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Can different biological indicators detect similar trends of marine ecosystem degradation?

Sofia Henriques[a,*], Miguel Pessanha Pais[a], Marisa Isabel Batista[a], Célia M. Teixeira[a], Maria José Costa[a,b], Henrique Cabral[a,b]

[a] Centro de Oceanografia, Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal
[b] Departamento de Biologia Animal, Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal

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ABSTRACT

Marine ecosystems are typically under the influence of multiple Human activities, which hinders the assessment of the effects of a specific activity upon their biological assemblages. In this context, distance-based linear models were used to analyse the relationships of several structural and functional metrics of both macroinvertebrates and fish assemblages with the specific types of pressure (i.e. fishing, organic, physical and non-point-source) as well as the global pattern of cumulative pressures. Both indicators detected similarly the effects of the global degradation and the analyses of the metrics' sensitivity (given the expected response trends) suggested that the non-point-source had the strongest contribution to this pattern, followed by organic pollution. The difficulties of assessing single pressure effects in a multiple pressures context are discussed. An approach based on the previous identification of pressure sources, a sampling strategy directed to those sources, together with indicator response is highly recommended, as it could be the only way to accurately predict human-induced changes on broad range ecosystems, with likely implications in the success of marine management plans.

1. Introduction

Awareness of the harmful effects of human pressures on the marine environment has resulted in an increasing attention to monitoring using biological indicators, in order to identify which human pressures are driving changes on the ecosystem structure and function, as well as design management plans to minimize impacts (Niemi et al., 2004; Rogers and Greenaway, 2005; Smale et al., 2010). In this context, recent policies have been developed with the purpose of promoting sustainable use of marine resources and protect marine ecosystems (e.g. Marine Strategy Framework Directive, MSFD; Directive 2008/56/CE). To implement the MSFD, an integrated ecosystem-based approach should be applied, giving priority to the attainment of a "good environmental status" through the assessment of physical and chemical elements, together with several biological indicators, among which are fish and macroinvertebrates (see Annex III in Directive 2008/56/CE).

Due to the difficulty of analysing patterns of change in complex, spatially and temporally diverse multi-species assemblages, the need to assess environmental status comes with new challenges concerning the use of biological indicators in marine waters (Mee et al., 2008; Niemi et al., 2004; Niemi and McDonald, 2004). Additionally, stress in marine ecosystems is usually characterized by the effects of multiple human pressure sources, and as physical boundaries between marine habitats are difficult to define, thus the identification of pressures that are affecting an area constitutes a complex task (Ban et al., 2010; Niemi et al., 2004). This way, coupling human pressure and biological response analyses is essential to link the causes of stress to the response of indicators. Otherwise, it would be extremely difficult to identify sources of disturbance, unless specific metrics for each pressure exist and detect such changes (Niemi et al., 2004; Niemi and McDonald, 2004).

Earlier attempts at comparing the response of fish-based and macroinvertebrate-based metrics have been focused on freshwater ecosystems (e.g. Hering et al., 2006; Johnson et al., 2006; Marzin et al., 2012). In general, these studies showed that macroinvertebrates and fish have different sensitivities depending on the human pressure analysed, with fish responding more to hydrological changes, while macroinvertebrates show a higher sensitivity to water quality and/or geomorphological changes (Hering et al., 2006; Marzin et al., 2012). However, these assemblages differ deeply from those of marine waters. For example, fish assemblages are known to be species-poor in streams (Hering et al., 2006). To the best of our knowledge, only few studies have compared the response of multiple indicators in coastal waters (marine and estuarine ecosystems), but through multimetric indices (e.g. Azevedo

* Corresponding author. Tel.: +351 217500826; fax: +351 750 02 07.
E-mail addresses: snpires@fc.ul.pt, henriques.sofia@gmail.com (S. Henriques).

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et al., 2011; Borja et al., 2009). Therefore, a complete approach based on structural and functional metrics is still lacking. Despite that, these studies showed that both fish and macroinvertebrates indices had a consistent response to water quality improvement (Borja et al., 2009) and in the detection of degraded sites (Azevedo et al., 2011).

Although it seems that both biological indicators (i.e. fish and macroinvertebrates) are capable of detecting ecosystem degradation, they have completely different biological traits. Fish have longer life cycles, occupy a variety of trophic levels (reflecting effects at all levels within food webs) and higher mobility (although some species have limited ranges), which probably makes them more sensitive to large-scale changes (Elliott et al., 2007; Whitfield and Elliott, 2002). Compared with fish, benthic macroinvertebrates have short life cycles and are relatively sedentary, which makes them more vulnerable to small variations in the ecosystem (Aarnio et al., 2011; Marzin et al., 2012). Based on these assumptions, it would be expected that these biological assemblages have different sensitivities to disturbance.

By analysing the response models of several macroinvertebrates and fish based metrics in a multiple pressure context, the present study aimed at addressing several key questions: (1) can fish and macroinvertebrate-based metrics detect the global pattern of marine ecosystem degradation? (2) Is it possible to distinguish single effects of specific types of pressure in a multiple pressure context? (3) Do both indicators detect types of pressure similarly (organic, fishing, physical, non-point-source)?

2. Materials and methods

2.1. Study area and human pressure gradients

The study area is located on the coastal shelf off Cascais and extends between Carcavelos (38°40′36″ N, 9°19′32″ W) and Cabo da Roca (38°46′51″ N, 9°30′2″ W), covering a depth range between 20 m and 50 m and a marine area of 109 km^2 (Fig. 1). The adjacent terrestrial area is highly populated (approximately 200.000 inhabitants) and consequently the study area is under the influence of multiple sources of pressure. These include a submarine sewage outfall (see Sampaio et al., 2010a for details), the influence of the Tejo estuary (see Vasconcelos et al., 2007 for details), bathing waters and polluted streams (see Viegas et al., 2009 for details), shellfish aquacultures in extensive regime, recreational (e.g. angling and spearfishing) and commercial (e.g. nets, pots, longlines) fishing activities, marina and anchoring areas, intensive recreational sport activities (sailing, windsurf, canoeing, surf, kitesurf, diving) and physical structures mainly related to urban and port development (Hidroprojecto, 2008).

In order to understand how human-driven changes are distributed across types of pressures, sources of pressure were grouped into the following categories: organic pollution, fishing (i.e. biological), physical and non-point-source (see Table 1 for details). In the present study, organic pollution only included the sewage outfall, since pressures that can result in several types of contamination were considered in the non-point-source category (high variety of pollutants).

Using a Geographical Information System (GIS) approach, "environmental risk surface" analysis was performed for each pressure type, with the purpose of classifying samples according to their level of influence. This analysis consists of a modelled composite raster surface that combines information about the extent and relative intensities of perceived environmental risks in the studied area (Schill and Raber, 2009). To do so, spatial information about each pressure source was mapped into a layer, and a relative scale was used to rank each layer according to intensity (measure of the degree of risk to the habitat), expected range of influence and weight (expected level of impact in the habitat) (see Table 1 for details). Intensity varied between 1 and 5 and was obtained by ranking the classification data chosen for each pressure source among locations (see Table 1 for details about data and metrics used for intensity classification). Mean values of classification data from the last 5 years were used whenever possible. Range of influence values were adapted from Ban and Alder (2008) and Ban et al. (2010) and complemented with inquiries to several local stakeholders and available legislation (DL n° 241/1998; Portaria n° 1102-D/2000; Portaria n° 1102-H/2002). Weight was obtained by averaging the values for Frequency and Magnitude attributed to each of the pressure sources. Frequency values were adapted from Halpern et al. (2007). A linear decay function was used to simulate decrease in the intensity of a pressure type with increasing distance to their source. The weight values used resulted from the mean value of frequency of occurrence (1-rare to 4-persistent) and the expected degree of impact on the marine environment (1 – low to 4 – high). Weight values obtained were then normalized into a 1–3 scale (1 – low, 2 – medium and 3 – high) (see Table 1 for details). The assignment of frequency and expected impact values was performed according to the authors' judgement, based on the values indicated in Halpern et al. (2007).

For each type of human pressure (i.e. organic, fishing, physical and non-point-source), a raster (100 m cell width) with the cumulative impact score (CIS) was created based on previous work by Halpern et al. (2008):

$$\text{CIS} = \sum_{i=1}^{n} A_i * w_i$$

where, A_i is the intensity of each human pressure source A in the location i, while w_i represents the weight given to each source for that location. Analyses were performed using the extension "Environmental Risk Assessment" of the package "Protected Area Tools v4" (Schill and Raber, 2009) in ArcGIS 10 software. Ultimately, a Human Pressure Index (HPI) was created by combining (summing cell values) raster layers representing individual pressures, hence reflecting the cumulative impacts for each location (henceforward mentioned as "global pattern of cumulative pressures") (Fig. 1).

2.2. Sampling strategy

During 2009, both fish and macroinvertebrates assemblages were surveyed in four sampling campaigns (March, June, September and November). In order to ensure that all the study area was equally covered in each sampling campaign, three sectors were delimited, where samples were randomly collected.

A total of 120 macroinvertebrate samples were collected using a 0.1 m^2 "Day" grab. These samples were then transported to the laboratory and washed over a 0.5 mm-mesh sieve. The material removed was conserved in ethanol (70%) and stained with Rose Bengal. Macroinvertebrates were sorted, counted and identified to the lowest taxonomic level whenever possible (usually to genus/species level). The total density (ind. m^{-2}) per taxa was estimated for each replicate. Additionally, 100 g of substrate were taken from each site in order to characterize the composition of bottom sediments (gravel – Ø > 2000 μm, sand – 2000 < Ø < 63 μm and mud – Ø < 63 μm) in percentage. All sample locations were recorded using a GPS (Global Positioning System) device.

Fish assemblages were sampled on board of a fishing vessel using an otter-trawl (12 m headline; 20 m footrope; 80 mm codend mesh), covering a total area of 280.452 m^2. A total of 24 hauls were performed, with a duration of 20 min each (6 in each sampling