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Contrasting tropical estuarine ecosystem functioning and stability: A comparative study

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A B S T R A C T

A comparative study of the Sine-saloum (Senegal) and Gambia (The Gambia) estuaries was performed based on trophic model outputs that describe the system structure and functioning. These trophic models were constructed such as to differentiate main energetic flows in the systems and express how climate change may have impacted ecosystem resilience to change. Estuarine fish assemblages are highly resilient despite exposure to vast hydrodynamic variations and stress. Coupled with strong anthropogenic-driven stresses such as fisheries and climate change, ecosystems may undergo severe regime shifts that may weaken their resilience and stability. Taxonomically related and morphologically similar species do not necessarily play similar ecological roles in these two ecosystems. Biomass and production in the Sine-saloum are concentrated at trophic levels (*TLs*) 2 and 3, while for the Gambia, both are concentrated at *TL3*. Higher *TL* biomasses in Gambia compared to Sine-Saloum may be explained by the latter ecosystem being characterized by inverse hypersalinity. Higher *TL* of production in Sine-Saloum is due to higher exploitations compared to Gambia where fishing activities are still less developed. High production and consumption rates of some groups in both ecosystems indicate high system productivity. Elevated productivity may be due to higher abundance of juvenile fishes in most groups that utilize the latter as refuge and/or nursery zones. Both ecosystems are phytoplankton-driven. Differences in group trophic and ecological roles are mainly due to adaptive responses of these species to seasonal and long-term climate and anthropogenic stressors. System indicators suggest different levels of ecosystem resilience and stability as a function of biodiversity. Relevance of other observations on ecosystem functioning and indicators in relation to perturbation is discussed.

1. Introduction

Tropical estuaries are considered as biogeochemical hotspots due to high levels of primary production, large reserves of organic matter and habitat diversity that offer optimal niches for numerous aquatic species which utilize these areas as refuge and/or nursery grounds and anthropogenic pressures on ecosystems (Baran, 2000; Cloern et al., 2013). Production in estuaries and coastal lagoons tend to be 10–15 times higher than those of other continental shelves (Duarte, 1995).

As transitional areas with intense fluctuations of environmental conditions, these ecosystems influence multi-species dynamics and impose physiological constraints on biota (Baran, 2000). Estuaries are often shallow with highly varying hydrological regimes and are structured by marine-freshwater inflows and bio-geographic regions (Whitfield et al., 2012). Biodiversity varies as a function of marine and/or continental water flows into these 'intermediate' systems (Deegan and Garritt, 1997; Blaber, 2002). Species abundance trends tend to decrease as salt marshes increase (Struyf et al., 2004; Ferreira et al., 2005). Changes in environmental conditions generally provoke diverse biological responses, allowing only tolerant species to persist (Glaser, 2003; Taylor et al., 2014).

Drivers to ecosystem changes include natural and anthropogenic processes. Due to their location, and the multitude of ecological services they provide, estuarine areas often attract large human populations, and thus the risks of environment degradation are also high (Glaser, 2003; Lotze et al., 2006). In developing countries, development of artisanal/traditional and industrialized fisheries and aquaculture in these ecosystems have also been growing, to meet increasing demand for local consumption and export (Welcomme, 2002; Lalèyè et al., 2007). However, fisheries usually target not only highly commercial stocks, but also impacts

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forage species, consequently impacting the dynamics of the entire ecosystem (Sadovy, 2001).

Apart from fisheries, another human-related threat to coastal wetlands is climate change. Five estuarine environmental factors can be impacted as a response to climate change: sea level, intensity and frequency of rainfall, salinity, freshwater-sediments-nutrients inputs and water circulation (Kennedy, 1990). Negative impacts of seasonal hydrologic regimes (Ponce Campus et al., 2013; Taylor et al., 2014) and global climate change (Kennedy, 1990; Alongi, 2008; James et al., 2013) on estuaries are well documented. Changes affect individual bio-ecological processes (i.e., osmoregulation, growth, reproduction) and community abundance and distribution. These eco-geomorphological alterations can have negative impact on biodiversity that can disrupt system integrity, leading to changes in structure, functioning, dynamics and productivity (Roessig et al., 2004; Ferreira et al., 2005).

In this study, two West African estuaries are considered and compared. As transitional ecosystems, they are noted for their high taxonomic richness due to a succession of species utilizing these environments as nurseries and refugia. Due to the limited geographical distance between these estuaries, close similarities of marine and estuarine fish faunas have been observed (Baran, 2000). However, differences in hydrological regimes have led to contrasting observations on fish ecology and utilization of these environments (Diouf, 1996; Vidy, 2000; Vidy et al., 2004; Villanueva, 2004; Panfili et al., 2006).

As highly productive and complex ecosystems, knowledge on the biological and ecological functioning of fish faunas utilizing, as well as, the environmental forces contributing to geographic specificities of these environments is vital for sustainable management and conservation of these ecosystems. Recognizing that anthropogenic activities impact not only on the environment, but the dynamics and functioning of its living resources, untangling ecosystem processes can increase understanding on its current health and resilience to change. An ecosystem-based approach that can synthesize multi-specific analyses and the combined influence of their characteristics (i.e., production, mortality, trophic interactions, physiological adaptation, etc.) following environmental changes can be valuable to understand and manage such fragile ecosystems (Imperial and Hennessey, 1996).

This study attempts to summarize and integrate existing data and to draw a larger picture of interactions among biological components and how abiotic conditions mould the structure and functioning of these ecosystems. This is also a comparative study of two systems with severely contrasting hydrological regimes: a 'normal', less exploited estuary (The Gambia) and an 'inverse hypersaline', highly exploited system (Sine-Saloum). Trophic models of these ecosystems are constructed in order to quantify energetic flows, trophodynamic links and transfer efficiencies among trophic levels (*TLs*) and identify differences in the species ecological functioning and ecosystem structure as adaptive response to contrasting hydrological regimes. Modelling ecological systems can be valuable in describing how an ecosystem is organized and how changes can affect system internal processes (Berlow et al., 2004). Modelling can also provide indicators to assess risks on ecosystem stability and biodiversity through the complex, but tractable depictions of energy transfers, trophic fluxes, assimilation efficiencies and dissipation (Rambouts et al., 2013). Results can provide critical insights that can be further utilized to evaluate the impacts of changes in biodiversity (Christian et al., 2005; Balvanera et al., 2006), ecosystem structure and functioning (Roessig et al., 2004; Villanueva et al., 2006) and verify multi-species management decisions and conservation (Imperial and Hennessey, 1996; Brando et al., 2004).

2. Methods

2.1. Study sites

The Sine-Saloum estuary (Fig. 1a) is 100 km south of Dakar, Senegal, 13°55′ and 14°10′ N and 16°03′ and 16°50′ W. It has a total area of approx. 543 km^2 opening into the Atlantic Ocean. As an inland type, deltaic system, it is characterized by flat river valleys with varying water levels depending on seasonal floods from adjacent marine ecosystems. It consists of three main branches from north to south: Saloum, Diomboss and Bandiala. At the western end of these branches are characterized by a network of fine creeks (locally called 'bolongs') dominated by dense mangrove trees. The Saloum extends up to 180 km with water depths from 25 m (mouth) to 13 m (upstream), while Diomboss and Bandiala have maximum water depths of 10 m. Water hypersalinity was a result of a perennial 'El Niño phenomenon' that had completely cut-off freshwater inputs (Pagès and Citeau, 1990; Simier et al., 2004). Aside from the system geomorphology, the inverse hypersalinity effect is due to small freshwater inflows, not compensating for a high evaporation. Water salinity in upstream areas can reach over 130 psu during the dry season (November–June) and remain between 45 and 50 psu during the rainy season (July–October). The average water temperature is 25 °C (Diouf, 1996).

The Gambia River Estuary (Fig. 1b) has a total catchment area of 78,000 km^2 (13°28′N; 16°34′W-13°41′N; 15°08′W). It originates in the Fouta-Djalon plateau and flows through Guinea. The estuary zone, considered in this study, has a total area of 654 km^2. Average depth varies from 3 to 15 m. The average water temperature is 27 °C and the average annual precipitation is 1500 mm. This ecosystem has a 'normal' decreasing down-to-upstream salinity gradient (Fig. 1a). Maximum river flow ranges from 4.5 to 1500 m^3 s^{-1}. Water salinity at the mouth of the estuary varies between 38 and 45 psu (Villanueva, 2004).

2.2. Ecosystem models

The Ecopath software implements an ecosystem model based on a set of simultaneous linear equations for each entity considered. It assumes mass-balance, i.e., group production is equal to the sum of all predations, non-predatory loses and exports (Christensen et al., 2005). In order to minimize information loss and taxonomic biases, biological components are pooled according to similarities of species trophic properties (i.e., diets, predators and metabolism) and distribution (Yodzis and Winemiller, 1999). Each trophic group has an energy balance expressed as:

$$B_i\left(\frac{P}{B_i}\right) = \sum_{j=1}^{n} B_j\left(\frac{Q}{B_i}\right) - DC_{ji} + (B_i)\left(\frac{P}{B_i}\right)(1 - EE_i) + EX_i \quad (1)$$

where B_i is the biomass of group *i*; P/B_i is the production rate of *i* equal to the total mortality coefficient (*Z*) (Allen, 1971); Q/B_i is the relative consumption rate; B_j is the biomass of the predating group *j*; DC_{ji}, the proportion of the predated group *i* in the diet of the predating group *j*; EE_i is the ecotrophic efficiency representing the part of the total production transferred to higher *TLs* through predation or captured in the fisheries; EX_i export or catch in fisheries of group *i*, assumed exploited in fisheries.

A total of 37 and 41 compartments were considered for the Sine-Saloum and Gambia models, respectively (Tables 1 and 2). The