	*Diapterus auratus* Ranzani, 1842 *	D/R	MM	ZB	1.44	2.17	4.08	0.79	20.7	21.2	2	2
	Diapterus rhombeus (Cuvier, 1829) *	D/R	MM	ZP	1.11	0.43	0.55	0.28	41.4	3.8	2	4
	Diapterus sp.	R			0.06		0.01		6.9		4	
	Eucinostomus argenteus Baird & Girard, 1855 *	D/R	MM	ZB	4.69	0.33	5.75	0.07	75.9	5.8	1	4

	Eucinostomus gula (Quoy & Gaimard, 1824)	D/R	MM	ZB	2.84		1.99		55.2		1	
	Eucinostomus havana (Nichols, 1912)	D/R	MM	ZB	0.18		0.25		17.2		4	
	Eucinostomus melanopterus (Bleeker, 1863)	R	MM	ZB	0.07		0.12		3.4		4	
	Eucinostomus sp.	D/R			0.52		0.05		20.7		4	
	Eugerres brasilianus (Cuvier, 1830)	D/R	MM	OV	0.03		0.01		6.9		4	
Haemulidae	*Anisotremus moricandi* (Ranzani, 1842)	D/R	MS	OV		0.43		0.06		7.7		4
	Anisotremus virginicus (Linnaeus, 1758)	R	MS	OV		0.43		0.08		1.9		4
	Conodon nobilis (Linnaeus, 1758)	D	MM	ZB		0.22		0.02		1.9		4
	Genyatremus luteus (Bloch, 1790)	R	MS	OP	0.02		0.11		3.4		4	
	Haemulon aurolineatum Cuvier, 1830	D	MS	ZB		0.22		0.06		1.9		4
	Haemulon parra (Desmarest, 1823)	D/R	MS	ZB		1.3		0.53		9.6		4
	Haemulon plumierii (Lacepède, 1801)	D	MS	ZB		6.18		0.89		11.5		2
	Haemulon steindachneri (Jordan & Gilbert, 1882)	D/R	MS	ZB		0.43		0.19		5.8		4
	Pomadasys corvinaeformis (Steindachner, 1868)	D/R	MS	ZB		2.93		0.45		11.5		2
	Pomadasys crocro (Cuvier, 1830)	D/R	MS	ZB	0.01		0.07		6.9		4	
Sparidae	*Archosargus probatocephalus* (Walbaum, 1792)	D	MS	OV	0.03		**		6.9		4	
	Archosargus rhomboidalis (Linnaeus, 1758) *	D/R	MS	ZB	0.81	0.54	0.19	0.32	27.6	7.7	2	4
Polynemidae	*Polydactylus virginicus* (Linnaeus, 1758) *	D/R	MM	ZB	0.02	3.14	0.05	1.01	6.9	3.8	4	2
Sciaenidae	*Bairdiella ronchus* (Cuvier, 1830)	D/R	MM	ZB	0.18		0.62		13.8		4	
	Cynoscion sp.	D			0.03		**		3.4		4	

	Cynoscion virescens (Cuvier, 1830)	D	MM	ZB	0.06		0.01		10.3		4	
	Isopisthus parvipinnis (Cuvier, 1830)	R	MM	PV		0.43		0.39		3.8		4
	Larimus breviceps Cuvier, 1830	R	MM	ZB		0.33		0.06		1.9		4
	Menticirrhus americanus (Linnaeus, 1758)	D/R	MM	ZB		0.43		0.23		5.8		4
	Ophioscion sp.	D			0.01		0.03		3.4		4	
	Paralonchurus brasiliensis (Steindachner, 1875)	D	MM	ZB		0.33		0.04		1.9		4
	Stellifer stellifer (Bloch, 1790)	D	ES	ZB	0.02		0.03		3.4		4	
Mullidae	*Pseudupeneus maculatus* (Bloch, 1793)	D	MS	ZB		0.11		0.02		1.9		4
Labridae	*Halichoeres radiatus* (Linnaeus, 1758)	D	MS	ZB		0.11		0.02		1.9		4
Scaridae	*Sparisoma radians* (Valenciennes, 1840)	R	MS	HV	0.65		0.14		1.9		4	
	Sparisoma axillare (Steindachner, 1878) *	D/R	MS	HV	0.23	0.65	0.04	0.09	10.3	7.7	4	4
	Sparisoma cf *amplum*	R	MS	HV		0.33		0.11		3.8		4
Ephippidae	*Chaetodipterus faber* (Broussonet, 1782) *	D/R	MM	OV	0.1	1.52	1.26	1.38	6.9	17.3	4	2
Pomacanthidae	*Pomacanthus paru* (Bloch, 1787)	R	MS	ZP		0.11		0.01		1.9		4
Eleotridae	*Guavina guavina* (Valenciennes, 1837)	D	ES	ZB	0.01		**		3.4		4	
Gobiidae	*Ctenogobius boleosoma* (Jordan & Gilbert, 1882)	D	ES	DV	0.13		0.01		3.4		4	
	Ctenogobius shufeldti (Jordan & Eigenmann, 1887)	D/R	ES	OV	0.17		0.03		20.7		4	
	Ctenogobius smaragdus (Valenciennes, 1837)	D/R	ES	DV	0.48		0.08		44.8		4	
	Ctenogobius stigmaticus (Poey, 1860)	D/R	ES	DV	3.83		0.35		48.3		2	
	Evorthodus lyricus (Girard, 1858)	D	MS	DV	0.01		**		3.4		4	

	Gobionellus oceanicus (Pallas, 1770)	D/R	ES	DV	2.44		4.01		58.6		1	
	Gobionellus stomatus Starks, 1913	D/R	ES	DV	53.5		18.5		58.6		1	
	Microgobius meeki Evermann & Marsh, 1899	D	MS	ZB	0.11				6.9		4	
Trichiuridae	*Trichiurus lepturus* Linnaeus, 1758	D/R	MS	PV		7.8		7.43		44.2		2
Acanthuridae	*Acanthurus bahianus* Castelnau, 1855	D/R	MS	HV		0.43		0.07		5.8		4
	Acanthurus chirurgus (Bloch, 1787) *	D/R	MS	HV	0.01	0.33		0.03	6.9	3.8	4	4
	Acanthurus coeruleus Bloch & Schneider, 1801	D	MS	HV		0.11		0.01		1.9		4
Sphyraenidae	*Sphyraena barracuda* (Edwards, 1771)	D/R	MM	PV	0.05		0.38		6.9		4	
	Sphyraena guachancho Cuvier, 1829 *	D	MS	PV	0.02	0.22	0.19	0.18	6.9	1.9	4	4
	Sphyraena viridensis Cuvier, 1829	D	MS	PV		0.11		0.12		1.9		4
Scombridae	*Scomberomorus brasiliensis* Collette, Russo & Zavala-Camin, 1978	D	MS	PV		0.22		0.13		1.9		4
Paralichthyidae	*Citharichthys* sp.	D/R			0.11		0.02		10.3		4	
	Citharichthys spilopterus Günther, 1862	D/R	MM	ZB	0.79		0.26		48.3		4	
	Etropus crossotus Jordan & Gilbert, 1882	R	MM	ZB	0.5		0.06		6.9		4	
	Paralichthys brasiliensis (Ranzani, 1842)*	D/R	MM	ZB	0.01	0.11	0.02	0.01	6.9	1.9	4	4
	Syacium micrurum Ranzani, 1842	D	MM	ZB		0.11		0.01		1.9		4
	Syacium papillosum (Linnaeus, 1758)	D	MS	ZB		0.11		0.01		1.9		4
Bothidae	*Bothus ocellatus* (Agassiz, 1831)	R	MM	ZB		0.11		**		1.9		4
Achiridae	*Achirus declivis* Chabanaud, 1940	D	ES	ZB	0.03		**		10.3		4	

	Achirus lineatus (Linnaeus, 1758)	D/R	ES	ZB	1.48	0.08	48.3	2
	Achirus sp.	D/R			0.68	0.03	13.8	4
	Trinectes paulistanus (Miranda Ribeiro, 1915)	D	MM	ZB	0.21	0.01	3.4	4
Cynoglossidae	*Symphurus tessellatus* (Quoy & Gaimard, 1824)	D/R	MM	ZB	0.04	0.04	17.2	4
Ostraciidae	*Lactophrys trigonus* (Linnaeus, 1758)	D	MS	ZB	0.11	0.28	1.9	4
Tetraodontidae	*Colomesus psittacus* (Bloch & Schneider, 1801)	D/R	MS	ZB	0.03	1.43	6.9	4
	Sphoeroides greeleyi Gilbert, 1900	D/R	ES	ZB	0.2	0.05	27.6	2
	Sphoeroides testudineus (Linnaeus, 1758)	D/R	ES	ZB	2.13	2.01	79.3	1
Diodontidae	*Chilomycterus spinosus spinosus* (Linnaeus, 1758)	R	MS	ZB	0.11	0.05	1.9	4

The PCO analysis based on the environmental guilds revealed that the main effect along the first axis (95.78%) was spatial as it discriminated the samples from the coast and the estuary. Estuarine samples were very similar between seasons whereas coastal samples presented a more heterogeneous pattern (Fig. 3). Such pattern were tested through Permanova and confirmed the location (estuary and coast) effect (p <0.05). No seasonal effect was observed (Table II, p=0.004).

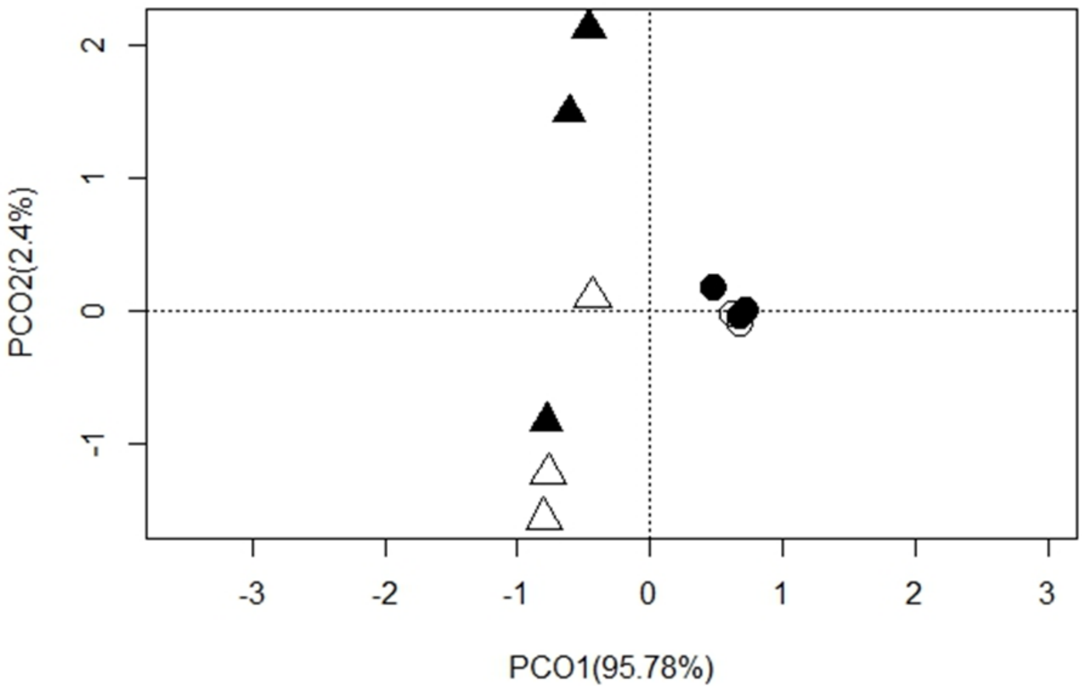

FIG. 3. Principal coordinates ordination analysis (PCO) of the abundance of environmentals guilds in the estuary (circle) and coast (triangle) during the dry (empty) and rainy (full) seasons in the Itapissuma/Itamaracá Complex.

TABLE II. PERMANOVA test results for the effects of environment and season on the abundance of environmentals guilds in the Itapissuma/Itamaracá Complex, northeastern Brazil. *p < 0.05

	d.f	SS	MS	Pseudo-F	p
Environment	1	1.316	1.316	124.490	0.004*
Season	1	0.001	0.001	0.147	0.636
Environment *vs.* Season	1	0.004	0.004	0.427	0.522
Residuals	8	0.084	0.010		
Total	11	1.407			

TROPHIC STRUCTURE

Zoobentivores were the richest trophic guild in the estuary (38 species, 41% and 28 species, 30% - in the dry and rainy seasons, respectively). The detritivores, stood out with higher abundance (15452 individuals, 62% and 10176 individuals, 53% - in the dry and rainy seasons, respectively) and biomass (203 kg, 70% and 82 kg, 47% - in the dry and rainy seasons, respectively) (Fig. 4). In the coast, zoobentivores also dominate in richness (30 species, 55.5% and 34 species, 60.1% - dry and rainy seasons, respectively) and abundance (372 individuals, 63.3% and 229 individuals, 50% - dry and rainy seasons, respectively), and piscivores had the greatest biomass (96 kg, 49% and 188 kg, 66.9% - dry and rainy seasons, respectively) (Fig. 4).

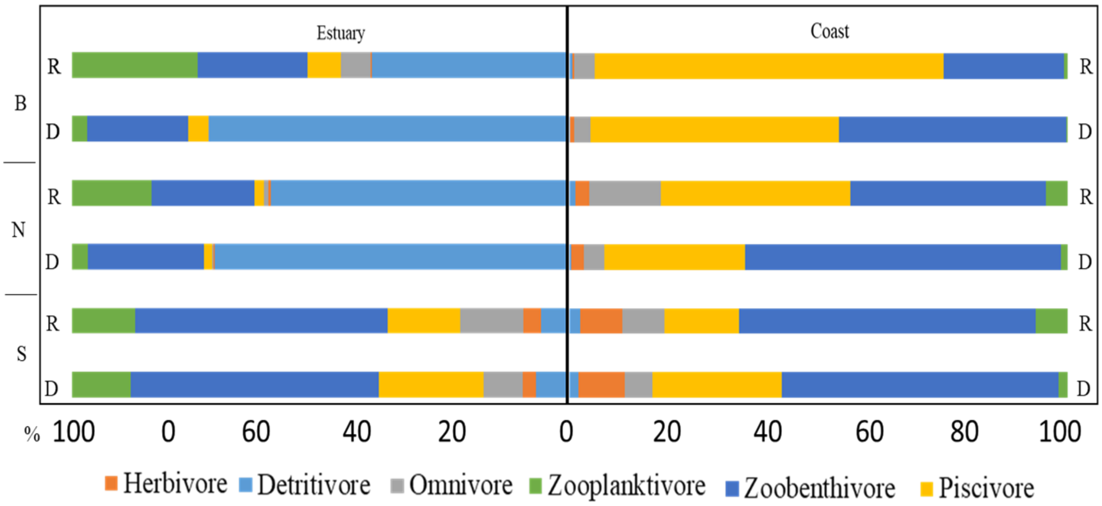

FIG. 4. Percentage participation (%) of richness (S), abundance (N) and biomass (B) of trophics guilds by season (D, dry; R, rainy) and location in the Itapissuma/Itamaracá Complex, northeastern Brazil.

The PCO based on trophic guilds discriminated samples from the estuary and the coast along the axis 1 (81.22%). Seasonally, in the estuary, differences were observed between the dry and rainy seasons (Fig. 5).

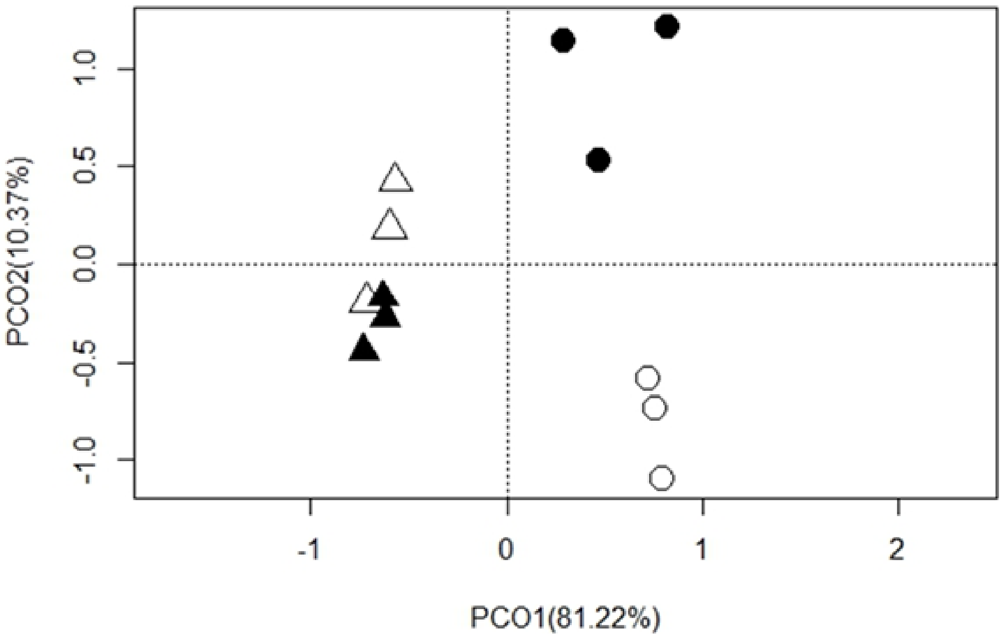

FIG. 5. Principal coordinates ordination analysis (PCO) of the abundance of trophics guilds in the estuary (circle) and coast (triangle) during the dry (empty) and rainy (full) seasons in the Itapissuma/Itamaracá Complex.

According to the Permanova, the environments (estuary and coast) significantly influenced the abundance of the trophic guilds in the IIC (Table III; p = 0.002), confirming the groups formed by PCO (Fig. 5).

TABLE III. PERMANOVA test results on the abundance of trophic guilds, testing for the effects of factors environment and season in the Itapissuma/Itamaracá Complex, northeastern Brazil. *p < 0.05

	d.f	SS	MS	Pseudo-F	p
Environment	1	0.939	0.939	37.518	0.002*
Season	1	0.040	0.040	1.602	0.637
Environment *vs.* Season	1	0.043	0.043	1.725	0.555
Residuals	8	0.200	0.205		
Total	11	1.223			

DISCUSSION

In this study, a multi-gear approach was conducted in order to provide a most complete estimate of fish assemblage structure (Kwak & Peterson, 2007). As a result, the observed species richness was close to the estimated richness indicating that sampling was satisfactory, through the concomitant implementation of active and passive fishing gear. A total of 140 species were recorded in Itapissuma/Itamaracá Complex (IIC), with 95 species recorded in the estuary and 74 in the coast. The IIC is one of the most productive and diversified marine sites of the Brazilian coast (Eskinazi-Lessa *et al*., 1999) similar to other tropical estuaries in Brazil (Paiva *et al*., 2008; Xavier *et al*., 2012; Mourão *et al*., 2014). Species richness is more influenced by regional and local factors that can further affect the process of community colonization in an estuary, including the connectivity with adjacent marine habitat, and, over smaller spatial extents, the size of these habitats (Vasconcelos *et al*., 2015). The structure of fish assemblage is influenced by the characteristics linked primarily to estuary mouth status and size (Vorwerk *et al*., 2003). The species richness has been shown to be higher in estuaries with a greater mouth size (Monaco *et al*., 1992; Nicolas *et al.*, 2010), and which are permanently open allowing the stability of connectivity with marine ecosystem (Harrison & Whitfield, 2006; Vasconcelos *et al*., 2015), as is the case of IIC.

The high richness of marine species in IIC can be attributed to the elongated U-shaped of the Santa Cruz Channel connected with the Atlantic Ocean at both ends (Medeiros & Kjerfve, 1993), permiting a permanent connectivity between the estuarine and marine environments during all the year. The positive effect of primary productivity on species richness allows larger populations to persist, thereby reducing extinction risk and supporting a higher diversity of niche specialists (Tittensor *et al.*, 2010). In terms of productivity, IIC is considered as one of the most productive ecosystems of the coast of Pernambuco due to its high biodiversity, primary and secondary productivity (CPRH, 2010; Vasconcelos Filho *et al*., 2010; Santana *et al*., 2013; Mérigot *et al*., 2016).

The fish fauna of IIC was composed mainly by rare and infrequent species with high richness, abundance and biomass of marine (migrants and stranglers) and estuarine species. According to Vasconcelos Filho & Oliveira (1999), marine species of the IIC are mostly juveniles, some of which are of commercial value. Migratory species have a great importance in predominantly open systems. It probably reflets a near-permanent connection with the sea, enhancing recruitment into predominantly open estuaries relative to intermittently open systems (Harrison & Whitfield, 2008). The high abundance of estuarine species within the channel was mainly due to gobiids. In the coastal environment of IIC, the marine stragglers predominated in richness, abundance and biomass in all periods, however the percentages of resident (ES) and dependent species (MM) were also expressive, thus confirming the connectivity and dependence between estuary and coast of the IIC. The coast of IIC offers favorable conditions for the development of the marine fish fauna as protection and food resource (Medeiros *et al.*, 2001).

The substrate of the IIC is of extreme importance for the high productivity in the system (Silva *et al.*, 2011) contributing for the high occurrence of species with feeding habits associated to the substrate, for example, zoobenthivorous and detritivorous. The high richness of zoobenthivores in the estuarine area of the IIC can be attributted to the great abundance of available benthic fauna (Silva, 2013). Benthos is one of the structuring elements of the food web and plays an important role in the system dynamics (Herman *et al.*, 1999), transferring energy to fishes in estuarine environments (Buchheister & Latour, 2015). Detrivores dominated in abundance and biomass mainly due to large supply of organic matter and detritus in the IIC (Neumann-Leitão *et al.*, 2001; Paiva *et al.*, 2005), that support estuarine trophic webs (Hoffman *et al.*, 2008). The estuarine organic material of the IIC originates from various rivers (Eskinazi-Lessa, *et al*., 1999). The rivers discharge, sediment resuspension, mangrove litter, waste input, terrestrial runoff, and atmospheric input are sources of nutrients in the IIC estuary (Medeiros, 1991). The highest proportion of detritus usually occurs in environments with great amount of organic matter. The detritus are consumed constituting a link between organic production and animal nutrition, which helps the efficiency of the transfer of energy between the trophic levels (Qasim & Sankaranarayanan, 1972).

The large supply of zoobenthic fauna (Silva, 2013) and the sandy substrate along the coast (Almeida & Manso, 2011) favoured the high species richness and abundance of zoobenthivores in the IIC coastal area. Benthophagous fish are highly associated with sandy substrates (Loureiro *et al*., 2016). The biomass dominance of piscivores is mainly due to large carangids that profit from a high supply of food in the area. Carangids are visual, active predators that spend a great part of their time on the reef searching for prey (Cervigón, 1972) and feed on fish and also consume components of the benthos to complement their diets (Moreno-Sánchez, 2016).

The IIC is an important ecosystem for several species that reside or visit the area, regardless seasonality. The ecological guilds revealed that many marine species (stragglers and migrants) feed in the IIC, as also do the resident species. This is the case of the marine migrants *Centropomus* spp. (Lira *et al*., 2017) and *E. argenteus* (Leão, 2016), with a high percentage of individuals feeding within the Santa Cruz Channel (Vasconcelos Filho *et al*., 2003). The IIC offers a variety of food resources for species of different trophic guilds supporting a large biomass of detritivorous and zoobenthivorous (Vasconcelos Filho *et al*., 2009; 2010). The favorable conditions of protection and food supply justify the dominance of marine species and detritivores in the estuary. Estuaries are essential habitats as feeding and breeding grounds and as part of migratory routes for marine species (Elliott *et al.*, 2007; Martinho *et al.*, 2007).

The connection between continental and marine environments is an essential characteristic in tropical areas as marine species are important exporters of energy to the adjacent coastal areas (Vasconcelos Filho *et al.*, 2009). Such essential habitats need to be preserved in order to sustain the local productivity. However, estuaries are exposed to multiple antropic pressures (Hughes *et al*., 2005; Blaber & Barletta, 2016) that led to alterations in the structure and function of the fish community of coastal environments (Baptista *et al*., 2015; Chevillot *et al.,* 2016; Dolbeth *et al*., 2016).

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4 - Artigo Científico 2

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Food web of a coastal ecosystem in Northeastern Brazil investigated by stable isotopes

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ABSTRACT

The stable isotope analyses (δ ^{13}C and δ ^{15}N) are widely used to describe the food web structure, the trophic niche of species and the connectivity between environments. Food web components (9 basal source, 8 invertebrate and 16 fish species) were sampled in the dry and rainy seasons of 2015 in the estuary and coast of Itapissuma/Itamaracá Complex (IIC), Northeastern Brazil. Six community-wide trophic metrics and standard ellipse areas (SEA) were used to (1) investigate the spatial and temporal isotopic variation of the food web components, (2) describe the isotopic niche of fishes, and (3) investigate the connectivity of fish community in the IIC. In the estuary, the $\delta^{13}C$ of epiphyton was the lower and the $\delta^{13}C$ of *Gobionellus oceanicus* was the more enriched, while $\delta^{15}N$ of *Rhizophora mangle* and *Bairdiella ronchus* were the more pooled and enriched, respectively. In the coast, the POM had the lower $\delta^{13}C$ and *Mugil curema* was more enriched, and *Ulva* sp. and *Micropogonias furnieri* had lowest and highest $\delta^{15}N$, repectively. The $\delta^{13}C$ and $\delta^{15}N$ of POM and SOM vary significantly between seasons and areas ($p<0.05$). In the estuary, the $\delta^{15}N$ of invertebrates was significantly more enriched in the rainy season ($p < 0.05$). The $\delta^{13}C$ and $\delta^{15}N$ of fish group did not vary significantly between seasons. The metrics indicated variations between estuary and coastal area. The carbon values were highest in the estuary and nitrogen was highest in the coast. The mean distance to the $\delta^{13}C$-$\delta^{15}N$ centroid and the convex hull area encompassed by all species was similar for estuary and coast. Standard ellipse areas (SEAc) showed a smaller isotopic niche width for species captured in estuary and indicated low overlap between the environments (20.36%). The results indicate that different resources support the IIC's trophic chain and confirmed the importance of this interconnected complex in the Northeastern Brazil.

Keywords: Community metrics, estuary, ^{13}C and ^{15}N, habitats, Itapissuma/Itamaracá Complex, trophic niche.

1. Introduction

Coastal ecosystems are among the most valuable natural systems (Costanza et al., 1997) and are important areas for fish fauna (Sheaves et al., 2014; Nagelkerken et al., 2015). Estuaries are widely explored for feeding (Campos et al., 2015), development (Elliott et al., 2007; Blaber, 2013) and nursery for many fish species (Whitfield, 2017). Although highly prized for a diversity of human activities, the coastal ecosystems are leading to unprecedented threats and damages (Abrantes et al., 2013; Bassett et al., 2013), especially in tropical areas with increasing population (Junk, 2002; Blaber and Barletta, 2016).

The stable isotope analyses, particularly carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) are widely used in ecological studies to describe the food web structure and trophic niche (Faye et al., 2011; Abrantes et al., 2014; Schalk et al., 2016), to evaluate the niche overlap between fish species (Layman et al., 2007; Chen et al., 2011; Shiffman et al., 2012) and the connectivity between environments (Claudino et al., 2015). Also, the spatial variation in isotopic values is particularly useful for the inference of movement in mobile marine fauna such as the nekton (Fry et al., 1999; Herzka et al., 2002; Vinagre et al., 2016). $\delta^{13}C$ reflects basal sources (Peterson and Fry, 1987), and $\delta^{15}N$ is indicative of the individual's relative position within the ecosystem (DeNiro and Epstein, 1981; Post et al., 2002). Individuals feeding at a single site should reflect the isotopic composition of that location, while transient individuals migrating between sites, or those which explore simultaneously several sites, will have a more varied isotopic composition, or intermediate values between several local isotopic signatures (Fry et al., 1999, 2003; Herzka et al., 2002).

The ecological niche concept has been strongly investigated and the combined use of $\delta^{13}C$ and $\delta^{15}N$ have been a core tool to measure and elucidate isotopic niche (Bearhop et al., 2004; Layman et al., 2007; Cherel et al., 2011; Jackson et al., 2011; Bowes et al., 2017), because the animal's chemical composition is directly influenced by what it consumes, as well as the habitat in which it lives (Newsome et al., 2007). The niche represents the overall trophic role of a species (Leibold, 1995) and is defined as the sum of all the interactions between species in an ecosystem (Elton, 1927). Niche parameters is of essential importance for the understanding of the food web structure, resource use and trophic interactions in aquatic ecosystems (Chen et al., 2011), and can respond very rapidly to changes in intraspecific and interspecific competition, as well as prey abundance (Bearhop et al., 2004).

In Brazilian coastal ecosystems, the use of stable isotopes have become a common tool for ecological studies in fish. Studies are mainly reported in the south region, including topics related to isotopic variation (Garcia et al., 2007), transport of nutrients (Oliveira et al., 2014), trophics alterations (Claudino et al., 2015a; Mont'Alverne et al., 2016) and assimilation of sources (Garcia et al., 2016; Pereira et al., 2017). Relationship of stable isotope ratios of consumers (Giarrizzo et al., 2011) and contributions of primary sources (Schwamborn and Giarrizzo, 2015) were investigated in estuaries of the north region. Although coastal northeastern Brazil has an extensive area and numerous environments, only the trophic web of Mamanguape, in the state of Paraíba, estuary was investigated through stable isotopes (Claudino et al., 2015). This study is the first to investigate the trophic web by calculating descriptive community-wide metrics in a Brazilian coastal ecosystem.

The IIC (Itamaracá/Itapissuma Complex) is considered one of the most important ecosystems of the coast of Pernambuco due to its high biodiversity (Vasconcelos Filho et al., 2010; Santana et al., 2013; Mérigot et al., 2016), and the fishery activity has a very important socio-economic role (CPRH, 2010). The estuarine and coastal areas of the IIC are connected by two entrances, and reefs restrict the exchange of water with offshore areas. This ecosystem is exposed to multiple anthropic impacts caused by industrial pollution, domestic sewage discharge, urban expansion, land reclamation and fisheries (Medeiros *et al.*, 2001). The IIC is formed by a large variety of connecting habitats which, along with the complexity of interactions within the fish community and the migratory nature of many species, makes difficult the assessment of the overall condition (Vasconcelos Filho et al., 2003).

The aim of this study was to describe the trophic structure of a coastal area in Northeastern Brazil specially (1) investigating the spatial and temporal isotopic variation of the basal sources, invertebrates and fish, (2) describing the isotopic niche of fishes and (3) investigating the connectivity of fish assemblage of the estuarine and coastal areas through the carbon and nitrogen stable isotope analysis. The understanding of those aspects is critical for an effective management of consumers and sources that contribute to the maintenance of the estuarine complex trophic chain, the interactions of species between the environments and the responses of the fauna to anthropic perturbations.

2. Materials and methods

2.1. Study area

The Itapissuma/Itamaracá Complex (IIC), located along the northern coast of Pernambuco, is part of the Marine Protected Area of Santa Cruz (CPRH, 2010). The area is highly impacted by industrial discharges, shrimp farming and fishing activity (Medeiros et al., 2001; Gondim, 2015). The estuarine area of the IIC, the Santa Cruz Channel, is flooded by seawater and connected with the South Atlantic Ocean by the Catuama and Orange entrances (Fig. 1). In the Santa Cruz Channel water temperature varies between 25ºC and 31ºC and the salinity between 18 e 34 (Macêdo et al., 1998). The river discharge is the principal source of nutrients in the Santa Cruz Channel, followed by sediment resuspension, mangrove litter, waste input, terrestrial runoff, and atmospheric input (Flores Montes, 1998). In the coastal area, the discontinuous sandstone ridges, as well as reefs and sand banks north of the Catuama and south of the Orange entrance, form a semi-open elongated lagoon-like coastal environment "Inner Sea" which restricts the exchange of water between the Santa Cruz Channel and offshore areas (Medeiros and Kjerfve, 1993). In the Inner Sea, water temperature varies between 27 and 31ºC (Manso et al., 1992) and the mean salinity is 34.7 (Bonifácio, 1990). The Inner Sea is defined by a reef barrier parallel to the coast, 4 km from the ocean beach (Kempf, 1967), functioning as a divider between coastal waters and the platform (Mabesoon, 1964).

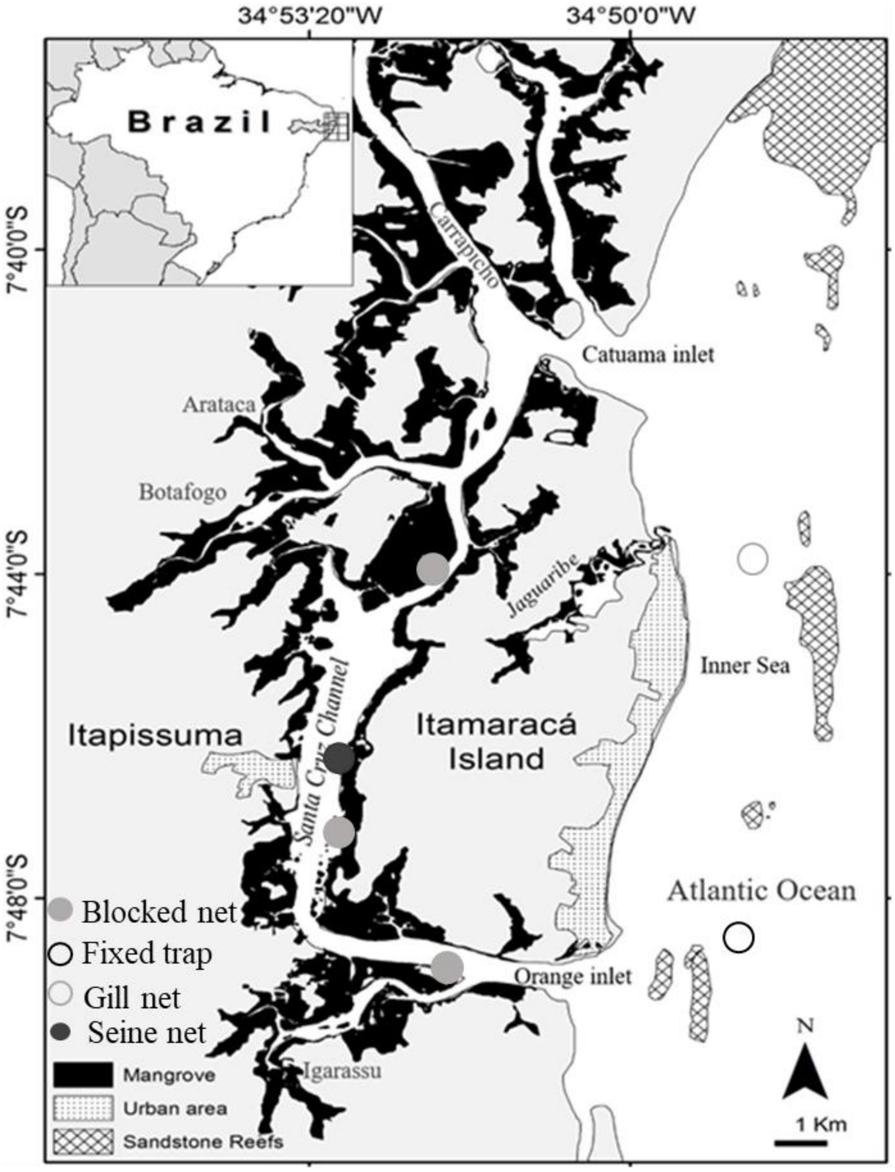

Fig. 1. Study area and location of the sampling sites in the estuary (Santa Cruz Channel) and coast (Inner Sea) of Itapissuma/Itamaracá Complex, Pernambuco, Brazil.

2.2. Data collection

Food web components were sampled in the dry (February and March) and rainy (August and September) seasons of 2015 in the estuary (Santa Cruz Channel) and coast (Inner Sea) of Itapissuma/Itamaracá Complex. Samples of basal food sources included suspended particulate organic matter (POM), particulate organic matter in the sediment (SOM), microphytobenthos, epiphytic macroalgae that grows on mangrove roots, mangrove leaves and macroalgae. Consumers included benthic invertebrate (Polychaeta and Olygochaeta), filter-feeding bivalve, zooplankton (copepods), macrocrustaceans (crab and shrimp) and fish species.

Basal food sources and consumers were collected, with appropriate sampling gear, in triplicate whenever possible. The microphytobenthos, epiphytic macroalgae, mangrove, macroalgae, crabs and bivalves were manually collected. Epiphytic algae were collected from substrate surface and rinsed repeatedly in deionized water to remove sediment particles and detritus. Particulate the microphytobenthos was obtained in the surface of the sediment during the low tide and extracted in the laboratory following the adapted method from Riera et al. (1996). The sediment was placed in clear plastic pans to a depth of 2 cm and a nylon screen (63 µm mesh). It was hence put on top of the sediment and this was covered with 2 mm thick layer of combusted sand. The pans stayed under the natural light until the first dense brown mats appeared at the surface (usually 4-6 h). The dense brown was removed and filtered with 47 mm GF-3 fibreglass filters pre-combusted. The POM was obtained by filtering 0.5 -1.0 l of water through a 63 µm mesh to remove zooplankton and detritus and, the remaining suspended matter was collected on 47 mm GF-3 fibreglass pre-combusted filters. The SOM was collected by using a tube core (2 cm of diameter) and 2 cm of surface sediment was removed.

The benthic invertebrates were collected with PVC tube (10 cm of diameter). Samples were washed through a sieve (0.25 mm mesh) with clean seawater. The zooplankton was sampled with a plankton net with 300 µm mesh size hauled horizontally for 10 minutes at subsurface. In the estuary, fishes and shrimps were obtained with a seine net (10 mm mesh size) and blocked nets (25, 30 and 35 mm mesh size) and, in the coast, with gill nets (25, 30 and 40 mm of mesh size) and fixed trap. Samples were preserved on ice until transported to the laboratory and later processed. Fishes (standard length - cm), bivalves and crustacean (shell's width - cm) were measured.

The selection of fish species for the stable isotopes analysis, was based on trophic guild, commercial value, abundance and occurrence in both estuarine and coastal area. Samples were processed following Garcia et al. (2007) protocol. Muscle tissue of large animals such as crabs, shrimp, bivalves and fish were dissected. Bivalves and shrimp abdomen muscle tissue were dissected after digestive tract had been removed. On fish, muscle tissue (~ 0.5 g) from the dorsal region was dissected for isotopic analysis due to the lower variability in isotopic composition compared to other body parts (Pinnegar and Polunin, 1999). Several whole organisms were analised for zooplankton and benthic invertebrates. All basal food sources and animal muscle were oven dried at 60 °C for 48 h. Dried samples were ground to a fine powder with a mortar and pestle, stored in clean Eppendorf tubes. The decarbonatation process was applied to the samples of POM, SOM and zooplankton (Ryba and Burgess, 2002) to remove all inorganic carbonates. Samples for $\delta^{15}N$ analysis were not acidified because this would result in a ^{15}N enrichment (Pinnegar and Polunin, 1999).

2.3. Stable isotope measurements

Carbon and nitrogen isotope ratios were determined considering a CN analyzer (Thermo ConFlo IV - Flash 2000) interfaced with a mass spectrometer (Therm Delta V+). Experimental precision, based on the standard deviation of repeated measurements of an internal laboratory standard (acetanilide and IVA), was <0.15‰ for $\delta^{15}N$ and <0.13‰ for $\delta^{13}C$. Results are expressed in delta notation: $\delta X = [(R_{sample}/R_{standard}) - 1] \times 1000$, where X is ^{13}C or ^{15}N and R is the corresponding ratio, $^{13}C/^{12}C$ or $^{15}N/^{14}N$. The standard material for carbon was Pee Dee Belemnite (PDB) limestone and the nitrogen standard was atmospheric nitrogen.

2.4. Data analysis

Spatial and temporal patterns in carbon and nitrogen stable isotope values of basal food sources and consumers were initially investigated using biplot diagrams (Fry, 2006). Fishes were assigned to feeding guilds (herbivorous, detritivorous, zoobenthivorous, omnivorous, zooplanktivorous, piscivorous) according to Elliott et al. (2007). The normality (Shapiro–Wilk test) and the homoscedasticity (Bartlett test) hypotheses were rejected. Non-parametric Kruskal-Wallis tests were performed separately for each isotope groups (source, invertebrate and fish) to compare differences in carbon and nitrogen isotope values between season (dry and rainy) in each zone. The $\delta^{13}C$ and $\delta^{15}N$ of POM and SOM were compared between season and zone (estuary and coast) and the $\delta^{13}C$ and $\delta^{15}N$ of each species analysed by standard ellipse areas were tested. The level of statistical significance considered was 5%.

Six community-wide trophic metrics proposed by Layman et al. (2007) were used to investigate the isotopic niche of the fish fauna in the estuary and coast (Table I). The isotopic niches of the species with occurrence in both the estuary and coastal area (*Sparisoma radians*, *Mugil curema*, *Lutjanus anallis*, *Diapterus auratus*, *Micropogonias furnieri*, *Opisthonema oglinum*, *Caranx hippos*, *Centropomus undecimalis*) were quantified based on standard ellipse areas (SEA) to investigate the niche overlap between the environments, which could be used as an inference of the trophic connectivity of species in the IIC. The SEA represents the core isotopic niche space and is a proxy of the richness and evenness of resources consumed by communities (Bearhop et al., 2004). A small sample size correction was applied to SEA (indicated by the subscript ‘‘c’’). SEAc are comparable to the univariate SD and contain c. 40% of the data (Jackson et al., 2011), providing a better and more comparable description of the isotopic niche of the community. A Bayesian approach was applied to incorporate uncertainty into the estimates of the Layman (2007) metrics and also to calculate the standard ellipse areas (SEA) using *SIBER*, an R statistical computing package (Jackson et al., 2011). All analyses were run with R 3.4.3 (R development team, 2017).

Table I. Community-wide trophic metrics to investigate trophic niche of the fish fauna in Itapissuma/Itamaracá Complex, Pernambuco, Brazil

Metric	Description	Goal
Carbono range - CR	Difference between the species with the most enriched and most depleted $\delta^{13}C$ ratio	Measure of basal resource diversity
Nitrogen range - NR	Difference between the species with the most enriched and most depleted $\delta^{15}N$ ratio	Measure of trophic length within a food chain
Centroid distance - CD	Mean Euclidean distance of each species to the $\delta^{15}N$-$\delta^{13}C$ centroid calculated for a community	Measure of trophic diversity and species spacing
Total area - TA	Data points from the $\delta^{13}C$ and $\delta^{15}N$ biplot space	Measure of trophic niche width
Nearest neighbour distance - NND	Mean of the Euclidean distances to each species’ nearest neighbor in biplot space	Measure of the overall density of species packing
Standard deviation of nearest neighbour distance – SDNND	Evenness of species packing in biplot space	Measure of the distribution/dispersal of individuals within an isotopic space

3. Results

3.1 Trophic structure

Carbon and nitrogen isotope signatures were determined for potential 9 basal source, 8 prey (invertebrate) and 16 fish species in the Itapissuma/Itamaracá Complex (see Table II). A total of 117 samples were analysed for estuarine (fish = 78, invertebrate = 42, basal source = 57) and 88 for coastal (fish = 43, invertebrate = 18, basal source = 27) areas (Table I). A wide range in isotopic signatures was observed in both environments, estuary and coast. In the estuary, the $\delta^{13}C$ of the overall community ranged from -32.42‰ (epiphyton) to -11.69‰ (*Gobionellus oceanicus*), while $\delta^{15}N$ varied from 1.10‰ (*Rhizophora mangle*) to 14.00‰ (*Bairdiella ronchus*). In contrast, the coastal area had a lower variability in $\delta^{13}C$, ranging from -20.62‰ (POM) to -13.90 ‰ (*Mugil curema*), and $\delta^{15}N$ varying from 4.97‰ (*Ulva* sp.) to 16.54‰ (*Micropogonias furnieri*).

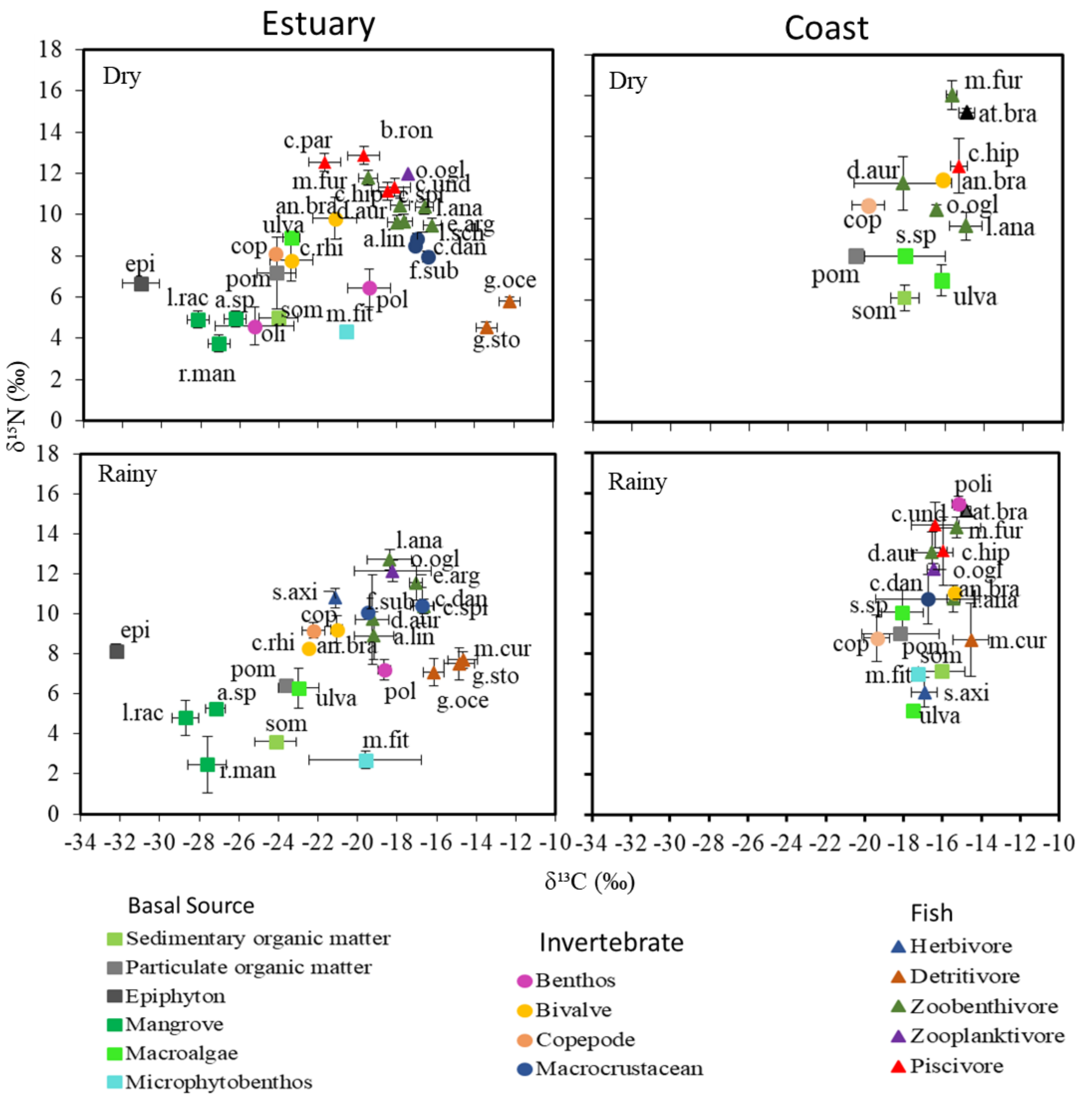

Fig. 2. Mean carbon and nitrogen isotope ratios (±SD) of basal sources, invertebrates and fishes caught in the estuary and coast during the dry and rainy seasons in the Itapissuma/Itamaracá Complex, Pernambuco, Brazil. See species abbreviations in Table I.

The $\delta^{13}C$ and $\delta^{15}N$ of basal sources, except POM and SOM, did not significantly vary between seasons. Between environments, for the POM and SOM, the $\delta^{13}C$ was significantly more enriched in the estuary ($p < 0.05$) and the $\delta^{15}N$ significantly greater in the coast ($p < 0.05$). The $\delta^{13}C$ of POM and SOM were significantly higher ($p<0.05$) in the rainy season, for both areas. Average $\delta^{13}C$ values of basal food sources in the estuary showed a large variation, with higher values for microphytobenthos (-19.60 ‰) and more depleted $\delta^{15}N$ for *R. mangle* (2.46 ‰ ± 1.43), in the rainy season. In the coast, the more enriched sources in $\delta^{13}C$ and $\delta^{15}N$ were the SOM (-16.04 ‰ ± 1.19) and *Sargassum* sp. (10.05 ‰ ± 1.10), respectively (Fig. 2).

In the estuary, the $\delta^{15}N$ of invertebrates was significantly more enriched in the rainy season ($p < 0.05$). The $\delta^{13}C$ values was greater for *Farfantepenaeus subtilis* (-16.40 ‰ ± 0.56), and olygochaetes (4.58 ‰ ± 1.07) are the most depleted in $\delta^{15}N$ during the dry season. In the coastal area, polychaeta was more enriched in $\delta^{13}C$ (-15.18 ‰ ± 0.34) and $\delta^{15}N$ (15.47 ‰ ± 0.34) in the rainy season (Fig. 2).

The $\delta^{13}C$ and $\delta^{15}N$ of fishes did not significantly vary between seasons, but $\delta^{13}C$ was more enriched in the estuary and $\delta^{15}N$ more enriched in the coast ($p<0.05$). In the estuary and during the dry season, the snook *Centropomus parallelus* (-21.67 ‰ ± 0.63) was the poorest while *G. oceanicus* (-12.21 ‰ ± 0.55) was the richest in $\delta^{13}C$ and had the lowest $\delta^{15}N$ (4.51 ‰ ± 0.24). In the coast, *O. oglinum* presented the lowest $\delta^{13}C$ value (-16.43 ‰ ± 1.91) and *M. curema* showed the highest (-14.54 ‰ ± 0.92), in the dry and rainy seasons, respectively. *S. axillare* was the more depleted (6.08 ‰ ± 0.73) and *M. furnieri* was the more enriched (16.04 ‰ ± 0.70) in $\delta^{15}N$ in the rainy and dry seasons, respectively.

3.2 Isotopic niches

The Bayesian results of Layman trophic niche metrics showed variation between estuary and coast (Fig. 3.) The carbon range (dCr) values were higher in the estuary than in the coast. In contrast, nitrogen range (dNr) was highest in the coastal area. The mean distance to the $\delta^{13}C$-$\delta^{15}N$ centroid (CD) and the convex hull area encompassed by all species in the $\delta^{13}C$-$\delta^{15}N$ bi-plot space (TA) was similar for estuary and coast, but wich increasing of niche space of the coastal fishes. The mean nearest neighbour distance (NND) and the standard deviation of nearest neighbour distance (SDNND) of the estuary was higher than the coast.

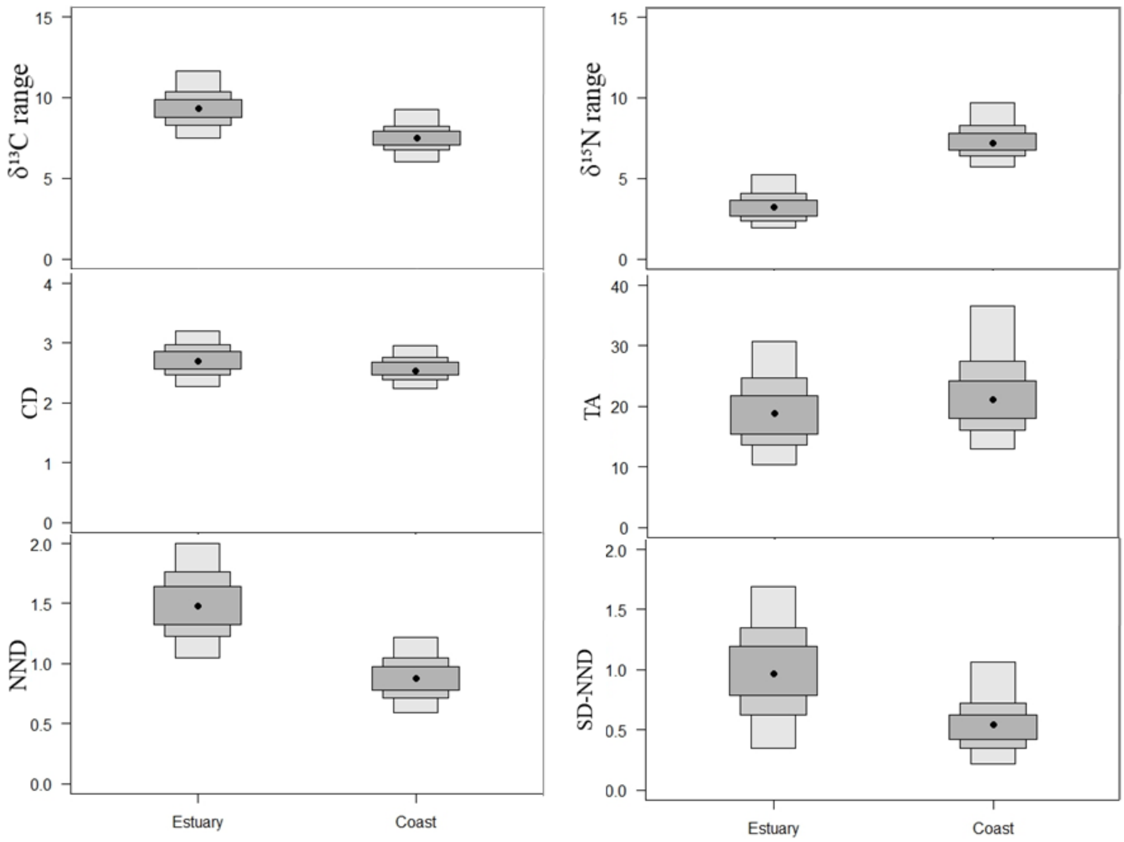

Fig. 3. Density plot of six isotopic niche metrics in the estuary and coast of Itapissuma/Itamaracá Complex, Pernambuco, Brazil. TA: total area of the convex hull, CD: mean distance to centroid, NND: nearest neighbour distance, and SD-NND: standard deviation of nearest neighbour distance. Box areas reflect 50%, 75%, and 95% credibility intervals.

Standard ellipse areas corrected for sample size (SEAc) showed a smaller isotopic niche width for species captured in estuary (n = 36, 10.63) than of species captured in the coast (n = 37, 11.35) and indicated low overlap between the environments (20.36%) (Fig. 4.A). The $\delta^{13}C$ of *S axillare, L. analis* and *C. hippos* and $\delta^{15}N$ of *S. axillare*, *D. auratus* and *C. undecimalis* were significantly different between estuary and coast ($p < 0.05$) (Fig. 4.B).

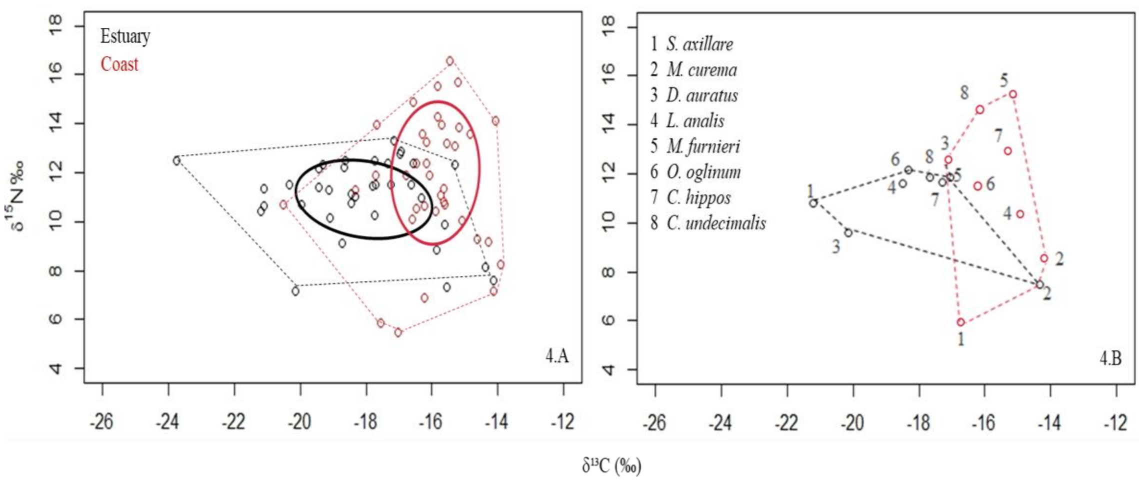

Fig. 4. Stable isotope composition of the fish community from the estuary and coastal area of Itapissuma/Itamaracá Complex, Pernambuco, Brazil. Solid lines (SEAc) represents the core isotopic niche space and dashed lines enclose the total area (SEA) of fish communities of environment. The points represent the $\delta^{13}C$ and $\delta^{15}N$ isotopic signatures of each individual in the fish community (4.A) and the mean carbon and nitrogen isotope ratios of each species (4.B).

4. Discussion

4.1 Stable isotope composition of consumers and sources

Carbon and nitrogen isotope compositions of the groups are different between environments and seasons revealing complex interactions of the trophic chain in IIC. Several studies have investigated, through $\delta^{13}C$ and ^{15}N, the complexity of trophic interactions and contributed to the understanding of tropical coastal ecosystems (Claudino et al., 2015; Mont'Alverne et al., 2016; Vinagre et al., 2016). This knowledge is necessary for detecting changes in trophic structure and habitat that can occur due to natural or anthropogenic effects. These modifications can alter the structure (biological diversity) and function (energy flows) of fish communities (Layman et al., 2007), affecting the overall trophic structure of this fauna (López-Rasgado et al., 2016; Wang et al., 2016).

The isotopic values $\delta^{13}C$ and $\delta^{15}N$ of the basal sources, invertebrates and fishes of the estuary presented a greater variation when compared to the coast, which may be associated to the multiple sources resulting from the interaction between marine and freshwater inputs (Warry et al., 2016). Food webs represent fundamental interactions that underpin ecosystem function, community structure, and population dynamics (Link et al., 2006; Pasquaud et al., 2007) and vary along environmental gradients across seasons (Schalk et al., 2016). The isotopic composition contributes to identify the sources of primary production supporting the fish biomass, to infer the movement patterns and the understand connectivity between environments (Kerzka, 2005; Schlacher and Connolly, 2009; Claudino et al., 2013).

In general, the coastal trophic web is supported by multiples sources (França et al., 2011; Selleslagh et al., 2015; Vinagre et al., 2015; Malek et al., 2016). Some studies in Brazilian estuarine systems reported large isotopic gradients in the sources and consumers. Also, it was observed that many sources (primary basal sources and invertebrates) support the estuarine food webs (Giarrizzo et al., 2011; Claudino et al., 2013). The $\delta^{13}C$ enable the determination of food sources consumed by an organism and the habitat where the consumer found its food (Post, 2002; Layman et al., 2007a). The great variability of $\delta^{13}C$ in the estuary may be linked to the fact that many species analyzed are migrants (Vasconcelos Filho and Oliveira, 2009) and assimilate resources from various areas (Hansson et al., 1997). Migratory fish species are major vectors of connectivity among aquatic habitats (Gillanders et al., 2003; Carrasou et al., 2016) and the IIC is a relevant feeding and nursery area for migratory species. The high percentage of marine species confirms the connectivity and dependence between estuarine and coastal area of the IIC (see chapter 1 of this thesis).

In the coast, the more enriched $\delta^{13}C$ and $\delta^{15}N$ of SOM and POM in the rainy season can be attributed to the increase of nutrients transported by rivers, mainly Jaguaribe River. Abrantes et al. (2013) observed that carbon of terrestrial origin, in five African estuaries, is transferred through several trophic links, from invertebrates to higher trophic fish level and are important for aquatic food webs. The low $\delta^{13}C$ values of the mangroves and epiphyton were observed in other tropical estuaries (Giarrizo and Schwamborn, 2011; Faye et al., 2011; Claudino et al., 2015). The microphytobenthos was highly enriched in $\delta^{13}C$, justifying the predominance of species that feed directly or indirectly on the substrate (e.g. detritivores and zoobenthivores) in the IIC. In the Curuçá estuary, north Brazil, the microphytobentos was an important source to consumers (Giarrizo and Schwamborn, 2011).

The detritivores (gobiids and mullets) were most enriched $\delta^{13}C$ since these species are at the base of the trophic chain and consume sources rich in $\delta^{13}C$, which also justifies the low $\delta^{15}N$. In IIC, *G. oceanicus* was more enriched in $\delta^{13}C$ and more depleted in $\delta^{15}N$, and *M. curema* was more depleted in $\delta^{13}C$ than in Mamanguape river for the same species (Claudino et al., 2015). The piscivore *C. parallelus* showed the more depleted $\delta^{13}C$ due to a more specific diet (Lira et al., 2016), and also given that top predators are more enriched in $\delta^{15}N$. More species had intermediate isotopic values, suggesting that they may have mixed diets across food webs or may specialize on prey from the benthic food web (Fry and Sherr, 1984).

4.1 Isotopic niche

Trophic niche occupancy and trophic organization of consumers are key components of ecosystem function that have been increasingly investigated using quantitative isotopic niche indices (Warry et al., 2016). A wide range in isotopic signatures was observed in both environments of IIC, estuary and coast, which may indicate that fish forage various habitats and feed on different preys, and broader species niches and more diverse assemblages have been observed in estuaries with greater marine exchange (Layman et al., 2007b). The carbon range (dCR) values were higher in the estuary than in the coast, indicating that estuarine species had a diverse diet and exploits a great variety of basal resources (Bearhop et al., 2004; Layman et al., 2007). In contrast, nitrogen range (dNR) was highest in the coast suggesting that the fishes feed on prey across different trophic levels (Bearhop et al., 2004; Layman et al., 2007) and the estuarine fishes consume a variety of prey with similar trophic positions. The mean distance to the $\delta^{13}C$-$\delta^{15}N$ centroid (CD) was nearly identical for estuary and coast, suggesting similar trophic diversity in these environments (Layman et al., 2007). Food webs, with a large proportion of species characterized by divergent trophic ecologies, exhibit a higher NND and low SDNND values, suggesting a more even distribution of trophic niches (Abrantes et al., 2014; López-Rasgado et al., 2016).

Overlap, although in a low value, was observed between the estuary and coast indicating similarities in basal carbon sources, suggesting resource partitioning (López-Rasgado et al., 2016; Malek et al., 2016), and evidences that fish do not exclusively feed in the area they were collected, reflecting trophic connectivity (Selleslagh et al., 2015). Connectivity can be defined as the rate of exchange of individuals of the same species among spatial units, and the movement of resources and consumers can strongly influence food web and community dynamics (Polis et al., 1997). The stable isotopes are efficient tools for tracing fish movements, fidelity and connectivity among habitats (Selleslagh et al., 2015). Differences observed in isotopic composition ($\delta^{13}C$

and $\delta^{15}N$) of *S. axillare, D. auratus*, *L. analis*, *C. hippos* and *C. undecimalis* between estuary and coast suggested some differentiation in the diet, which could be related to differential size of the individuals and hence diet changes or resource availability. In general, in the estuarine area, with a nursery role hosting little-sized individuals, we reported the highest $\delta^{13}C$ and the lowest $\delta^{15}N$ values.

The parrotfish *S. axillare* seems to exhibit an ontogenetic diet shift, possibly due to a gradual physiological adaptation allowing to consume and digest macroalgae (Dromard et al., 2017). The high $\delta^{15}N$ values in the estuary can be due to the considerable proportion of food sources with low C/N ratios (invertebrates, biofilm, detritus and epiphytes) observed in the diet of juveniles of *S. axillare* (Dromard et al., 2017). The high $\delta^{13}C$ and low $\delta^{15}N$ values for parrotfish *S. axillare* in the coast was also observed for *S. viride* in coral reef in the Bahamas (O'Farrell et al., 2014). The higher value of $\delta^{15}N$ of *D. auratus* in the coast suggests the consumption of larger prey than in the estuary. Spatial segregation was observed in the diet of *D. auratus* since larger individuals feed on larger prey in the upper estuary of Mamanguape, Brazil (Pereira and Pessanha, 2017). Juveniles of *L. analis* fed mostly on crustaceans and adults consumed basically fish (Freitas et al., 2011). The variation of $\delta^{13}C$ of *L. analis* can be due to the ontogenetic migration of the juvenile fish from the coastal area into the mangrove, confirming the dependence of estuarine food web for their growth (Tanaka et al., 2011). The contribution of primary sources for *C. hippos* in the coral reef of Gulf of Mexico indicated that juveniles were more enriched in $\delta^{13}C$ than adults (Carreón-Palau et al., 2013). This was also observed in the IIC. *C. undecimalis* in the IIC exploited similar sources of $\delta^{13}C$ in the estuary and coast but, in the coast, larger individuals consumed more enriched preys of $\delta^{15}N$ suggesting an ontogenetic shift in prey preference. Blewett et al. (2006) observed positive relationship between predator and prey size, and juveniles feed mainly on shrimps and adults on fishes. The estuary of IIC is used as a feeding ground for *C. undecimalis* (Lira et al., 2017) and it was not observed differences of $\delta^{13}C$ and $\delta^{15}N$ between juveniles of this species in the estuary of IIC (Gonzalez, 2017).

This study shows the importance of the interconnected IIC complex for the trophic web. The results indicate that different resources support the Complex's trophic chain, corroborating with other studies carried out in the area (Vasconcelos Filho et al., 2003; Vasconcelos Filho et al., 2009; 2010). It has been observed that the estuarine trophic chain is supported by many resources, and the high number of sources promote lower trophic redundancy within the food web, which may enhance ecosystem resilience, as the loss of one species can be compensated by another species with the same ecological niche (Catry et al., 2016). The high niche width in the coast suggests that prey of different trophic levels supported the trophic web suggesting that the ecology conditions are favorable. Low niche width can be related to the little variability in $\delta^{15}N$ within food webs (Layman et al., 2007a).

The knowledge of the trophic connectivity among aquatic habitats is a crucial step toward the proposition of appropriate measures for the integrative management of adjacent ecosystems (Deegan, 1993; Ray, 2005; Secor and Hooker, 2005). The structure and the links of trophic webs between environments allows the identification of species that act as direct links between them. Moreover, the large variation of the isotopic niche of consumers in an interlinked complex suggests the importance of these habitats in providing a high diversity of resources and consumer types (Sepúlveda-Lozada et al., 2017**)**. The management based on the food web impacts of species can substantially improve conservation outcomes (McDonald-Madden et al., 2015). However, specifically in our study case, more isotopic information is needed on ontogenic changes and on other species combined with stomach content analysis to better understand the ecological role of fishes in the trophic web of IIC. Also, other complementary tools can be applied in order to investigate the connectivity between coastal environments: otolith elemental signatures (Reis Santos et al., 2013), genetic structure (Sahyoun et al., 2016) and larval dispersion (Christie et al., 2010).

Acknowledgements

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Table II. Samples code and mean±sd values of stable isotope ratios of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) of basal food sources and consumers of Itapissuma/Itamaracá Complex, Northeastern Brazil.

Group/species		Estuary				Coast			
		Dry		Rainy		Dry		Rainy	
	Code	$\delta^{13}C$ Mean±SD	$\delta^{15}N$ Mean±SD	$\delta^{13}C$ Mean±SD	$\delta^{15}N$ Mean±SD	$\delta^{13}C$ Mean±SD	$\delta^{15}N$ Mean±SD	$\delta^{13}C$ Mean±SD	$\delta^{15}N$ Mean±SD
Basal sources									
Particulate organic matter	pom	-24.11±0.44	7.15±1.74	-23.15±0.25	6.42±0.31	-20.54±0.07	8.18±0.05	-18.18±1.98	8.99±0.22
Sedimentary organic matter	som	-24.02±2.97	5.00±0.31	-24.13±1.04	3.61±0.11	-18.04±0.7	6.1±0.64		
Microphytobenthos	m.fit	-20.56	4.33	-19.59±2.84	2.70±0.43			-17.29±0.28	7.00±0.24
Epiphyton	epif	-31.06±0.93	6.65±0.20	-32.20±0.23	8.14±0.36				
Avicennia sp.	a.sp	-26.02±0.76	5.23±0.41	-28.45±1.04	4.82±0.35				
Laguncularia racemosa	l.rac	-27.41±0.5	5.86±0.26	-28.61± 0.55	4.71± 0.25				
Rhizophora mangle	r.man	-26.05±0.56	3.90±0.54	-28.30±0.89	2.74±1.85				
Sargassum sp.	s.sp					-18.05±2.06	8.16±0.08	-18.08±1.07	10.06±1.10
Ulva sp.	ulva	-23.36±0.42	8.88±0.23	-22.98±0.38	6.30±0.19	-16.18±0.35	6.97±0.76	-17.53±0.26	5.16±0.27
Invertebrate									
Polychaeta	pol	-19.39±1.10	6.44±0.72	-18.64±0.31	7.22±0.51			-15.19± 0.34	15.48±0.34
Olygochaeta	oli	-25.25±2.03	4.59±1.07						
Anomalocardia brasiliana	an.bra	-20.91±0.27	9.53±0.35	-21.05±0.29	9.22±0.68	-15.88±0.25	12.41±0.36	-15.38±0.25	11.06±0.25
Crassostrea rhizophorae	c.rhi	-23.03±0.19	7.63±0.43	-22.47±0.12	8.28±0.15				
Copepoda	cop	-24.20±1.01	8.10±0.12	-22.23±0.58	9.16±0.39	-19.92±0.82	10.65±0.23	-19.37±0.65	8.77±1.16
Callinectes danae	c.dan	-17.06±1.32	8.48±0.45	-16.73±0.58	10.41±0.90			-18.20±1.38	10.03±0.39
Farfantepenaeus subtilis	f.sub	-16.41±0.57	7.95±0.12	-19.49±0.11	10.09±0.13				
Litopenaeus schmitii	l.sch	-16.95±1.76	8.82±0.06						
Fish									
Herbivore									

Sparisoma axillare	s.axi			-21.13±0.05	10.79±0.48	-16.19±0.01	12.36±0.17	-16.93±0.67	6.09±0.73
Detritivorous									
Gobionellus oceanicus	g.oce	-12.22±0.55	5.78±0.22	-16.15±0.51	7.08±0.68				
Gobionellus stomatus	g.sto	-13.40±0.53	4.51±0.25	-14.86±0.79	7.51±0.81				
Mugil curema	m.cur			-14.68±0.76	7.70±0.41			-14.55±0.93	8.70±1.80
Omnivore									
Atherinella brasiliensis	at.bra					-14.88±0.42	15.18±0.21	-14.79±0.24	15.11±0.24
Zoobenthivore									
Achirus lineatus	a.lin	-17.98±0.93	9.62±0.56	-19.17±0.98	8.90±1.19				
Citharichthys spilopterus	c.spi	-17.82±0.47	10.44±.76	-16.65±0.53	10.37±0.38				
Diapterus auratus	d.aur	-17.64±1.55	9.66±1.17	-19.25±0.85	9.72±2.24	-18.13±2.49	11.73±1.32	-16.53±1.05	13.05±1.05
Eucinostomus argenteus	e.arg	-16.17±1.31	9.48±0.44	-17.05±0.34	11.56±0.85				
Lutjanus analis	l.ana	-16.56±1.08	10.37±0.56	-18.37±1.11	12.71±0.52	-14.93±0.84	9.63±0.68	-15.45±0.33	10.74±0.66
Micropogonias furnieri	m.fur	-19.45±0.01	11.78±0.56			-15.65±0.27	16.04±0.70	-15.27±1.25	14.29±0.52
Zooplanktivore									
Opisthonema oglinum	o.ogl	-17.41±2.37	11.97±1.13	-18.22±1.93	12.14±0.53	-16.43±0.19	10.42±0.27	-16.47±0.30	12.22±0.29
Piscivore									
Bairdiella ronchus	b.ron	-19.66±0.33	12.85±0.30	-19.61±1.10	13.83±0.22				
Caranx hippos	c.hip	-18.46	11.13	-17.66±1.01	11.74±0.40	-15.28±0.44	12.58±1.34	-15.96±0.18	13.11±1.69
Centropomus parallelus	c.par	-22.53±2.07	13.09±0.48	-18.09±0.47	10.87±0.52				
Centropomus undecimalis	c.und	-19.54±2.83	11.09±1.24	-17.52±0.70	11.86±0.79			-16.38±1.24	14.42±1.14

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5 - Artigo Científico 3

Artigo científico redigido segundo as normas da revista Ecological Modelling. ISSN: 0304-3800.

Mass balanced model to assess the trophic web in a tropical estuary, Northeastern Brazil

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Abstract

Trophic web is a network of complex interactions of species and energy links between them and the ecosystem. These interactions can be simplified into mass balanced models, such as the Ecopath model. In this study, an Ecopath model was developed for the estuary of Santa Cruz Channel (SCC), Northeastern Brazil, aiming at evaluating the particular role of functional groups on the ecosystem, also investigating the flows of energy and biomass that supports the food chain. The model was narrowed to 32 functional groups (3 primary producers, 5 invertebrates, 22 fish and 1 detritus). The pedigree index (0.44) indicated an acceptable accuracy of input parameters. High ecotrophic efficiency of invertebrates (worms, gastropod and shrimp), *Lutjanus* spp. and *Gobionelus oceanicus* indicated that these groups are highly consumed or exported in the SCC. Most of the fish biomass dominates in low trophic levels and the primary consumers were the main sources of detritus flow. The predators feed predominantly on prey of the few trophic levels, mainly benthonic groups, indicating a low Omnivore index (0.16). The key species were snook *Centropomus* spp., jack *Caranx* spp. and barracuda *Sphyraena* spp.. The increase of the fishery would negatively impact several groups, mainly the snook, in contrast, would positively impact *Sphyraena* spp.. The System overhead (67.54 %) suggest an intermediate-to-high level of resilience of the ecosystem. The low Finn's cycling index (2.71) values for SCC was similar to the observed in other tropical systems considered immature. The trophic level estimated by Ecopath and the $\delta^{15}N$ in the SCC were highly correlated (R=0.77). The SCC is considered a system with high level of energy and an immature ecosystem with high potential for adaptation and resilience capacity.

Keywords: Biomass, Ecopath, ecology, energy flows, Santa Cruz Channel

1. Introduction

Food webs are maps of the trophic interactions between species, usually simplified into networks, showing the energy links between them, and populations to ecosystem properties such as production and element cycling (Thompson et al., 2012). However, the ecosystem consists of so many interacting pieces that it becomes impossible to understand how it functions by examining the component relationships in isolation (Allen, 1988). Simplified models, which have enough of the characteristics of the original system to resemble reality, are, at the same time, simple enough to be understood (Brown, 2004).

Ecopath with Ecosim (EwE), within the family of ecosystem models (Christensen et al., 2005), is, globally, the most widely applied tool for modelling marine and aquatic ecosystems (Colléter et al., 2013). This approach describes the ecosystem resources and the interactions among different ecological groups, identifying and quantifying major energy flows in an ecosystem (Heymans and Baird, 1995; Rybarczyk and Elka, 2003; Han et al., 2011; Rakshit et al., 2017). EwE has been recognized as one of NOAA's (National Oceanic and Atmospheric Administration) top ten scientific breakthroughs (Heymans et al., 2016). Furthermore, EwE is useful to evaluate the direct and indirect effects of fisheries (Freire et al., 2007; Lercari et al., 2014; Halouani et al., 2016; Natugonza et al., 2017), especially in coastal regions where fishing and other anthropogenic perturbations are most intense (Jackson et al., 2001).

Estuaries play an important role in the development of numerous species that use these systems for spawning, feeding or completing their life cycle (Elliott et al., 2007; Potter et al., 2015). Many researches have contributed to the increasing knowledge of the biological and ecological aspects of estuaries (Elliott and McLusky, 2004; Elliott et al., 2007; Blaber, 2013), including trophic web interactions in the Brazilian estuaries (Campos et al., 2015; Claudino et al., 2015; Dolbeth et al., 2016; Medeiros et al., 2017). The Brazilian coast hosts large estuarine areas, and the Pernambuco state, in Northeastern Brazil, has 14 important estuaries, highlighting, Santa Cruz Channel estuary (SCC), which integrates the Santa Cruz Environmental Preservation Area (CPRH, 2010). The SCC is one of the most productive estuarine complex in Pernambuco, with a high fish biodiversity (Mérigot et al., 2016), and important fishery activity, mainly small-scale, extremely relevant when considering the socio-economic viewpoint (CPRH, 2010; Andrade and Silva, 2013). The SCC has a complex trophic web supported by high energy and biomass flows between estuarine and marine organisms (Vasconcelos Filho et al., 2003; 2010; Figueiredo et al., 2006; Melo Júnior et al., 2007). However, it is the one of the most densely populated coastal region in Pernambuco and subject to domestic pollution, industrial and touristic activity and habitat degradation (Leitão et al., 2007; CPRH, 2010) which can alter the productivity, biodiversity and, consequently, the trophic interactions in the area. As in other parts of the world, most of the estuaries have had a long association with humans and have become gradually altered as a result of anthropic activities (Blaber and Barletta, 2016). Hence, food web models may help us to understand how biodiversity and ecosystems respond to perturbations (Heymans et al., 2014).

In Brazil, the majority of the studies with Ecopath models were carried out in the coastal zone and south region of the country (Rocha et al., 1998; Gasalla and Rossi-Wongtschowski, 2004; Velasco and Castello, 2005; Rocha et al., 2007; Nascimento et al., 2011; Araújo et al., 2017; Bornatowski et al., 2017). One estuarine model was carried out in the North region (Wolf et al., 2000), and two studies were developed in the Northeastern Brazil (Xavier, 2013; Lira et al., 2017).

In this study, an Ecopath model for the SCC estuary was developed, aiming at describing the food web structure, specifically (1) evaluating the particular role of functional groups on the ecosystem, (2) investigating the flows of energy and biomass that support the food chain, (3) comparing trophic level of fish species estimated by Ecopath to nitrogen estimated by stable isotopes analysis. The management of resources, implies in the understanding of the structure and functioning of the ecosystem, and in the comprehension of the interactions between functional groups and their changes due to human and environmental factors (Coll et al., 2006). These informations will contribute to the understanding of the ecosystem and may provide some support for the management of the estuarine ecosystem of SCC. Moreover, this study is an important step forward in the food web modelling for tropical estuaries.

2. Materials and Methods

2.1 Study area

The Santa Cruz Channel Estuary (SCC) is considered the largest estuarine system in the State of Pernambuco (Fig. 1). The channel bottom consists of quartz sand and muddy banks dominated by *Rhyzophora mangle*, *Laguncularia racemosa* and *Avicennia* sp. dominate (Neumann-Leitão and Schwamborn, 2000). The Catuama, Carrapicho, Botafogo, Congo, Igarassu and Paripe rivers flow in to the SCC that communicates with the Atlantic Ocean through the Catuama and Orange bars, in the north and south of Itamaracá Island, respectively (Fig. 1). The channel is approximately 22 km long, with width of up to 1.5 km and an average depth of 5 m (Macedo et al., 1973). The surface water temperature varies between 25º and 31ºC and salinity between 18 and 34 (Macedo et al., 1998). The model of SCC has a total area of 56.2 km^2 (Fig. 1).

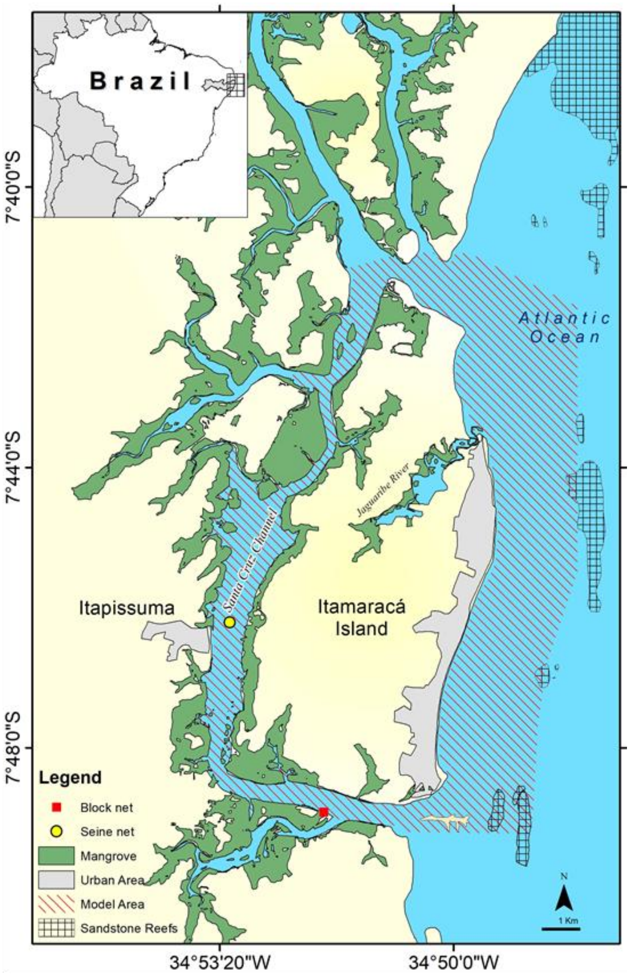

Figure 1. Santa Cruz Channel estuary, Northeastern Brazil, sampling stations and model area.

2.2 Ecopath model

The Ecopath model was proposed by Polovina (1984) and further developed by Christensen and Pauly (1992). The model estimates the annual production of biomass and consumption and describes the trophic structure, analysing the energy flows in the ecosystem (Christensen et al., 2008). The model is based on two master equations for production and consumption: (1) Production = catch + predation + net migration +

biomass accumulation + other mortality; and (2) Consumption = production + respiration + unassimilated food (Christensen and Pauly, 1992).

The overall equation of the Ecopath model is given below (Christensen and Walters, 2004):

$$B_i\ (P/B_i) = \sum_{j=1}^{n} B_j\ (Q/B_i) - DC_{ji} + (B_i)(P/B_i)(1\text{-}EE_i) + EX_i \qquad (3)$$

Where B is the biomass of each prey ($_i$) and predators ($_j$); P_i/B_i is the production/biomass ratio of i equivalent to the total mortality coefficient (Z) or natural mortality rate (Allen, 1971); Q/B_i is the is the food consumption per unit biomass of group i; DC_{ji}, the proportion of the predated group i in the diet of the predator j; EE_i is the ecotrophic efficiency representing the part of the total production transferred to higher trophic levels or captured by fisheries; EX_i is the export of (i) and refers to the biomass that is caught through fishing and/or that migrates to other environments. Biomasses and flows were expressed in $t.km^{-2}$ and in $t.km^{-2}.year^{-1}$, respectively.

2.3 Data collection

Fish data were obtained monthly, from October 2013 to September 2014, with a seine net of 67.5 m long and mesh size of 10 mm. Three replicates were carried out for each sample. The captured fish were identified and weighed. For some species, the stomach contents were analysed and used as input for the diet matrix (Table 1). The sampled area was obtained by GPS tracking using the open source image processing software ImageJ.

Landing data, considering the years of 2000 to 2007, were obtained from Brazilian official statistics (IBAMA, 2017) (See Table S.1).

2.4 Functional groups and biomass data

The model was defined with 32 functional groups given their importance in biomass, landings and ecological guilds: three primary producers, six invertebrates, 22 fish compartments and one detritus group. Specifically, for fish groups we created 12 functional groups with ecologically similar species when considering feeding habitats (Anchovies, Clupeiformes, Batrachoididae, jack, *Diapterus* spp., *Lutjanus* spp., *Eucinostomus* spp., *Sphyraena* spp., flatfish, puffer).

The biomass for the fish functional group was estimated by the sum of the individual weights of each group divided by the total trawled area ($t.km^{-2}$). The catchability model proposed by Lauretta et al. (2013) and applied in Northeastern Brazil by Lira (2017) was used for fish functional groups in order to correct the biomass values which are underestimated because of gear selectivity (Table S.2). For species that only occupy part of the model area of model, their biomasses were pro-rated by area (Heymans et al., 2016). This was the case of the gobiids, estuarine and non-migrants (Vasconcelos Filho and Oliveira, 1999), restricted to the channel area (9.12 km^2). The biomass of phytoplankton, epiphyton and bivalve were obtained by the literature. Microphytobenthos, zooplankton, gastropod, worms, blue crab and shrimp biomass were estimated by Ecopath.

2.5 Parameters estimates

Production refers to the increase of living tissue within a functional group over a given period of time. The production/biomass rate (P/B) can be estimated under steady state conditions as total mortality Z (Allen, 1971), which is the sum of fishing mortality (F) and natural mortality (M). In this study, Z was estimated by linearized length converted catch curves (Chapman and Robson, 1960; Pauly, 1983), using data from the study area (Fig. S.1). For species not fished, P/B is equal to M, computed as Pauly (1980):

$$M = k^{0.65} \times L\infty^{-0.279} \times T^{0.463} \quad (4)$$

Where M is natural mortality ($year^{-1}$), k is the growth coefficient ($year^{-1}$), L_∞ is the asymptotic length (cm) and T is the mean water temperature (°C). The parameters k and L_∞ were obtained from the literature or using the empirical equations of Le Quesne and Jennings (2012) and Froese and Binohlan (2000), respectively (Table S.3). Temperature data were measured *in situ*, during fish sampling, and the mean annual value was 29°C.

Consumption is the intake of food by a group over a given interval of time. The consumption/biomass rate (Q/B) for fish was estimated according to the following equation (Palomares and Pauly, 1998):

$$\log Q/B = 7.964 - 0.204 \times \log W_\infty - 1.965 \times T' + 0.083 \times Ar + 0.532 \times H + 0.398 \times D \quad (5)$$

Where W_∞ is the asymptotic weight (g), T\` is temperature in Kelvin ($T' = 1000/(T°C+273.15)$), and Ar is aspect ratio of the caudal fin (See details in Table S.4). H and D represent the feeding type (H = 1 for herbivores; D = 1 for detritivores; H = D = 0 for other feeding habits). For the productors and invertebrate’s functional groups, P/B and Q/B values were obtained from the literature, using information from similar estuarine systems (Table S.5).

A diet composition matrix (DC) was constructed to account for the trophic interactions of all functional groups in the system. Diet information for some fish species was obtained from stomach contents analyses of the study area (Vasconcelos Filho et al., 2003; Vasconcelos Filho et al., 2010; Temóteo et al., 2015; Pina et al., 2015; Leão, 2016; Lira et al., 2017) or literature of SCC.

2.6 Balancing the model

The biomass of microphytobenthos, zooplankton, gastropod, worms, blue crab, shrimp, herring and bivalves was estimated by model. Given the absence of data, the EE of microphytobenthos, zooplankton, gastropod, worms, blue crab, shrimp and herring of other estuarine models (Wolff et al., 2000; Villanueva, 2015) was utilised.

Ecopath model is considered ecologically and thermodynamically balanced when (Darwall et al., 2010; Heymans et al., 2016): (i) EE < 1 for all functional groups, (ii) values of P/Q (Production/ Consumption rate or Gross efficiency of food conversion - GE) are between 0.1 and 0.35, except for some fast growing groups (Guenette, 2014), (iii) R/A (Respiration/Food assimilation) < 1, (iv) R/B (Respiration/Biomass) are between 1 and 10 for fishes and higher values for small organisms, (v) NE (Net efficiency of food conversion) > GE and (vi) P/R (Production/Respiration) < 1 (Christensen et al., 2008; Heymans et al., 2016). These assumptions were considered in this study and the reliability of the model was analyzed through the PREBAL routine (Link, 2010). Pedigree index was considered in order to quantify model uncertainties for reliable parameterization of Ecopath model (Christensen et al., 2005). Pedigree index values are decided by the modeller and its range from 0 (low precision information) to 1 (data and parameters fully rooted in local data).

2.7 Ecological indicators

Some ecosystem indicators, which describe the ecosystem bioenergetics, community structure and recycling of the system (Table 3), were selected based on Christensen (1995) and Gubiani et al. (2011). The Matrix Trophic Impact - MTI (Ulanowicz and Puccia, 1990) was performed in order to analyse the direct and indirect impacts from a single functional group on the other. This analysis allows the identification of key groups of the system quantified by the keystonness index developed by Valls et al. (2015).

Table 1. Diet composition matrix of the Santa Cruz Channel estuary model, Northeastern Brazil. * Isotopes data.

		Predator													
	Prey	Zooplankton	Bivalve	Gastropod	Worms	Blue crab	Shrimp	Herring	Clupeiformes	Anchovies	Batrachoididae	Mullet	*Hyporhamphus unifasciatus*	Snook	Jack
1	Epiphyton			0.210		0.009						0.03	0.01		
2	Microphytobenthos		0.200	0.480	0.401	0.070	0.158			0.002	0.040	0.06	0.55		
3	Phytoplankton	1.000	0.418		0.072	0.0001	0.130	0.200	0.330			0.17			
4	Zooplankton		0.110		0.107	0.0001	0.194	0.800	0.670			0.015			0.009
5	Bivalve*				0.001	0.005	0.001			0.0003					0.009
6	Gastropod				0.001	0.0005	0.001				0.080		0.005		
7	Worms					0.004	0.004			0.007	0.008		0.005		0.004
8	Blue crab*					0.007					0.190		0.005	0.014	
9	Shrimp*					0.140				0.002	0.100			0.057	0.004
10	Herring*					0.005				0.249				0.029	0.002
11	Clupeiformes					0.050				0.254				0.050	0.009
12	Anchovies													0.002	0.009
13	Batrachoididae													0.001	
14	Mullet*														

Continued (Table 1)

15	*Hyporhamphus unifasciatus*												0.001	0.001
16	Snook*													
17	Jack*												0.002	0.001
18	*Oligoplites* spp.												0.001	0.017
19	Snapper*												0.005	0.001
20	*Lutjanus* spp.												0.002	0.001
21	*Diapterus* spp.*												0.092	0.001
22	*Eucinostomus* spp.*				0.0003								0.001	0.001
23	*Archosargus rhomboidalis*				0.003								0.001	
24	*Sparisoma radians**													0.001
25	*Gobionelus stomatus**				0.004					0.106			0.306	0.339
26	*Gobionelus oceanicus**				0.004					0.070			0.300	0.299
27	Gobiidae				0.002								0.001	0.089
28	*Sphyraena* spp.												0.020	
29	*Citharichthys spilopterus**				0.0004								0.030	0.003
30	Flatfish				0.0002								0.002	0.003
31	Puffer												0.036	0.025
32	Detritus	0.272	0.310	0.417	0.695	0.500			0.485	0.406	0.725	0.425	0.045	0.154

2.8 Ecopath data versus Isotopes data

The results of Ecopath model has been combined with Stable Isotopes Analyses approach to describe food web structure (Milessi et al., 2010; Navarro et al., 2011; Deer et al. 2014). Fractionation of $\delta^{15}N$ between the consumer and its food source increases with the trophic level (Post, 2002; Vanderklift and Ponsard, 2003) and constitutes a useful tool to determine trophic position in the web. In this study, the relationship between the trophic level estimated by Ecopath and nitrogen stable isotope ($\delta^{15}N$) values were tested by the Spearman's correlation (Zar, 1984), considering some functional groups of the SCC, whose values of $\delta^{15}N$ were available (See Table 1). The application of both methodologies simultaneously could provide more accurate information of the structure and functioning of food web and be a highly relevant tool to validate results of the model (Navarro et al., 2011). Isotopes data collection and analysis is detailed in Chapter II of this Thesis.

3. Results

3.1 Model balancing

To balance the model, we adapted the diet matrix for some groups of fish which initially presented EE > 1. In relation to the criteria and assumptions applied to evaluate the reliability of the model, the P/Q, P/R, R/A, R/B and NE ratios reached the accepted ranges (see Table S.6). Based on the PREBAL routine, the relations between B, P/B and Q/B showed negative correlations with the trophic level (TL). The P/Q values ranged from 0.03 (*S. radians* and *G. stomatus*) to 0.33 (zooplankton and snook) (Table S.6).

3.2 Basic estimates

The results of the model (Tables 2 and 3) suggest that several functional groups (*Hyporhamphus unifasciatus*, puffer, Batrachoididae) were weakly consumed while other were highly predated and/or exploited (e.g. *Lutjanus* spp., *Sparisoma radians*, G*obionelus* oceanicus) in the SCC. Microphytobenthos, worms and gastropod were highly predated, as for shrimp and some fish group (i.e. *Lutjanus* spp., *G. oceanicus*), which were also exploited in the SCC. The Omnivory Index of the functional groups of SCC were low, indicating diet specialization of these groups and only anchovies had the highest Omnivory Index (0.7), suggesting a high food plasticity (Table 2).

Table 2. Basic inputs and estimated outputs (in bold) of the functional groups of the Santa Cruz Channel estuary model, Northeastern Brazil. TL = trophic level, B ($t.km^{-2}$) = biomass, P/B ($year^{-1}$) = production per unit of biomass, Q/B ($year^{-1}$) = consumption rate per unit of biomass, EE = Ecotrophic Efficiency, OI = Omnivory Index, Y ($t.km^{-2}$) = landings. Bold values were estimated by Ecopath.

Functional group	TL	B	P/B	Q/B	EE	OI	Y
Epiphyton	**1**	1.37	153.31		**0.36**		
Microphytobenthos	**1**	**1.41**	209.61		0.90		
Phytoplankton	**1**	6.40	652.71		**0.35**		
Zooplankton	**2**	**6.89**	50.21	150.65	0.80		
Bivalve	**2.1**	**11.28**	2.00	9.00	**0.87**	**0.09**	8.32
Gastropod	**2**	**5.51**	2.65	38.83	0.90		
Worms	**2.1**	**5.98**	2.91	17.26	0.95	**0.09**	
Blue crab	**2.2**	**7.24**	2.00	8.00	0.80	**0.31**	4.89
Shrimp	**2.2**	**11.22**	2.81	26.90	0.95	**0.16**	2.29
Herring	**2.8**	**8.54**	2.00	19.36	0.80	**0.16**	11.55
Clupeiformes	**2.6**	3.39	2.28	26.46	**0.57**	**0.22**	
Anchovies	**2.8**	0.30	1.58	18.92	**0.21**	**0.74**	
Batrachoididae	**2.6**	1.20	1.10	8.37	**0.03**	**0.33**	
Mullet	**2.0**	1.23	2.20	33.68	**0.87**	**0.01**	2.37
Hyporhamphus unifasciatus	**2.0**	0.37	1.12	4.50	**0.01**	**0.01**	
Snook	**3.1**	0.15	1.96	6.00	**0.85**	**0.14**	0.25
Jack	**2.9**	0.24	0.47	6.95	**0.84**	**0.20**	0.07
Oligoplites spp.	**3.1**	0.04	0.97	15.95	**0.96**	**0.21**	
Snapper	**2.5**	0.15	0.33	6.92	**0.55**	**0.37**	
Lutjanus spp.	**2.5**	0.25	0.33	6.10	**0.98**	**0.41**	
Diapterus spp.	**2.5**	0.76	4.08	12.10	**0.08**	**0.30**	0.07
Eucinostomus spp.	**2.4**	2.58	1.35	11.92	**0.03**	**0.29**	
Archosargus rhomboidalis	**2.3**	1.91	1.01	8.11	**0.09**	**0.29**	
Sparisoma radians	**2.0**	0.11	0.99	29.12	**0.99**	**0.07**	1.16
Gobionellus stomatus	**2.0**	9.26	1.18	33.34	**0.41**	**0.05**	
Gobionellus oceanicus	**2.0**	4.50	1.45	30.65	**0.97**	**0.05**	
Gobiidae	**2.0**	0.54	1.33	31.25	**0.94**	**0.05**	

Sphyraena spp.	**3.2**	0.15	0.42	6.47	**0.28**	**0.10**
Citharichthys spilopterus	**2.4**	0.50	1.30	13.1	**0.08**	**0.33**
Flatfish	**2.4**	0.50	1.40	13.0	**0.02**	**0.33**
Puffer	**2.6**	5.70	1.50	6.10	**0.01**	**0.34**
Detritus	**1**				**0.21**	**0.25**

3.3 Trophic flows

The mean trophic level was 2.41 (Table 4) and the top one was 3.2 for snook and *Sphyraena* spp. (Table 2). The flow diagram indicates high biomass of phytoplankton and important transference of biomass from microphytobenthos and detritus to the higher trophic levels. The biomass of invertebrates and fish functional groups (i.e. *G. stomatus, G. oceanicus, Eucinostomus* spp., puffer) were relevant in the TL 2 indicating several consumers in low trophic levels of the food web of SCC (Fig. 2).

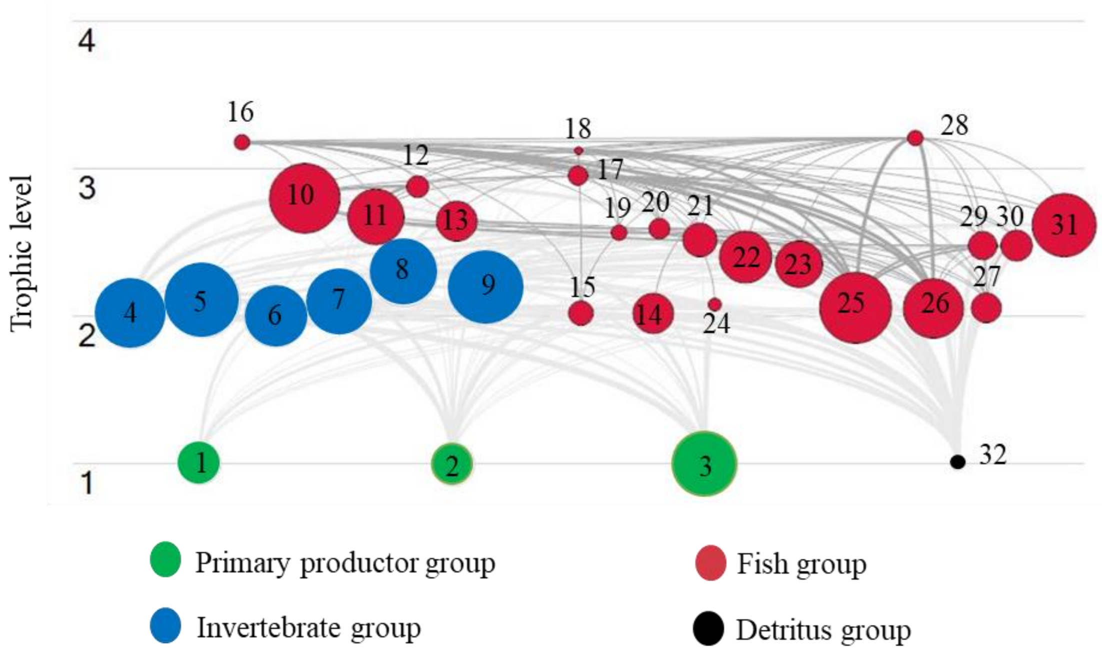

Figure 2. Flow diagram of the Santa Cruz Channel estuary, Northeastern Brazil. The size of each circle is proportional to the biomass of the functional group. The numbers identify the functional groups of the model (Table 1). The thickness of the connecting lines is proportional to the magnitude of trophic flows.

Table 3. Statistic and ecological indicators analysed in the Santa Cruz Channel estuary, Northeastern Brazil.

Code	Ecosystems indicators	Description	Goal
TST	Total System Throughput	Sum of all the flows through the ecosystem	Represent the size of the entire system in terms of flow
TPP/TR	TPP/Total Respiration	Ratio between Total Primary Production and Total Respiration in a system	Represent the maturity degree of an ecosystem. In mature systems, the ratio should approach 1
TPP/TB	TPP/Total Biomass	Ratio between Total Primary Production and Total Biomass in a system	Represent the maturity degree of an ecosystem. In mature systems, the TPP/TB should be low
SOI	System Omnivory index	Variance mean of trophic levels in the diet composition	Description of the trophic amplitude associated to maturity. SOI should increase with mature systems
CI	Connectance Index	Ratio of the number of actual links to the number of possible links in food web	Description of the trophic links associated to maturity. In mature system, a high CI indicate a food web with large number of value trophic links
AC	Ascendency	Index of the optimization of a food web (%)	In mature systems, the percentage of AC should be high
SO	System Overhead	Reserve energy of the ecosystem (%; AC+SO=100%)	In resilient systems, the percentage of SO should be high
FCI	Finn's cycling index	Quantifies the flows in of recycling process	Description of the system maturity, resilience and stability. Higher values indicate more mature and resilient systems

Most of the fish biomass and ecological production take place at around TL II. The Herbivore is almost two times higher than Detritivore (1545 x 796.4 t*km^{-2}*year^{-1}). The transfer efficiencies (TE) for TL II was 15% and decreased with increasing TL (Fig. 3).

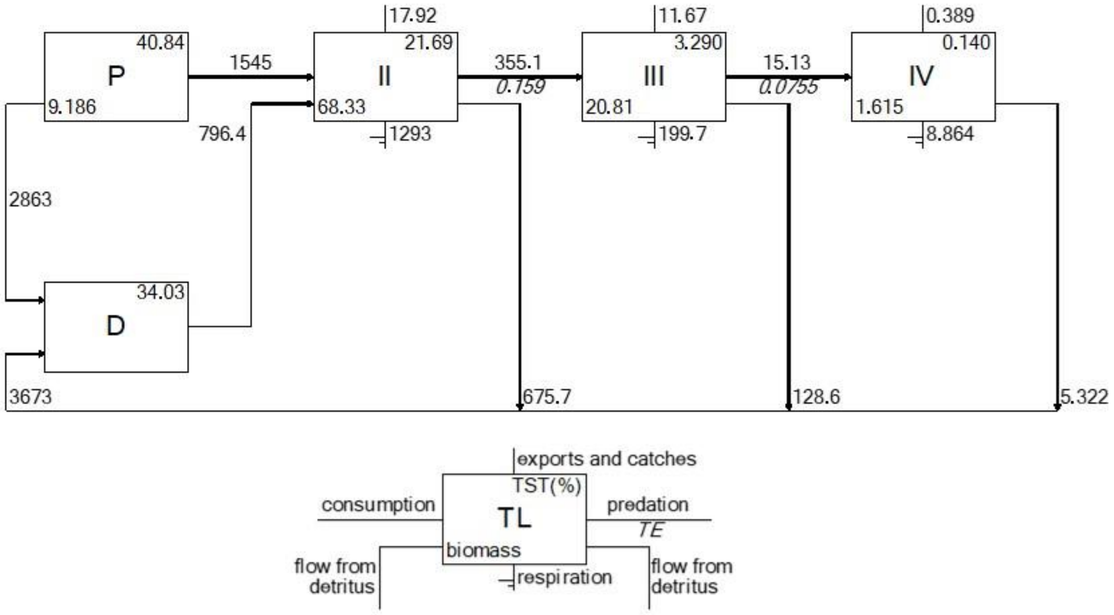

Figure 3. Lindeman spine representation of the Santa Cruz Channel estuary, Northeastern Brazil. Trophic level (TL) I is composed by primary producers (P) and detritus (D). Flows are represented in t·km^{-2}·year^{-1} and biomass in t·km^{-2}.

The Mixed Trophic Impact (MTI) analysis showed that increasing blue crab biomass would have negative effects over Clupeiformes, *Archosargus rhomboidalis* and flatfish. Similarly, the increasing of *Gobionellus stomatus* biomass has negative impacts over worms and gastropod, whereas an increase of the fishery may cause negative effects on *Sparisoma radians*, mullet, snook and jack but increase the *Sphyraena* spp. biomass (Fig. 4).

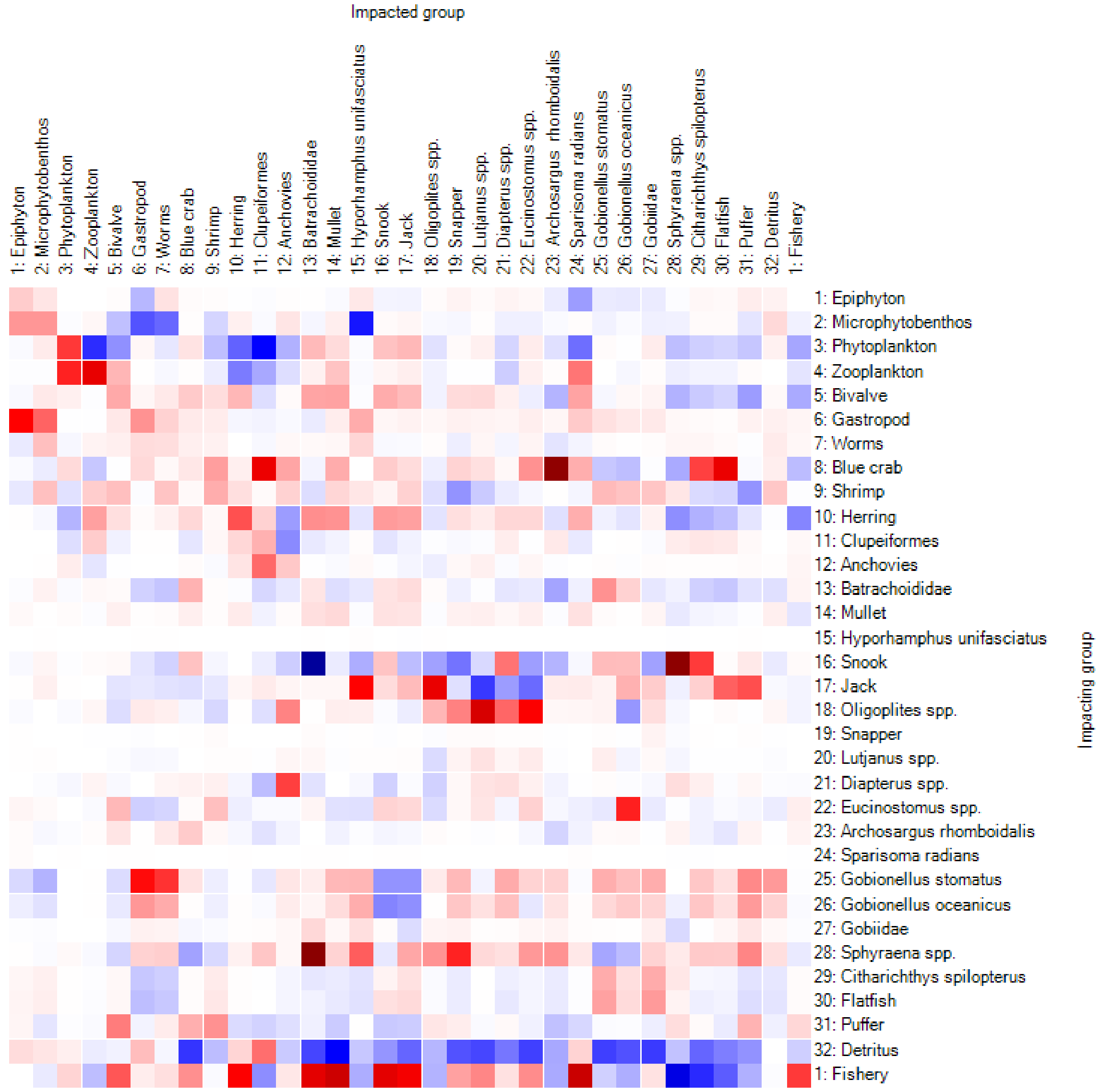

Figure 4. Mixed Trophic Impact (MTI) analysis of the Santa Cruz Channel estuary, Northeastern Brazil. Positive (blue) and negative (red) impacts.

The invertebrates had high biomass and lower impact in the SCC, except blue crab which showed high impact. The predators snook, jack and *Sphyraena* spp. were considered key groups with low biomass and high impact within the trophic web of SCC (Fig. 5).

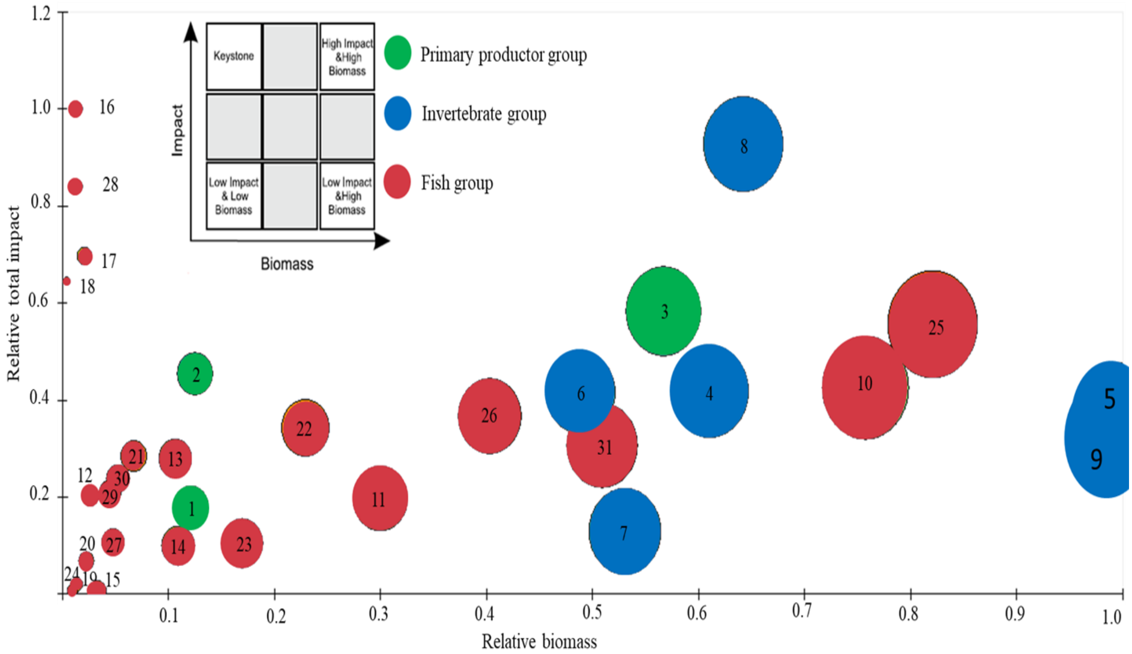

Figure 5. Functional groups plotted against relative total impact and relative biomass of the Santa Cruz Channel estuary, Northeastern Brazil. The numbers identify the functional groups of the model (listed in Table 1). The size of each circle is proportional to the biomass of the functional group.

3.4 Statistics and ecological indicators

In the SCC, the total system throughput (TST) was 10794.54 t.km^{-}2.y^{-1} and the rate of TPP/TR and TPP/TB were 3.10 and 46.84, respectively (Table 4). The System Omnivory Index was low (0.16) indicating that the predator feeds on few trophic levels. Connectance Index was 0.25, Ascendancy was 32.46% and System overhead was 67.54 %. Finn's cycling index was 2.71 with a Transfer Efficiency Total value of 9.1%, similar to the theoretical value of 10%. The pedigree index (0.44) indicated acceptable accuracy of inputs parameters (Table 3).

Table 4. Characteristics, statistics and ecological indicators for the Santa Cruz Channel estuary, Northeastern Brazil.

Indicators	Values	Units
Number of functional groups	32	
Sum of all consumption (TC)	2712.91	$t \cdot km^{-2} \cdot year^{-1}$
Sum of all exports (TE)	2906.84	$t \cdot km^{-2} \cdot year^{-1}$
Sum of all respiratory flows (TR)	1501.47	$t \cdot km^{-2} \cdot year^{-1}$
Sum of all flows into detritus (TD)	3673.30	$t \cdot km^{-2} \cdot year^{-1}$
Total system throughput (TST)	10794.54	$t \cdot km^{-2} \cdot year^{-1}$
Sum of all production (TP)	5199.11	$t \cdot km^{-2} \cdot year^{-1}$
Mean trophic level of the catch (TLc)	2.41	
Gross efficiency (catch/net p.p.)	0.006	
Calculated total net primary production (TNPP)	4684.56	$t \cdot km^{-2} \cdot year^{-1}$
Net system production (NSP)	3183.08	$t \cdot km^{-2} \cdot year^{-1}$
Total biomass (excluding detritus) (TB)	100.01	$t \cdot km^{-2}$
Total catches (TC)	29.98	$t \cdot km^{-2} \cdot year^{-1}$
Total primary production/Total respiration (TPP/TR)	3.10	
Total primary production/Total biomass (TPP/TB)	46.84	
Total biomass/total throughput (TB/TST)	0.009	/year
Connectance Index (CI)	0.25	
System Omnivory Index (SOI)	0.16	
Finn's cycling index (of total throughput) (FCI)	2.71	% of TST
Finn's mean path length (PL)	2.44	
Ascendancy (AC)	32.46	%
System overhead (SO)	67.54	%
Transfer Efficiency Total (TT)	9.07	%
Ecopath pedigree index	0.44	

3.5. Ecopath and isotopes

The relationship between TL estimated by Ecopath and the $\delta^{15}N$ in the SCC were highly correlated ($r = 0.77$; $p < 0.05$) (Fig. 6).

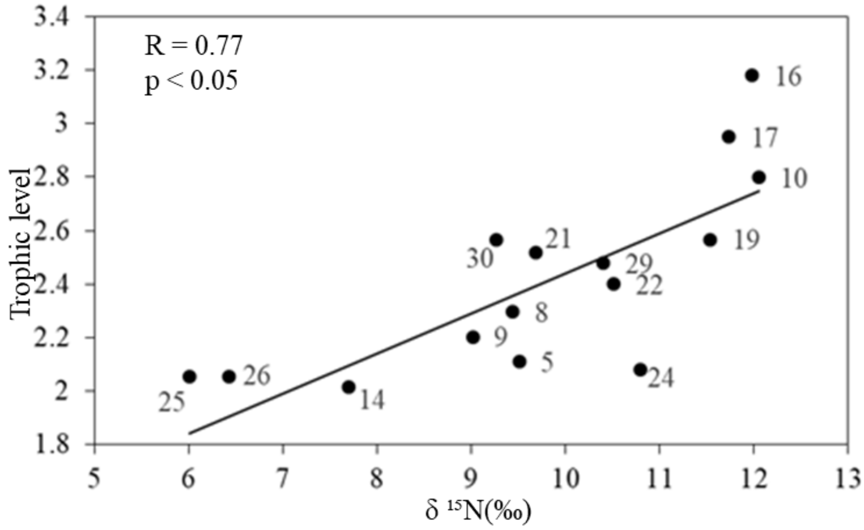

Figure 6. Correlation between trophic level (TL) estimated by Ecopath and the $\delta^{15}N$ values calculated from stable isotope analysis conducted along Santa Cruz Channel estuary, Northeastern Brazil. The numbers in the figure identify the functional groups of the model (listed in Table 1).

4. Discussion

Estuaries are important ecosystems for fish species, as nursery, migration routes and feeding areas (Elliott et al., 2002; 2007). It is largely recognized their role as nutrient and detrital sinks that stimulate high levels of both primary and secondary production (Correll, 1978) which, in turn, naturally support a large biomass of fishes (Houde and Rutherford, 1993; Whitifield, 2016). These fishes are interconnected by trophic links resulting in a complex food web and flows of biomass and energy between functional groups of the ecosystem (Winemiller, 1990; Christensen and Pauly, 1992). These interactions can be modelled in order to minimize the complexity of the processes, allowing for the understanding of their functioning (Christensen and Pauly, 1993; Thompson et al., 2012).

Our study developed an Ecopath model in the most productive estuary of Pernambuco State, the Santa Cruz Channel estuary, Northeastern Brazil. In overall, our model respected the general rules/principles recommended by Darwall et al. (2010) and Heymans et al. (2016), and was consistent with the recommendations of Link (2010), available within the PREBAL routine. This approach has been widely applied to assess whether data are coherent to the system level by respecting some basic laws, rules, and principles of ecosystem ecology (Lassalle et al., 2014; Alexander et al., 2015). The pedigree index obtained for SCC indicated an acceptable quality of the model (Morissette, 2006; Lassalle et al., 2014). Moreover, the results revealed a clear correlation between the TLs calculated by the Ecopath model and $\delta^{15}N$ values, indicating that the model may be reliable in predicting, with good accuracy, the shifts and changes in trophic level and diet as measured by stable isotopes. Similar correlation values were observed for other studies in coastal areas (Milessi et al., 2010; Navarro et al., 2011; Deer et al. 2014).

An EE with value just above zero indicates that the group apparently was not consumed by any other group in the system. Conversely, a value close or equal to 1 indicates that the group was being heavily preyed and/or fished, leaving no individuals to die of old age (Ullah et al., 2012). EE values are expected to be low for the top predator (Christensen et al., 2000). However, the high values for the predators snook and jack can be related to the predominance of juveniles, which are predated by other species in the SCC. The high EE of *Lutjanus* spp. and *G. oceanicus* showed that these groups are highly predated and exploited in the SCC, mainly by fishing (IBAMA, 2007). The estimated EE values for microphytobenthos were less than 1.0, which was in agreement with values suggested by Christensen and Pauly (1992) for primary producers. The high EE of invertebrates (worms, gastropod and shrimp) can be due to the dominance of benthivores and detritivores in the SCC that predate these groups (Vasconcelos Filho et al., 2003; 2010). Also, shrimp is one of the main fishing targets in the SCC (IBAMA, 2007).

In general, the functional groups showed a specialist diet with low Omnivory index, except for anchovies, which integrate the functional group of different trophic guilds. The P/Q values in the SCC ranged from 0.03 to 0.33. High P/Q values are observed in immature and tropical estuaries (Lira, 2017). High production and consumption rates of some groups indicate high productivity, which may be due to the high abundance of juvenile fishes in most groups, that utilize the area as refuge and/or nursery grounds (Villanueva, 2015). The SCC is a highly productive ecosystem (Macêdo *et al.*, 2000; Figueiredo et al., 2006; CPRH, 2010), and many species, mainly migrants (see also Chapter 1 of this thesis), utilise this area for nursery, growth and feeding (Vasconcelos Filho and Oliveira, 1999).

The transfer efficiencies for TL II were compatible to the one proposed by Ryther (1969), within the range of 10–20% suggested by Odum (1971) and Barnes and Hughes (1988). In the SCC, a highest biomass of primary consumers (i. e. invertebrate and fish) was observed, given the dominance of fish of lower trophic level (Vasconcelos Filho et al., 2003). Direct and indirect interactions within the ecosystem were analyzed by means of the MTI. The blue crab has high biomass and impact in the trophic web, given its high abundance (Araujo et al., 2012) and explotation (CPRH, 2010) in the area. Detritivore fish (i.g., gobiids and mugilids) showed a wide impact on invertebrate functional groups, highlighting the importance of these groups in the ecosystem (Paiva et al., 2005). Within this group, an increase of the fishery would negatively impact several other groups, mainly the snook, in contrast, positively impact *Sphyraena* spp., possibly due to top-down effects or trophic cascades caused by removal of predators (Christensen et al., 2004).

The keystone species (snook, jack and *Sphyraena* spp.) identified by Ecopath model in the SCC were also observed in the Sirinhaém estuary (snook, jack) (Lira, 2017), revealing its high impact in the estuarine ecosystem food web. These species have a high ecological and commercial relevance, despite the unregulated fisheries. Keystone species are predators with relatively low biomass (Libralato et al., 2006) and strong influence on the abundance of other species and ecosystem dynamics (Mills et al., 1993; Power et al., 1996; Libralato et al., 2006). They play an important ecological function, that maintain the food-web structure of their community (Perry, 2010; Valls et al., 2015; Bornatowski et al., 2017), and helps a better understanding of ecosystem functioning and processes (Jordan, 2009; Clemente et al., 2010). Changes to the abundance of key functional groups might have significant implications for the functioning of ecosystems and should be avoided through management (Heymans et al., 2014).

Ecological indicators are useful tools to analyse ecosystems and plausible future scenarios while evaluating environmental status (Coll and Steenbeek, 2017). The ecological indicators showed that SCC is an immature ecosystem with an acceptable degree of stability and resilience. The low values of TST, TPP/TB and TPP/TR were similar to other estuaries in northeastern Brazil (Xavier, 2013; Lira; 2017). The low values of SOI, CI and AC confirmed that the trophic web of SCC is typical of immature system. The low SOI of SCC were also observed in other tropical systems (Villanueva, 2015; Lira, 2017). This indicates that in the SCC predators feed predominantly on prey of the few trophic levels, as observed by Vasconcelos Filho et al. (2003; 2009; 2010). The low Ascendency (AC) in the SCC reflected the low level of organisation of the food webs and a growing and developing ecosystem (Ulanowicz, 1986; Heymans et al., 2014). The model indicated low FCI values for SCC, as observed in other tropical systems considered immature (Xavier, 2013; Villanueva, 2015; Lira, 2017).

Although the SCC is immature, the SO suggests an intermediate-to-high level of resilience (SO = 67 %). The high overhead (SO) of the network reflects a high proportion of parallel pathways in the system (Allesina et al., 2005), indicating a high ‘‘energy reserve” (Ulanowicz, 1986; Heymans et al., 2014), and consequently, high resilience. However, these features indicate a kind of paradox, since the lower the system’s ascendancy, the higher its overhead, its resilience, and hence its ability to favourably respond to perturbations (Elliott and Quintino, 2007).

The ecological indicators of the model considered this ecosystem as immature and resilient, with highest biomass within lower trophic levels. The key species in the SCC were the predators and the prey were mainly benthonic groups. Understanding the links between prey and predator and how they may affect the ecosystem functioning is relevant especially when providing the knowledge on the likely impact of anthropogenic related activities on ecosystem health (Villanueva, 2015), as observed in SCC.

Despite the lack of some basic biological information on SCC, the results of this research were consistent with literature on the SCC and to estuaries in general, and confirmed that the tool employed in this study is an important step toward the knowledge of the link between the ecological assemblage structure and ecosystem function in estuarine areas. In this study, it was provided a snapshot of the food web of SCC. The development of an ecosystem model for the SCC is an important effort to integrate the available data, which will allow a better knowledge and understanding of aspects of trophic structure and flows of ecosystem.

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7 - Considerações Finais

As informações obtidas através da integração de múltiplas ferramentas (guildas ecológicas, isótopos estáveis e modelagem) para investigar a estrutura trófica do Complexo Itapissuma/Itamaracá foram convergentes e complementares.

De uma forma geral, os resultados indicaram que a ictiofauna do Complexo Itapissuma/Itamaracá é formada predominantemente por espécies marinhas que migram entre as áreas estuarina (Canal de Santa Cruz) e costeira (Mar de Dentro) do complexo e exploram tais áreas para o seu desenvolvimento, contribuindo para o fluxo de matéria e energia entre o estuário e a costa. Observou-se também diferentes assimilações pela mesma espécie no estuário e na costa, indicando uma conectividade trófica e uma baixa sobreposição de nicho entre esses ambientes. Estes resultados podem estar relacionados ao tamanho dos indivíduos e ao ambiente, uma vez que a composição isotópica de algumas fontes variou significativamente entre os ambientes.

No estuário, observou-se a predominância de espécies zoobentívoras e detritívoras e que a cadeia trófica é sustentada por diversas fontes (grande variação de $\delta^{13}C$), destacando se o POM (Matéria Orgânica Particulada), SOM (Matéria Orgânica no Sedimento), microfitobentos, zooplâncton, poliqueta e camarão. Os detritívoros gobíideos, localmente chamados de mingula, são altamente predados e/ou explorados pela pesca. Este grupo é capturado, principalmente como fauna acompanhante da pesca do camarão feita com o mangote e estudos feitos com conteúdo estomacal mostraram o mingula como item alimentar de várias espécies no canal. Os grandes predadores camurim (*Centropomus* spp.), xaréu (*Caranx* spp.) e barracuda (*Sphyraena* spp.) tem um alto impacto sobre os demais elos tróficos. A cadeia trófica estuarina mostrou uma menor variação de nitrogênio, ou seja, é uma cadeia mais curta do que a costeira. Este resultado é esperado para ambientes expostos a perturbações antrópicas, com maior resiliência, corroborado pelos indicadores ecológicos do modelo que mostraram que o ambiente é resiliente com boa capacidade de resistência a perturbações externas. Na costa, a cadeia trófica apresentou maiores valores de nitrogênio ($\delta^{15}N$), justificados pela predominância de espécies zoobentivoras e piscívoras, porém a assimilação de carbono foi menor do que no estuário, devido ao menor número de fontes disponíveis, principalmente os produtores (mangue, epifíton).

O Complexo Itapissuma/Itamaracá é considerado o mais produtivo do estado de Pernambuco e várias iniciativas como a criação da APA Santa Cruz, buscam a preservação e manejo dos recursos de forma o mais sustentável possível. Espera-se que as informações geradas por este estudo somadas às disponibilizadas por outras pesquisas contribuam para o manejo sustentável dos recursos do Complexo Itapissuma/Itamaracá. Vale ainda ressaltar a necessidade de estudos que investiguem a estrutura trófica dos rios que drenam o complexo e também os efeitos da pesca nos ecossistemas estuarinos e costeiros.

Embasadas nos resultados obtidos nesta Tese, algumas ações são sugeridas a fim de contribuir para o manejo sustentável dos recursos pesqueiros no Complexo Itapissuma/Itamaracá:

- Levantamento de dados sobre a produção pesqueira. A falta de informação limita inferências, simulações através de modelagem trófica (por ex: ECOSIM) e conclusões mais assertivas sobre os efeitos da pesca na estrutura trófica;
- Fiscalização e controle das atividades humanas como desmatamento e despejo de resíduos. A predominância de espécies zoobentívoras e detritívoras indica a importância que o substrato tem para os organismos bentônicos e, consequentemente, para a ictiofauna
- Manejo para as espécies consideradas espécies-chave no complexo por terem um alto impacto na cadeia trófica e uma grande importância comercial (camurim, xareu)
- Medidas que considerem o canal de Santa Cruz e o Mar de Dentro como áreas complementares e dependentes para a ictiofauna, e não de maneira isolada.

Vale também ressaltar algumas lacunas deste trabalho que devem ser consideradas e solucionadas nas futuras pesquisas através de:

- Informações detalhadas sobre a dieta dos organismos no estuário e na costa, pois algumas espécies mudam a dieta dependendo do tamanho e ambiente.

- Ampliação do número de fontes a serem analisadas através dos isótopos estáveis, principalmente no estuário, entre elas, capim marinho e organismos bentônicos

- Adição de outros grupos funcionais na modelagem: aves, caranguejos, pois a literatura e observações feitas na área mostram que muitas aves predam os peixes na maré baixa no canal de Santa Cruz.

- Aplicação do multi-ztanza, ferramenta do Ecopath que possibilita investigar grupos com diferentes idades ou tamanhos, e em diversas fases de vida (adultos e juvenis, por exemplo).

- Simulação temporal, através do Ecosim (modelagem dinâmica do Ecopath) para avaliar o efeito da pesca de espécies alvo (camarão, manjuba) na rede trófica.

- Investigação da conectividade entre os ambientes estuarino e costeiro através de outras ferramentas: microquímica de otólito, genética e dispersão de larvas.

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Anexos

Supplementary material - Capítulo 1

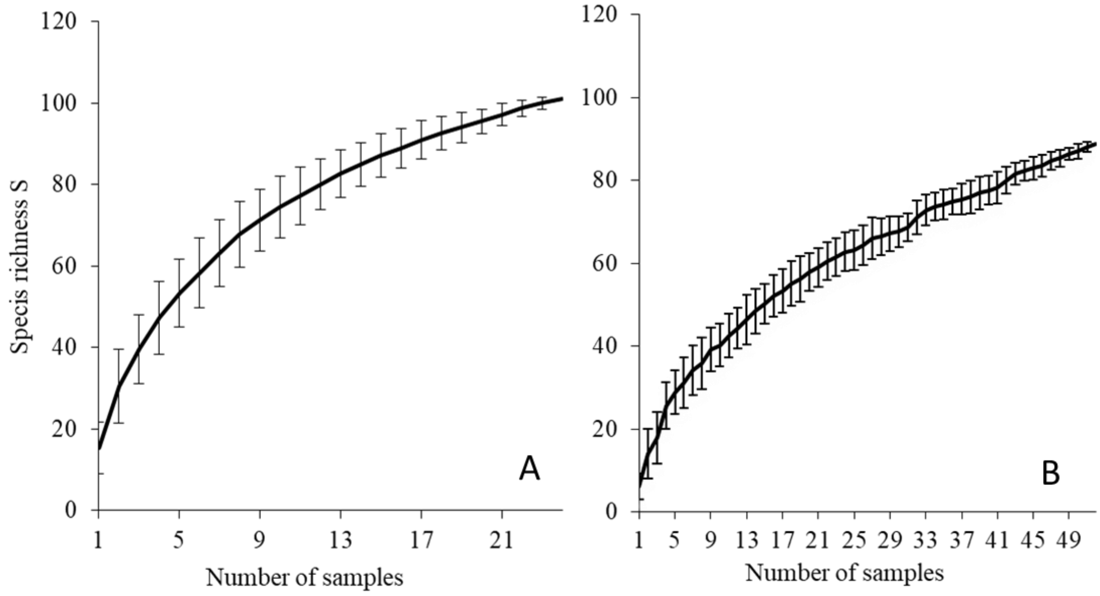

FIG S1. Species accumulation curve of the estuary (A) and coast (B) in the Itapissuma/Itamaracá Complex, northeastern Brazil, computed by a random method without replacement. Mean species richness value ± SD.

TABLE S1. Data collection dates according to the environmental and type of fishing gear utilised in the Itapissuma/Itamaracá Complex, northeastern Brazil.

Environmental	**Season**	**Fishing gear**	**Date**	**Set**
Estuary	Dry	Block net	January-13	1
			November-13	1
			March-14	1
		Seine net	January-13	3
			November-13	3
			March-14	3
	Rainy	Block net	May-13	1
			August-13	1
			May-14	1
		Seine net	May-13	3
			August-13	3
			May-14	3
Coast	Dry	Gill net	February-13	3
			November-13	3
			March-14	3
		Tidal fixed trap	February-13	6
			November-13	6
			February-14	6
	Rainy	Gill net	May-13	3
			August-13	3
			June-14	3
		Tidal fixed trap	May-13	6
			August-13	6
			May-14	6

TABLE S2. Literature utilised for classication of the ecologic guilds of the ichthyofauna captured in the Itapissuma/Itamaracá Complex, northeastern Brazil. EUFG-Estuarine Use Functional Groups; FMFG-Feeding Mode Functional Groups, basead Elliott *et al*. (2007).

Species	Reference	
	EUFG	FMFG
Rhizoprionodon porosus	Lessa & Almeida, 1997	Lessa & Almeida, 1997
Rhizoprionodon lalandii	Silva & Almeida, 2001	Bornatowski *et al*., 2012
Dasyatis guttata	Vasconcelos Filho & Oliveira, 1999	Gianeti, 2011
Dasyatis marianae	Shibuya & Rosa, 2011	Shibuya & Rosa 2011
Elops saurus	Vasconcelos Filho & Oliveira, 1999	Froese & Pauly, 2007
Gymnothorax funebris	Vasconcelos Filho & Oliveira, 1999	Froese & Pauly, 2007
Gymnothorax ocellatus	Froese & Pauly, 2007	Santos & Castro, 2003
Anchoa lyolepis	Froese & Pauly, 2007	Froese & Pauly, 2007
Anchoa marinii	Froese & Pauly, 2007	Froese & Pauly, 2007
Anchoa spinifer	Vasconcelos Filho & Oliveira, 1999	Nizinski & Munroe, 2002
Anchoa tricolor	Araújo *et al*., 2008	Araújo *et al*., 2008
Anchovia clupeoides	Vasconcelos Filho & Oliveira, 1999	Paiva *et al*., 2008
Cetengraulis edentulus	Vasconcelos Filho & Oliveira, 1999	Paiva *et al*., 2008
Engraulis anchoita	Froese & Pauly, 2007	Vasconcellos *et al*., 1998
Lycengraulis grossidens	Mai & Vieira, 2013	Bortoluzzi *et al*., 2006
Harengula clupeola	Vasconcelos Filho & Oliveira, 1999	Paiva *et al*., 2008

Opisthonema oglinum	Vasconcelos Filho & Oliveira, 1999	Vasconcelos Filho, 1979
Rhinosardinia bahiensis	Clarck & Pessanha, 2015	Clarck & Pessanha, 2015
Sardinella brasiliensis	Castello, 2007	Castello, 2007
Chaetodon ocellatus	Hailey, 2012	Hailey, 2012
Aspistor luniscutis	Denadai *et al.*, 2012	Denadai *et al.*, 2012
Aspistor quadriscutis	Denadai *et al.*, 2012	Denadai *et al.*, 2012
Bagre marinus	Segura-Berttolini & Mendoza-Carranza, 2013	Mendonza-Carranza, 2003
Cathorops agassizii	Dantas, 2012	Dantas, 2012
Cathorops spixii	Vasconcelos Filho & Oliveira, 1999	Possato, 2010
Sciades herzbergii	Vasconcelos Filho & Oliveira, 1999	Possato, 2010
Sciades proops	Vasconcelos Filho & Oliveira, 1999	Guedes & Vasconcelos Filho, 1980
Synodus foetens	Vasconcelos Filho & Oliveira, 1999	Cruz-Escalona *et al*., 2005
Batrachoides surinamensis	Froese & Pauly, 2007	Collette, 2010
Thalassophryne nattereri	Vasconcelos Filho & Oliveira, 1999	Sampaio & Nottingham, 2008
Guavina guavina	Vasconcelos Filho & Oliveira, 1999	Teixeira, 1994
Ctenogobius boleosoma	Vasconcelos Filho & Oliveira, 1999	Vasconcelos Filho *et al*., 2009
Ctenogobius shufeldti	Wyanski & Targett, 2000	Contente & Spach, 2012
Ctenogobius smaragdus	Vasconcelos Filho & Oliveira, 1999	Lima, 2015
Ctenogobius stigmaticus	Vasconcelos Filho & Oliveira, 1999	Lima, 2015
Evorthodus lyricus	Vasconcelos Filho & Oliveira, 1999	STRI

Gobionellus oceanicus	Vasconcelos Filho & Oliveira, 1999	Vasconcelos Filho *et al.*, 2009
Gobionellus stomatus	Vasconcelos Filho & Oliveira, 1999	Lima, 2015
Microgobius meeki	WoRMS, 2017	Froese & Pauly, 2007
Mugil curema	Vasconcelos Filho & Oliveira, 1999	Medeiros, 2013
Atherinella brasiliensis	Vasconcelos Filho & Oliveira, 1999	Paiva *et al.*, 2008
Tylosurus acus acus	WoRMS, 2017	Froese & Pauly, 2007
Hemiramphus brasiliensis	Vasconcelos Filho & Oliveira, 1999	Schwamborn, 2004
Hyporhamphus unifasciatus	Vasconcelos Filho & Oliveira, 1999	Trigueiro, 2013
Carangoides bartholomaei	Santos, 2012	Paiva *et al.*, 2008
Caranx crysos	Hailey, 2012	Sley *et al.*, 2009
Caranx hippos	Vasconcelos Filho & Oliveira, 1999	Temóteo *et al.*, 2015
Caranx latus	Vasconcelos Filho & Oliveira, 1999	Temóteo *et al.*, 2015
Caranx ruber	Hailey, 2012	Hailey, 2012
Chloroscombrus chrysurus	Vasconcelos Filho & Oliveira, 1999	Silva & Lopes, 2002
Oligoplites palometa	Vasconcelos Filho & Oliveira, 1999	Vasconcelos Filho *et al.*, 2010
Oligoplites saliens	Vasconcelos Filho & Oliveira, 1999	Winik *et al.*, 2007
Oligoplites saurus	Vasconcelos Filho & Oliveira, 1999	Vasconcelos Filho *et al.*, 2010
Selene brownii	WoRMS, 2017	Bomfim, 2014
Selene spixii	WoRMS, 2017	Froese & Pauly, 2007
Selene vômer	Vasconcelos Filho & Oliveira, 1999	Daros, 2014

Trachinotus carolinus	Denadai *et al*., 2013	Stefanoni, 2008
Trachinotus falcatus	Vasconcelos Filho & Oliveira, 1999	Hoflin *et al*., 1998
Trachinotus goodei	WoRMS, 2017	Stefanoni, 2008
Sphyraena barracuda	Vasconcelos Filho & Oliveira, 1999	Akadje *et al*., 2013
Sphyraena guachancho	Bonecker *et al*.; 2014	Lopes *et al*., 2012
Sphyraena viridensis	Barreiros *et al*., 2002	Barreiros *et al*., 2002
Citharichthys spilopterus	Vasconcelos Filho & Oliveira, 1999	Vasconcelos Filho *et al*., 2010
Etropus crossotus	Oliveira & Favarro, 2011	Paiva *et al*., 2008
Paralichthys brasiliensis	Vasconcelos Filho & Oliveira, 1999	Froese & Pauly, 2007
Syacium micrurum	Vasconcelos Filho & Oliveira, 1999	Lucato, 1997
Syacium papillosum	Lucato, 1997	Lucato, 1997
Lutjanus alexandrei	Fernandes *et al*., 2012	Moraes, 2012
Lutjanus analis	Vasconcelos Filho & Oliveira, 1999	Freitas *et al*., 2011
Lutjanus jocu	Vasconcelos Filho & Oliveira, 1999	Monteiro *et al*., 2009
Lutjanus synagris	Vasconcelos Filho & Oliveira, 1999	Hailey, 2012
Diapterus auratus	Vasconcelos Filho & Oliveira, 1999	Temóteo, 2015
Diapterus rhombeus	Vasconcelos Filho & Oliveira, 1999	Temóteo, 2015
Eucinostomus argenteus	Vasconcelos Filho & Oliveira, 1999	Leão, 2016
Eucinostomus gula	Vasconcelos Filho & Oliveira, 1999	Zahorcsak *et al*., 2000
Eucinostomus havana	Vasconcelos Filho & Oliveira, 1999	Froese & Pauly, 2007

Eucinostomus melanopterus	Chaves & Bouchereau, 2000	Araújo *et al*., 2016
Eugerres brasilianus	Vasconcelos Filho & Oliveira, 1999	Vasconcelos Filho *et al*., 2009
Anisotremus moricandi	Dias, 2007	Dias, 2007
Anisotremus virginicus	Vasconcelos Filho & Oliveira, 1999	Dias, 2007
Conodon nobilis	Vasconcelos Filho & Oliveira, 1999	Lira *et al*., 2013a
Genyatremus luteus	Vasconcelos Filho & Oliveira, 1999	Almeida *et al*., 2005
Haemulon aurolineatum	Vasconcelos Filho & Oliveira, 1999	Dantas, 2012
Haemulon parra	Vasconcelos Filho & Oliveira, 1999	Paiva *et al*., 2008
Haemulon plumierii	Shinozaki-Mendes *et al*., 2013	Costa & Silva, 2015
Haemulon steindachneri	Daros, 2014	Daros, 2014
Pomadasys corvinaeformis	Vasconcelos Filho & Oliveira, 1999	Denadai *et al*., 2013
Pomadasys crocro	Froese & Pauly, 2007	Froese & Pauly, 2007
Polydactylus virginicus	Vasconcelos Filho & Oliveira, 1999	Lopes & Oliveira-Silva, 1998
Bairdiella ronchus	Vasconcelos Filho & Oliveira, 1999	Pina *et al*., 2015
Cynoscion virescens	Froese & Pauly, 2007	Froese & Pauly, 2007
Isopisthus parvipinnis	Silva Junior *et al*., 2015	Lira *et al*., 2013b
Larimus breviceps	Bessa *et al*., 2014	Bessa *et al*., 2014
Menticirrhus americanus	Haluch *et al*., 2011	Lira *et al*., 2013c
Paralonchurus brasiliensis	Silva Junior *et al*., 2015	Lira *et al*., 2013d
Stellifer stellifer	Dantas, 2012	Pombo *et al*., 2013

Pseudupeneus maculatus	Vasconcelos Filho & Oliveira, 1999	Dantas, 2012
Halichoeres radiatus	Froese & Pauly, 2007	Froese & Pauly, 2007
Sparisoma radians	Vasconcelos Filho & Oliveira, 1999	Paiva *et al.*, 2008
Sparisoma axillare	Feitosa & Ferreira, 2014	Feitosa & Ferreira, 2014
Sparisoma aff. *amplum*	Francini-Filho *et al.*, 2008	Francini-Filho *et al.*, 2008
Chaetodipterus faber	Froese & Pauly, 2007	Vasconcelos Filho *et al.*, 2009
Pomacanthus paru	Vasconcelos Filho & Oliveira, 1999	Cerqueira & Haimovici, 1990
Prionotus punctatus	Vasconcelos Filho & Oliveira, 1999	Longo *et al.*, 2015
Centropomus parallelus	Vasconcelos Filho & Oliveira, 1999	Lira *et al.*, 2016
Centropomus pectinatus	Jackson & Bockelmann-lobello, 2006	Lira *et al.*, 2016
Centropomus undecimalis	Vasconcelos Filho & Oliveira, 1999	Lira *et al.*, 2016
Epinephelus adscensionis	Nelson *et al.*, 2006	Medeiros *et al.*, 2017
Epinephelus marginatus	Andrade *et al.*, 2003	Machado *et al.*, 2008
Mycteroperca bonaci	Daros, 2014	Daros, 2014
Trichiurus lepturus	Vasconcelos Filho & Oliveira, 1999	Vasconcelos Filho *et al.*, 2010
Scomberomorus brasiliensis	Vasconcelos Filho & Oliveira, 1999	Menezes, 1970
Bothus ocellatus	Vasconcelos Filho & Oliveira, 1999	Hostim-Silva *et al.*, 2005
Achirus declivis	Vasconcelos Filho & Oliveira, 1999	Couto & Farias, 2011
Achirus lineatus	Vasconcelos Filho & Oliveira, 1999	Vasconcelos Filho *et al.*, 2003
Trinectes paulistanus	Vasconcelos Filho & Oliveira, 1999	Contente *et al.*, 2009

Symphurus tessellatus	Pina, 2009	Lima, 2012
Acanthurus bahianus	Vasconcelos Filho & Oliveira, 1999	Pimentel, 2012
Acanthurus chirurgus	Vasconcelos Filho & Oliveira, 1999	Longo *et al.*, 2015
Acanthurus coeruleus	Longo *et al.*, 2015	Longo *et al.*, 2015
Archosargus probatocephalus	Castilho Rivera *et al*., 2007	Castilho Rivera *et al*., 2007
Archosargus rhomboidalis	Vasconcelos Filho & Oliveira, 1999	Yáñez-Arancibia *et al*., 1986
Lactophrys trigonus	Paiva *et al.*, 2008	Froese & Pauly, 2007
Colomesus psittacus	Vasconcelos Filho & Oliveira, 1999	Araujo, 2012
Sphoeroides greeleyi	Schultz, 2002	Lima, 2014
Sphoeroides testudineus	Vasconcelos Filho & Oliveira, 1999	Vasconcellos *et al*., 1998
Chilomycterus spinosus	Vasconcelos Filho & Oliveira, 1999	Almeida-Silva *et al*., 2015

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Supplementary material - Capítulo 2

Table I (Supplementary). Code and standart length amplitude of samples from Itapissuma/Itamaracá Complex, Northeastern Brazil.

		Estuary		Coast	
Group/specie	Code	n	$SL_{min-max}$	n	$SL_{min-max}$
Particulate organic matter	pom	6		6	
Sedimentary organic matter	som	6		6	
Microphytobenthos	m.fit	3		3	
Epiphyton	epif	6			
Avicennia sp.	a.sp	6			
Laguncularia racemosa	l.rac	12			
Rhizophora mangle	r.man	12			
Sargassum sp.	s.sp	6		6	
Ulva sp.	ulva	6		6	
Polychaeta	pol	6			
Olygochaeta	oli	3			
Anomalocardia brasiliana	an.bra	6	2.0 - 2.5	6	2.1 - 3.4
Crassostrea rhizophorae	c.rhi	6	3.1 - 4.4		
Copepoda	cop	6			
Callinectes danae	c.dan	6	4.8 - 8.6	6	4.2 - 7.2
Farfantepenaeus subtilis	f.sub	6	1.6 - 2.2		
Litopenaeus schmitii	l.sch	3	2.4 - 2.6		
Sparisoma axillare	s.axi	3	6.8 - 12.1	3	23.2 - 25.6
Gobionellus oceanicus	g.oce	6	11.3 - 18.2		
Gobionellus stomatus	g.sto	6	7.8 - 8.2		
Mugil curema	m.cur	3	13.9 - 14	3	21.5 - 21.9
Atherinella brasiliensis	at.bra			6	9.0 – 11.0
Achirus lineatus	a.lin	6	4.0 - 5.1		
Citharichthys spilopterus	c.spi	6	5.1 - 13.2		
Diapterus auratus	d.aur	6	7.3 - 9.7	6	11.9 - 25.2
Eucinostomus argenteus	e.arg	6	6.3 - 10.9		
Lutjanus analis	l.ana	6	10.3 - 11.4	6	27.5 - 31.8
Micropogonias furnieri	m.fur	2	17.4 – 18.0	5	36.5 – 44.0
Opisthonema oglinum	o.ogl	6	10.1 - 13.2	6	9.8 - 17.2
Bairdiella ronchus	b.ron	6	13.4 - 16.6		
Caranx hippos	c.hip	4	13.9 - 16.4	5	24.0 - 68.0
Centropomus parallelus	c.par	6	18.0 - 25		
Centropomus undecimalis	c.und	6	21.5 - 33.2	3	40.7 - 43.5

Supplementary material - Capítulo 3

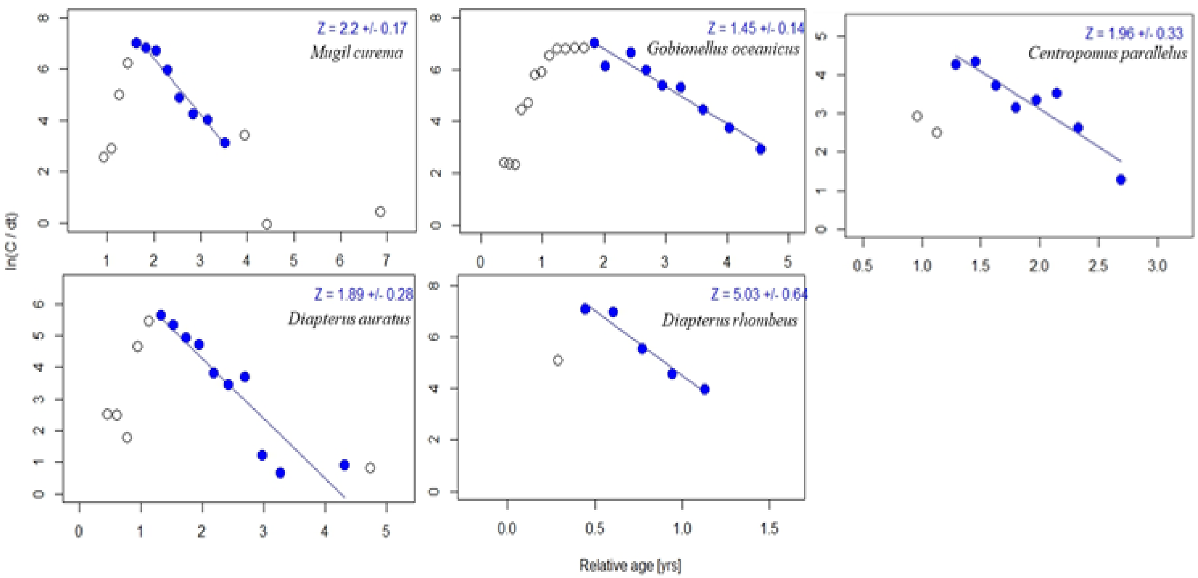

Figure S.1. Linearized length converted catch curve to estimate total mortality (Z ± SE) (Chapman and Robson, 1960; Pauly, 1983) for the some fish species caught by local fishery of Santa Cruz Channel estuary, Northeastern Brazil.

Table S.1. Mean fishery landings of catches carried out in Itapissuma, Northeastern Brazil, from 2000 to 2007 (t) for each functional group.

	Bivalve	Blue crab	Shrimp	Herring	Mullet	Snook	Jack	*Diapterus* spp.	*Sparisoma radians*
2000		12.8	127	364.3	31.1	6.4	4.6	0.1	15.8
2001	1.2	1.9	70.8	266.2	19.1	6.4		0.9	0.4
2002	301.1	6.3	93.0	748.8	163.1	15.2	0.2		4.2
2003	40.3		78.9	922.1	0.4	6.3			3.1
2004	599.1	82.2	99.9	463.6	197.3	20.9	19.1	2.9	19.2
2005	658.3	1123.7	224.8	63.7	345.6	1.5	0.1		0.1
2006	923.9	805.0	189.1	1713.2	288.0	9.4	8.2	0.9	8.2
2007	1246.4	167.7	147.8	652.1	22.2	47.9	0.5	22.8	1.4
/year	471.29	274.95	128.92	649.25	133.35	14.26	4.09	3.95	6.55
t/km^2/year	8.38	4.89	2.29	11.55	2.37	0.25	0.07	0.07	0.11

Table S.2. Biomass (t.km^{-2}) of fish in the Santa Cruz Channel estuary, Northeastern Brazil. q*L* = mean catchability coefficient (based on similar groups of Lauretta et al. (2013)), p = mean proportion of the population captured by the fishing gear, B_o = observed biomass, B_c = corrected biomass obtained as p*B_o.

Functional group	B_o(t.km^{-2})	q*L*	p	B_c (t.km^{-2})	Caudal fin form
Herring					
Clupeiformes	0.0230	0.814	0.0067	3.3972	A
Anchovies	0.0020	0.814	0.0067	0.3014	A
Batrachoididae	0.0036	0.365	0.0030	1.2009	B
Mullet	0.0005	0.814	0.0067	0.0844	A
Hyporhamphus unifasciatus	0.0025	0.814	0.0067	0.3794	A
Snook	0.0002	0.688	0.0057	0.0485	D
Jack	0.0013	0.688	0.0057	0.2408	D
Oligoplites spp.	0.0002	0.688	0.0057	0.0477	D
Snapper	0.0007	0.582	0.0048	0.1577	E
Lutjanus spp.	0.0012	0.582	0.0048	0.2598	E
Diapterus spp.	0.0043	0.688	0.0057	0.7632	D
Eucinostomus spp.	0.0148	0.688	0.0057	2.5864	D
Archosargus rhomboidalis	0.0093	0.582	0.0048	1.9189	E
Sparisoma radians	0.0003	0.582	0.0048	0.0717	E
Gobionellus stomatus	0.1735	0.365	0.0187	9.2652	B
Gobionellus oceanicus	0.0853	0.365	0.0187	4.5541	B
Gobiidae	0.0102	0.365	0.0187	0.5467	B
Sphyraena spp.	0.0009	0.715	0.0059	0.1523	D
Citharichthys spilopterus	0.0022	0.54	0.0044	0.5098	B
Flatfish	0.0026	0.54	0.0044	0.5983	B
Puffer	0.0357	0.748	0.0062	5.7434	C
Caudal fin shape					

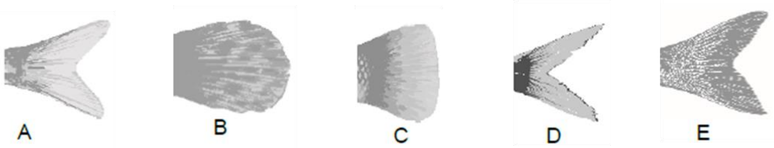

Table S.3. Parameters and references used for the estimation of P/B in the Santa Cruz Channel estuary, Northeastern Brazil. L_{max} is the maximum length captured of the species (cm); L_∞ is the asymptotic length (cm) and k is growth coefficient. $^*L_\infty$ and k were based on the empirical relationships: $\log L_\infty = 0.044+0.9841^*\log(L_{max})$ (Froese and Binohlan, 2000) and $k=2.15^*L_\infty^{-0.46}$ (Le Quesne and Jennings, 2012).

Functional group	L_{max} (cm)	L_∞ (cm)	k	Reference
Herring		33.7	1.2	Lessa et al. (2008)
Clupeiformes		15.6	1.05	Souza-Conceição and Schwingel (2011)
Anchovies*	15	15.89	0.60	Viana et al. (2016)
Batrachoididae*	28	29.38	0.45	Viana et al. (2016)
Mullet		38.01	0.36	Santana et al. (2009)
*Hyporhamphus unifasciatus**	21.3	22.45	0.51	Gondolo (2008)
Snook		140.8	0.07	Mendonça (2004)
Jack*	124	127.09	0.23	Cervigón et al. (1992)
Oligoplites spp.*	35	36.60	0.41	Cervigón et al. (1992)
Snapper		77.22	0.11	Rezende and Ferreira (2004)
Lutjanus spp.		77.22	0.11	Rezende and Ferreira, 2004
Diapterus spp.		44.1	0.24	Elliff et al. (2013)
Eucinostomus spp.		28.31	0.61	Silva et al. (2014)
*Archosargus rhomboidalis**	32.5	34.02	0.42	Cervigón et al. (1992)
Sparisoma radians		33.6	0.41	Lessa et al. (2015)
*Gobionellus stomatus**	24.9	26.18	0.47	Viana et al. (2016)
*Gobionellus oceanicus**	27.9	29.28	0.45	Viana et al. (2016)
Gobiidae*	20.3	21.41	0.52	Viana et al. (2016)
Sphyraena spp.*	150	153.28	0.21	Cervigón et al. (1992)
*Citharichthys spilopterus**	20	21.10	0.52	Cervigón et al. (1992)
Flatfish*	18.1	19.12	0.55	Viana et al. (2016)
Puffer		29.5	0.77	Tzeek-Tuz et al. (2012)

Table S.4. Parameters used as input for the estimation of the annual food consumption/biomass ratio (Q/B) of the fish group, in the Santa Cruz Channel estuary, Northeastern Brazil. W_∞ = asymptotic weight, obtained from equation $W_\infty = a.\ L_\infty^b$, where, a = regression intercept; b = regression slope (see Viana et al., 2016). H and D represent the feeding type: H = 1 and D = 0 for herbivores, H = 0 and D = 1 for detritivores, H = 0 and D = 0 for carnivores. **Ar = aspect ratio of the caudal fin: $Ar = h^2/s$, where, h = height of caudal fin and s = surface area of the caudal fin (based on Palomares and Pauly, 1998).

Functional group	a	b	*W∞ (g)	H	D	h (mm)	s (mm^2)	**Ar
Herring	0.0082	3.01	325.07	0	0	38.44	362.39	4.07
Clupeiformes	0.0068	3.09	33.057	0	0	19.38	114.61	3.27
Anchovies	0.0051	3.13	29.37	0	0	24.23	420.87	1.39
Batrachoididae	0.0117	3.23	646.10	0	0	9.63	215.3258	0.43
Mullet	0.0110	2.98	561.67	0	1	74.97	2030.53	2.76
Hyporhamphus unifasciatus	0.7900	3.91	151721.60	0	0	65.80	2135.8	2.02
Snook	0.0055	3.13	29207.14	0	0	57.44	1606.55	2.05
Jack	0.0126	2.97	20788.97	0	0	46.02	669.58	3.16
Oligoplites spp.	0.0151	2.75	301.05	0	0	45.03	678.54	2.98
Snapper	0.0122	3.07	7615.35	0	0	36.06	629.6	2.06
Lutjanus spp.	0.0146	3.09	10159.60	0	0	36.84	790.83	1.71
Diapterus spp.	0.0098	3.09	1204.38	0	0	38.09	480.34	3.02
Eucinostomus spp.	0.0079	3.19	344.01	0	0	18.85	221.32	1.60
Archosargus rhomboidalis	0.0126	3.14	813.50	0	0	6.2	74.91	0.51
Sparisoma radians	0.0057	3.42	946.13	1	0	7.5	59.38	0.94
Gobionellus stomatus	0.0054	2.93	77.11	0	1	14.7	363.3	0.59
Gobionellus oceanicus	0.0061	2.87	98.74	0	1	9.53	216.32	0.41
Gobiidae	0.0069	3.14	105.66	0	1	7.47	94.28	0.59
Sphyraena spp.	0.0091	2.77	10299.98	0	0	58.9	1703.55	2.03
Citharichthys spilopterus	0.0050	3.23	94.75	0	0	8.89	104.34	0.75
Flatfish	0.0091	3.22	121.91	0	0	19.57	394.08	0.97
Puffer	0.2150	2.90	3934.79	0	0	18.53	458	0.74

Table S.5. Input data and references by functional group for the Santa Cruz Channel estuary, Northeastern Brazil. B: biomass; P/B: production per unit of biomass; Q/B: consumption rate per unit of biomass; EE: ecotrophic efficiency.

Functional group	**Parameter**	**Reference**	**Species aggregation**	**Trophic guild**
Epiphyton	Biomass	Baltar et al. (1996)	Epiphyton	Producer
	P/B	Baltar et al. (1996)		
	EE	Estimation from Ecopath		
Microphytobenthos	Biomass	Estimation from Ecopath	Microphytobenthos	Producer
	P/B	Underwood and Kromkamp (1999); Migné et al. 2009)		
	EE	Wolff et al. (2000)		
Phytoplankton	Biomass	Figueiredo et al. (2006)	Phytoplankton	Producer
	P/B	Silva (2009)		
	EE	Estimation from Ecopath		
Zooplankton	Biomass	Estimation from Ecopath	Zooplankton	Primary consumer
	P/B	Albouy et al. (2010); Angelini and Vaz-Velho (2011); Chen et al. (2015); Villanueva (2015); Chea et al. (2016)		
	Q/B	Albouy et al. (2010); Angelini and Vaz-Velho (2011); Chen et al. (2015); Villanueva (2015); Chea et al. (2016)		
	EE	Albouy et al. (2010); Angelini and Vaz-Velho (2011); Chen et al. (2015); Villanueva (2015); Chea et al. (2016)		
	Diet	Kleppel et al. (1996); Schwamborn (1997); Schnetzer and Steinberg (2002)		
Bivalves	Biomass	El_Deir et al. (2009)	*Anomalocardia brasiliana*	Filter

	P/B	Opitz (1996)	(Gmelin, 1791)	
	Q/B	Opitz (1996)		
	Diet	Azevedo (1980)		
	EE	Estimation from Ecopath		
Gastropods	Biomass	Estimation from Ecopath	*Neritina virginea*	Grazer
	P/B	Brey (1999); Absalao et al. (2009)	(Linnaeus, 1758)	
	Q/B	Nichols (1974)		
	EE	Albouy et al. (2010)		
	Diet	Da Cunha Lana and Guiss (1991); Opitz (1996); Blanco and Scatena (2007)		
Worms	Biomass	Estimation from Ecopath	Polychaeta, Olygochaeta, Nematoda	Deposit-feeder
	P/B	Santos (1994); Brey (1999); Souza and Borzone (2007); Otegui et al. (2012)		
	Q/B	Nichols (1974)		
	EE	Milessi et al. (2010		
	Diet	Opitz (1996)		
Shrimp	Biomass	Estimation from Ecopath	*Farfantepenaeus subtilis*	Detritivore
	P/B	Opitz (1996)	(Pérez Farfante, 1967)	
	Q/B	Opitz (1996)	*Litopenaeus schmitti*	
	EE	Albouy et al (2010); Du et al (2015); Zetina-Rejón et al (2015)	(Burkenroad, 1936)	
	Diet	Moriarty and Barclay (1981); Newell et al. (1995); Branco et al. (2001)		
Herring	Biomass	Estimation from Ecopath	*Opisthonema oglinum*	Zooplanktivore
	P/B	Estimation from Pauly (1980)	(Lesueur, 1818)	
	Q/B	Estimation from Palomares and Pauly (1998)		

	Diet	Vasconcelos Filho et al. (2003)		
Clupeiformes	Biomass	Estimated by this study	*Anchoa lyolepis* (Evermann & Marsh, 1900); *Anchoa marinii* Hildebrand, 1943;	Zooplanktivore
	P/B	Estimation from Pauly (1980)	*Anchovia clupeoides* (Swainson, 1839); *Cetengraulis edentulus* (Cuvier, 1829); *Chirocentrodon bleekerianus* (Poey, 1867);	
	Q/B	Estimation from Palomares and Pauly (1998)	*Platanichthys platana* (Regan, 1971); *Rhinosardinia bahiensis* (Steindachner, 1879)	
	Diet	Vasconcelos Filho et al. (2003)		
Anchovies	Biomass	Estimated by this study	*Anchoa tricolor* (Spix & Agassiz, 1829);	Zoobenthivore
	P/B	Estimation from Pauly (1980)	*Anchoa spinifer* (Valenciennes, 1848);	
	Q/B	Estimation from Palomares and Pauly (1998)		
	Diet	Vasconcelos Filho et al. (2003)	*Lycengraulis grossidens* (Spix & Agassiz, 1829)	Piscivore
Batrachoididae	Biomass	Estimated by this study	*Batrachoides surinamensis* (Bloch & Schneider, 1801); *Thalassophryne nattereri* Steindachner, 1876	Zoobenthivore
	P/B	Estimation from Pauly (1980)		
	Q/B	Estimation from Palomares and Pauly (1998)		

	Diet	Fishbase		
Mullet	Biomass	Estimated by this study	*Mugil curema* Valenciennes, 1836	Detritivore
	P/B	Z=P/B from Allen (1971)		
	Q/B	Estimation from Palomares and Pauly (1998)		
	Diet	Vasconcelos Filho et al. (2003)		
Hyporhamphus unifasciatus	Biomass	Estimated by this study	*Hyporhamphus unifasciatus* Ranzani, 1841	Omnivore
	P/B	Estimation from Pauly (1980)		
	Q/B	Estimation from Palomares and Pauly (1998)		
	Diet	Vasconcelos Filho et al. (2003)		
Snook	Biomass	Estimated by this study	*Centropomus parallelus* Poey, 1860;	Piscivore
	P/B	Z=P/B from Allen (1971)	*Centropomus pectinatus* Poey, 1860;	
	Q/B	Estimation from Palomares and Pauly (1998)	*Centropomus undecimalis* (Bloch, 1792)	
	Diet	Lira et al. (2017)		
Jack	Biomass	Estimated by this study	*Caranx crysos* (Mitchill, 1815);	Piscivore
	P/B	Estimation from Pauly (1980)	*Caranx hippos* (Linnaeus, 1766);	
	Q/B	Estimation from Palomares and Pauly (1998)	*Caranx latus* Agassiz, 1831;	Zoobenthivore
	Diet	Vasconcelos Filho et al. (2003); Temoteo et al. (2015)	*Chloroscombrus chrysurus* (Linnaeus, 1766)	

Oligoplites spp.	Biomass	Estimated by this study	*Oligoplites palometa* (Cuvier, 1832)	Piscivore
	P/B	Estimation from Pauly (1980)	*Oligoplites saliens* (Bloch, 1793);	
	Q/B	Estimation from Palomares and Pauly (1998)	*Oligoplites saurus* (Bloch & Schneider, 1801)	
	Diet	Vasconcelos Filho et al. (2010)		
Snapper	Biomass	Estimated by this study	*Lutjanus analis* (Cuvier, 1828)	Zoobenthivore
	P/B	Estimation from Pauly (1980)		
	Q/B	Estimation from Palomares and Pauly (1998)		
	Diet	Freitas et al. (2011)		
Lutjanus spp.	Biomass	Estimated by this study	*Lutjanus alexandrei* Moura & Lindeman, 2007;	Zoobenthivore
	P/B	Estimation from Pauly (1980)	*Lutjanus jocu* (Bloch & Schneider, 1801);	
	Q/B	Estimation from Palomares and Pauly (1998)	*Lutjanus synagris* (Linnaeus, 1758)	
	Diet	Monteiro et al. (2009), Moraes (2012)		
Diapterus spp.	Biomass	Estimated by this study	*Diapterus auratus* Ranzani, 1842;	Zoobenthivore
	P/B	Z=P/B from Allen (1971)		
	Q/B	Estimation from Palomares and Pauly (1998)	Diapterus rhombeus (Cuvier, 1829)	
	Diet	Temoteo et al. (2015)		
Archosargus romboidalis	Biomass	Estimated by this study	*Archosargus rhomboi*dalis (Linnaeus, 1758)	Zoobenthivore
	P/B	Estimation from Pauly (1980)		
	Q/B	Estimation from Palomares and Pauly (1998)		
	Diet	Fishbase		

Sparisoma radians	Biomass	Estimated by this study	*Sparisoma radians* (Valenciennes, 1840)	Herbivore
	P/B	Estimation from Pauly (1980)		
	Q/B	Optiz (1996)		
	Diet	Fishbase		
Gobionelus stomatus	Biomass	Estimated by this study	*Gobionelus stomatus Starks, 1913*	
	P/B	Estimation from Pauly (1980)		
	Q/B	Estimation from Palomares and Pauly (1998)		
	Diet	Lima (2015)		
Gobionellus oceanicus	Biomass	Estimated by this study	*Gobionellus oceanicus* (Pallas, 1770)	Detritivore
	P/B	Z=P/B from Allen (1971)		
	Q/B	Estimation from Palomares and Pauly (1998)		
	Diet	Vasconcelos Filho et al. (2009)		
Gobiidae	Biomass	Estimated by this study	*Ctenogobius boleosoma* (Jordan & Gilbert, 1882); Ctenogobius smaragdus (Valenciennes, 1837)	Detritivore
	P/B	Estimation from Pauly (1980)	Ctenogobius stigmaticus (Poey, 1860)	
	Q/B	Estimation from Palomares and Pauly (1998)	Ctenogobius shufeldti (Jordan & Eigenmann, 1887); *Bathygobius*	Omnivore
	Diet	Silva (2004)	*soporator* (Valenciennes, 1837)*;Microgobius meeki* Evermann & Marsh, 1899	Zoobenthivore

Sphyraena spp.	Biomass	Estimated by this study	*Sphyraena barracuda* (Edwards, 1771)	Piscivore
	P/B	Estimation from Pauly (1980)		
	Q/B	Estimation from Palomares and Pauly (1998)	*Sphyraena guachancho* Cuvier, 1829	
	Diet	Vasconcelos Filho et al. (2003)		
Citharichthys spilopterus	Biomass	Estimated by this study	*Citharichthys spilopterus* Günther, 1862	Zoobenthivore
	P/B	Estimation from Pauly (1980)		
	Q/B	Estimation from Palomares and Pauly (1998)		
	Diet	Vasconcelos Filho et al. (2010)		
Flatfish	Biomass	Estimated by this study	*Etropus crossotus* Jordan e Gilbert, 1882, *Etropus longimanus* (Norman, 1933),	Zoobenthivore
	P/B	Estimation from Pauly (1980)	*Paralichthys brasiliensis* (Ranzani, 1842)	
	Q/B	Estimation from Palomares and Pauly (1998)	*Achirus declivis* Chabanaud, 1940	
	Diet	Vasconcelos Filho et al. (2003); Vasconcelos Filho et al. (2010)	*Achirus lineatus* (Linnaeus, 1758)	
Puffer	Biomass	Estimated by this study	*Lagocephalus laevigatus* (Linnaeus, 1766)	Zoobenthivore
	P/B	Estimation from Pauly (1980)	*Sphoeroides greeleyi* Gilbert, 1900	
	Q/B	Estimation from Palomares and Pauly (1998)	*Sphoeroides testudineus*	
	Diet	Vasconcelos Filho et al. (2010); Barros et al. (2014)	(Linnaeus, 1758) (Linnaeus, 1758)	

Table S.6. Production/consumption and respiration rates used for evaluating the balance of the Santa Cruz Channel estuary model, Northeastern Brazil.

Functional group	Production/ Consumption	Respiration/ Assimilation	Respiration/ Biomass (/year)
Zooplankton	0.33	0.58	70.31
Bivalves	0.22	0.72	5.20
Gastropods	0.06	0.91	28.41
Worms	0.16	0.78	10.9
Blue crab	0.25	0.68	4.40
Shrimps	0.10	0.86	18.71
Herrings	0.10	0.82	9.61
Clupeiformes	0.08	0.85	13.60
Anchovies	0.08	0.86	9.77
Batrachoididae	0.13	0.83	5.58
Mullet	0.06	0.89	18.01
Hyporhamphus unifasciatus	0.25	0.68	2.47
Snook	0.32	0.59	2.84
Jack	0.06	0.91	5.08
Oligoplites spp.	0.06	0.92	11.78
Snapper	0.04	0.93	5.20
Lutjanus spp.	0.05	0.93	4.54
Diapterus spp.	0.33	0.57	5.59
Eucinostomus spp.	0.11	0.85	8.18
Archosargus rhomboidalis	0.12	0.84	5.47
Sparisoma radians	0.03	0.94	16.47
Gobionellus stomatus	0.03	0.94	18.82
Gobionellus oceanicus	0.04	0.92	16.47
Gobiidae	0.04	0.92	17.42
Sphyraena spp.	0.06	0.91	4.75
Citharichthys spilopterus	0.10	0.87	9.21
Flatfish	0.10	0.86	9.02
Puffer	0.25	0.68	3.36