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The effects of long-term climate variability on the trophodynamics of an estuarine ecosystem in southern South America

Rodolfo Vögler[a,b,*], Francisco Arreguín-Sánchez[c], Diego Lercari[a,d], Pablo del Monte-Luna[c], Danilo Calliari[b,e]

[a] Centro Universitario de la Región Este – sede Rocha, Universidad de la República (CURE-Rocha, UDELAR), Rocha, Uruguay
[b] Ecología Funcional de Sistemas Acuáticos, CURE-Rocha, UDELAR, Uruguay
[c] Laboratorio de Modelación y Dinámica de Ecosistemas Acuáticos, Departamento de Pesquerías y Biología Marina, Centro Interdiscplinario de Ciencias Marinas – Instituto Politécnico Nacional, Av. Instituto Politécnico Nacional s/n. Col. Playa Palo de Santa Rita, Casilla 952, La Paz, Baja California Sur, Mexico
[d] Unidad de Ciencias del Mar (UNDECIMAR). Facultad de Ciencias, Universidad de la República, Iguá 4225, CP 11400 Montevideo, Uruguay
[e] Laboratorio de Oceanografía y Ecología Marina, Facultad de Ciencias, UDELAR, Iguá 4225, CP 11400 Montevideo, Uruguay

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ABSTRACT

The trophodynamics of the Río de la Plata ecosystem over a long time scale (from 1948 to 2008) were simulated using a food-web model forced by two environmental factors. The Atlantic Meridional Mode (meridional sea surface temperature anomalies) was used as regional forcing, and the Río de la Plata (RdlP) runoff was applied as local forcing. The entire food web was impacted by the regional forcing on a decadal scale; at the inter-annual scale, this remote factor had partial effects on the base of the food web. The RdlP runoff impacted primary producers and secondary consumers at the inter-annual scale. The higher effects of the local forcing were temporally coupled with seven of the strongest El Niño events from 1950 to 2008 (1957–1958, 1965–1966, 1972–1973, 1982–1983, 1986–1987, 1991–1992, 1997–1998). In contrast, the lower effects of RdlP runoff on the food web were coupled with six of the strongest La Niña events since 1950 (1950–1951, 1954–1956, 1964, 1970–1971, 1974–1975, 1988–1989). Total system biomass (trophic web attribute) and a measure of system entropy (holistic indicator) were used to identify ecosystem degradation. The entropy and total biomass of the RdlP ecosystem showed two opposite phases: before and after the early 1970s. During the period 1948–1971, the system showed high entropy and low total biomass, indicating high degradation. This cycle was reversed after 1972, and prevailed until the beginning of the 2000s. During this new cycle, the system entropy decreased and it was compensated by an increase in total system biomass. A sustainable entropy gain occurred after 2003, suggesting a new period of ecosystem degradation. The findings are discussed in light of temporal changes in the structural properties of this coastal ecosystem.

1. Introduction

Trophodynamics, by regulating the cycling of mass, energy and nutrients, determine how marine ecosystems function and respond to both internal and external pressures, as food web pathways adapt to facilitate ecosystem resilience and persistence (Libralato et al., 2014). Marine ecosystems are influenced by drivers that operate and interact over multiple scales, resulting in nonlinear or abrupt responses to perturbations (Fu et al., 2012). Certain environmental drivers affect the food web dynamics of marine ecosystems at an inter-annual time scale (such as El Niño-La Niña events; see Watters et al., 2003), whereas others act over an inter-decadal time scale (such as regime-shift drivers; see Tomczak et al., 2013). Inter-annual variability has a strong influence on the precipitation in southeastern South America (SESA), particularly in spring (Grimm et al., 2000). Consequently, the freshwater discharges to the Atlantic Ocean from large point sources such as the Río de la Plata (RdlP) estuary and Lagoa dos Patos increase during El Niño and decrease during La Niña (Mechoso and Pérez Iribarren, 1992; Barros et al., 2002; Piola et al., 2008). Thus, the relationship between El Niño (La Niña) and the increase (decrease) of river runoff may provide a tool to analyze climatic-oceanographic variability effects on the trophodynamics of coastal ecosystems. In this sense, the trophic structure of the RdlP ecosystem and the spatial

* Corresponding author at: CURE-Rocha, UDELAR, Ruta Nacional N° 9 km 285, CP 27000 Ciudad de Rocha, Rocha, Uruguay. Tel.: +598 44727001x387; fax: +598 44729507.
E-mail address: rodolfovogler@gmail.com (R. Vögler).

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distribution of the fish assemblage areas during the extreme events of 1998/99 El Niño/La Niña were assessed by applying two Ecopath models (Milessi et al., unpublished results) and oceanographic-fisheries data. Although temporally limited, this inter-annual research indicated that oceanographic changes that occurred during extreme events affected the spatial distribution of the RdlP fish assemblage but not its trophic structure.

At present, the most immediate and important consequences of global climate change for the world's coasts include coastal erosion, variations in sea levels, saltwater intrusion and ecosystem alterations (IPCC, 2007). In the SESA region, there are clear increments of climatic (e.g., precipitation) and hydrological (e.g., river runoff) trends that are likely related to the latest trend of global warming initiated in the 1970s (Barros, 2006). In this sense, amongst sub-continental regions of the world, the SESA region has shown the greatest increase in precipitation during the last century (Giorgi, 2002). This condition exists despite the fact that the region includes subtropical Chile, which has experienced a decrease in precipitation (Minetti and Vargas, 1998). The increase in annual precipitation in the last 40 years (1965–2005) has exceeded 10% over most of the region, but in some places, it has reached 30% or more (Castañeda and Barros, 1994; Minetti et al., 2003). Increased precipitation has led to increased river runoff (García and Vargas, 1998; Genta et al., 1998), as evaporation, controlled by temperature, does not appear to have changed considerably (Berbery and Barros, 2002). The percent rate of change in river runoff was amplified when compared to the corresponding rate of change in the basin average precipitation in the RdlP (Collinshon et al., 2001; Berbery and Barros, 2002; Clarke, 2003). The inter-annual variability of river discharge in certain sub-basins of the RdlP basin has been studied, and linkages to sea surface temperatures (SSTs) in the Pacific and Atlantic oceans have been found (Mechoso and Pérez Iribarren, 1992; Robertson and Mechoso, 2000; Camilloni and Barros, 2000). Díaz et al. (1998) found that precipitation in Uruguay and southern Brazil was positively correlated with SST anomalies in the southwestern tropical Atlantic during spring and summer. Precipitation in the RdlP basin south of 25°S is positively correlated with the SST near the South Atlantic convergence zone; in contrast, precipitation near the Paraná headwaters is negatively correlated with the SST in the southwestern Atlantic (Barros et al., 2000; Nogués-Paegle et al., 2002; Doyle and Barros, 2002).

The functioning of the RdlP ecosystem is linked to continental runoff. Freshwater is the main source of nutrients that fuel primary production within the estuary (Nagy et al., 2002; Calliari et al., 2005, 2008). Production is generally light limited in the freshwater zone, but nutrient limited in the brackish and high-salinity areas seaward of the turbidity front (Calliari et al., 2005, 2008; Kruk et al., 2015). Higher runoff and nutrient fluxes can thus be expected to enhance the production of plankton and higher consumers.

With regard to trophic functioning, the RdlP ecosystem exhibits a similar structure to other estuaries: outstanding primary production that exceeds consumption, detritus accumulation in the system, elevated total system throughput, and an intermediate state in terms of ecosystem growth and development (Lercari et al., 2014).

Several groups of organisms have shown a key role in the RdlP ecosystem due their position as top predators (marine mammals and seabirds) or as tertiary consumers (sharks, such as *Squatina guggenheim* and *Galeorhinus galeus*), and also as species of middle trophic levels (Sciaenidae fishes and *Rapana venosa*, an invasive gastropod). In this sense, marine mammals and seabirds have consumptive impacts at different trophic levels, affecting several species of fish such as *G. galeus*, *Urophycis brasiliensis*, *Micropogonias furnieri*, *Cynoscion guatucupa*, as well as squid (Bergamino et al., 2012). An important issue is that all of these preys are commercially important species. *Squatina guggenheim* has been described as an important generalist predator (Vögler et al., 2003) linking demersal and pelagic communities. The trophic role of *R. venosa* was recently investigated in detail (Lercari and Bergamino, 2011), featuring a conspicuous biomass and notable trophic overlap with *M. furnieri*. Additionally, primary producers (i.e., phytoplankton) and benthic invertebrates with low trophic levels also constitute keystone groups in this ecosystem (Lercari et al., 2014). Thus, the trophic interactions in the RdlP ecosystem can be seen as controlled by both top-down (e.g., marine mammals, seabirds, coastal sharks) and bottom-up (i.e., phytoplankton) mechanisms.

Fisheries activities produce different effects on the RdlP ecosystem. The industrial bottom-trawling fleets generate wider impacts (e.g., affecting a major number of functional groups), whereas artisanal fisheries cause specific and acute mixed impacts over a small number of functional groups (Defeo et al., 2011). Overall, the effects of fishing at the ecosystem level exhibit minor system consequences through weak loss of secondary production, suggesting exploitation rates that are at sustainable levels (Defeo et al., 2011).

The temporal ecosystem-level monitoring of the RdlP ecosystem trophodynamics has not been evaluated until now. Here, we analyze the long-term fluctuations (60 years: 1948–2008) of the functional groups' biomass, from primary producers to top predators, assessing their relationship with two physical factors: the anomaly of the RdlP runoff (a local forcing with temporal variability of high frequency) and the Atlantic Meridional Mode sea surface temperature Index (AMM; a regional forcing with temporal variability of low frequency). For this purpose, we postulate the following hypothesis: The long-term fluctuations of trophic web attributes (i.e., total system biomass, biomass per trophic level) and the variability of a holistic indicator (i.e., a measure of entropy) are affected by the local influence of the RdlP runoff (at an inter-annual scale) and/or by the regional influence of the AMM (at two time scales: inter-annual and inter-decadal). The hypothesis was tested by examining two levels of the effects of forcing factors: (i) abrupt changes in the modeled biomass at each trophic level and (ii) variability in entropy, which is linked with ecosystem degradation. By using a hindcast procedure, we incorporated the two environmental variables as forcings acting from the base of the food web or affecting certain functional groups with specific ecological roles or with commercial value.

2. Materials and methods

2.1. Río de la Plata basin: hydrological and climatic features in a regional context

The RdlP basin has an area of approximately 3.1 million km^2 and is shared by five countries (Brazil, Argentina, Paraguay, Bolivia and Uruguay) with a population surpassing 200 million. This basin has the second-largest drainage area in South America and fifth-largest in the world (Barros, 2006). The RdlP basin is divided into three large sub-basins, corresponding to the Paraná, Paraguay and Uruguay Rivers. The sub-basin of the Paraná River, with a surface drainage of 1.51 million km^2 (without including the basin of the Paraguay River), occupies close to half of the area of the RdlP (Coronel et al., 2006). The sub-basin of the Uruguay River has a total drainage area of 365,000 km^2 and has its source at the convergence of the Pelotas and Peixe Rivers. The Uruguay River travels 2200 km and ends in the RdlP (Coronel et al., 2006).

2.2. Modeling the study area

The study area modeled comprises the middle and outer RdlP estuary and adjacent coastal shelf waters to 50 m deep, covering an area of approximately 70,500 km^2, between 34°10′–37°30′ S and