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Spatio-temporal modelling of the maturity, sex ratio, and physical condition of nylon shrimp *Heterocarpus reedi* (Decapoda, Caridea), off Central Chile

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ABSTRACT

Two key elements in the adequate, sustained exploitation of any fishery should be considered; the biological attributes of the species and how these vary over time and space. Research is needed to obtain a more thorough understanding of these effects, how they vary, and how they relate to environmental factors. For 17 years, biological information has been collected for *Heterocarpus reedi* (nylon shrimp) caught off central Chile (25–37 °S). Here, we analyze these data using generalized linear models and determine the factors responsible for changes in carapace length, body weight, maturity, and sex ratio. The environmental and alimentary conditions are better south of 32 °S, and this is probably associated with the better physical condition and reproductive attributes of *H. reedi* there. For example, individuals are larger, females are longer at first maturity ($CL_{50\%}$), and mature females are less prevalent. We outline a theoretical foundation that can guide future research on *H. reedi*. We also suggest that future conservation measures consider biological attributes within a spatial context.

1. Introduction

Important changes in the abundance and distribution of many marine benthic species are determined by substrate, environmental characteristics, and exploitation (e.g., Loneragan and Bunn, 1999; Diaz-Ochoa et al., 2004; Encarnacao et al., 2013; Sancinetti et al., 2014; Canales et al., 2016). These factors also affect seasonal differences in, and the persistence of, biological parameters (e.g., Company et al., 2001, 2004; Araújo et al., 2014) and may even give rise to discrete population units or metapopulations (e.g., Fogarty and Botsford, 2006; Josileen, 2011; Sethi et al., 2013; Sal-Moyano et al., 2014).

Heterocarpus reedi (nylon shrimp) is one of the most important decapod crustaceans exploited in Central Chile (25–37 °S), with catches of ~4000 tons year^{-1}. This species is distributed continuously on the continental shelf and upper slope, between 200 and 400 m depth (Fig. 1), occupying a heterogeneous habitat made up of clay soil, sedimentary rock, sand, and mud. The water column in this area contains both equatorial subsurface waters, which are low in dissolved oxygen, and Antarctic intermediate waters, which are cool (10–12 °C), but have relatively high salinity (34.5–34.9 g kg^{-1}) (Silva, 2012). In the south of the study area, river discharge (Canales et al., 2016) and coastal upwelling (mainly in spring) (Silva and Valdenegro, 2003) lead to important amounts of organic matter.

Our understanding of the biology of *H. reedi* is varied. Much information is restricted to finite time periods, for example the early works on reproductive process, growth, and condition factor of *H. reedi* (Arana and Tiffou, 1970; Bahamonde and Henríquez, 1970; Arana et al., 1976). Those authors suggested, among other things, probable spatial heterogeneity in length at first maturity as a response to environmental conditions. Nonetheless, research that extends the space-time dimension or that focuses on other biological attributes (e.g., physical condition, sex ratio, length at maturity) and their variations in time and space remains limited.

We analyzed 17 years of biological information gathered while monitoring the extraction activities of *H. reedi* to understand the patterns and trends of the factors and variables that determine the spatio-temporal changes in its biological attributes, maturity state, physical condition, body length, and sex ratio. Our results contribute to understanding the spatial heterogeneity of these attributes as affected by the environmental conditions observed off the coast of Chile between 1997 and 2013.

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2. Materials and methods

2.1. Data source

Biological samples were taken by the Fisheries Development Institute (Instituto de Fomento Pesquero, IFOP). Samples were taken in south-central Chile (25°–36 °S) between 1997 and 2013, as part of a program that not only monitors fishing activity at the main landing ports and processing plants, but also performs on-board sampling. The individuals used for biological samples were selected to represent, in a nonrandom manner, the greatest size range possible. Specimens were taken from the final haul of each fishing trip, allowing us to measure variables that would have been difficult to measure on land (e.g., body weight, morphometric measurements). Statistically, this sample was consistent with prior studies that showed, for example, weight and state of maturity to be heavily dependent on individual carapace length. Because of this, more observations should be made at either end of the size frequency spectrum. For each individual, we recorded: the date and geographic location of capture, sex, carapace length (CL) in millimeters, and total wet weight in grams. For females, the reproductive status (mature or immature) was also recorded, as determined by the presence or absence of eggs in the abdomen.

2.2. Statistical analysis

We used Generalized Linear Models (GLM; McCullagh and Nelder, 1984) to analyze four biological response variables (CL, individual weight, maturity, sex ratio), in the same sense as several other authors have used GLM to analyze maturity at size (or age) and the sex ratio (e.g., ICES, 2008; Lambert et al., 2009; Wheeler et al., 2009; Stewart et al., 2010). The models were specified and fit using the language and environment for statistical computation and graphics R (R Development Core Team, 2009). An analysis of deviance was used to evaluate the importance and significance of each predictor variable included in the model. This was complemented by an Akaike Information Criterion (AIC) analysis (Akaike, 1974), which was used to evaluate the relative increase of AIC after excluding specific terms from the full model through the *drop1* function included in R language.

This analysis considered four factors as discrete predictor variables: year (Y), quarter (Q), zone (Z), and sex (M: male, F: female, MF: mature female); and carapace length (CL) as a continuous predictor variable. The models describing the proportion of mature females, total females, and body weight included CL. While analysis focused on model main effects, the first-order interaction defined by quarter × zone also was evaluated to know if seasonality of some dependent variable is determined by spatial influences (zones). Other interactions were not considered to avoid decompensation of the design matrix. Both CL and the logarithm of weight were assumed to be normally distributed (Gaussian error model) with link functions “log” and “identity”, respectively, whereas the proportions (of mature and of total females) were assumed to have a binomial distribution with a “logit” link function (Table 1).

Only females (126,252 individuals) were used for the analysis of the proportion of mature individuals. Maturity was designated as a binary variable (p) according to the presence (1) or absence (0) of eggs in the pleopods. After fitting the model and regardless of the year, the length at first maturity was calculated in each zone and for quarter (Q^*) with the highest proportion of mature females, using

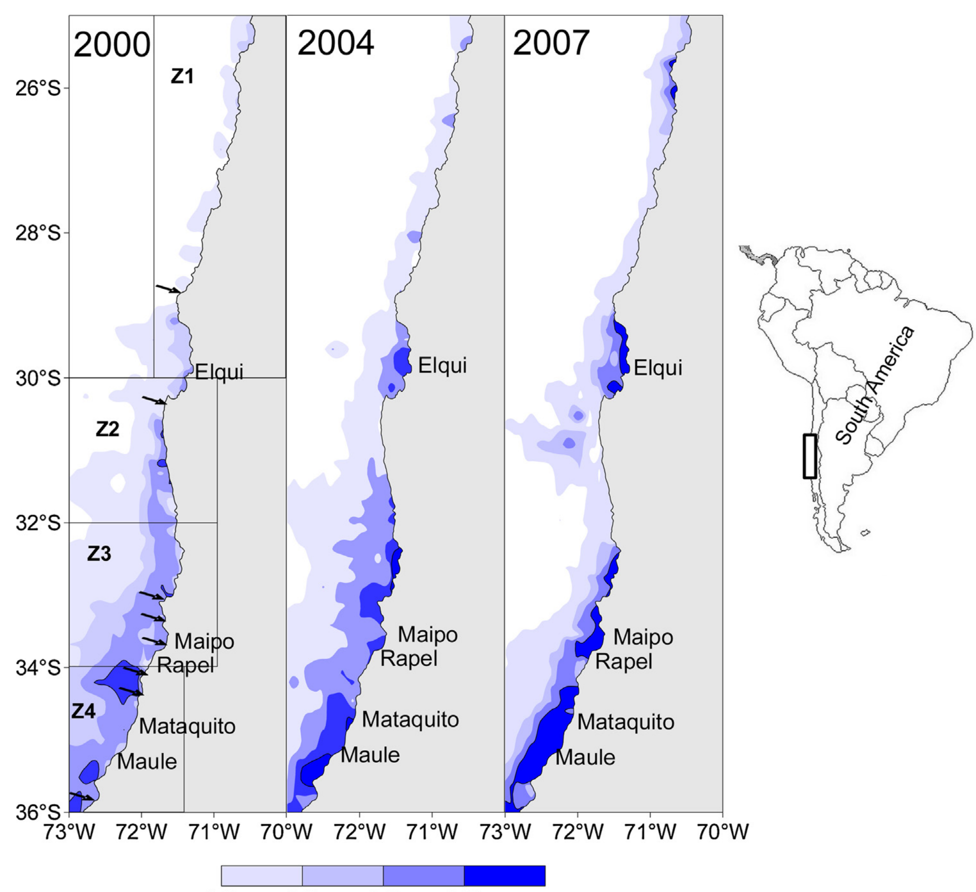

Fig. 1. Study zone and distribution of cumulative organic matter and dissolved detritus between September and December in three years, with the main river names included. The black arrows indicate the main upwelling zones. The rectangles make reference to subzones of analysis.