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Relationships among fisheries exploitation, environmental conditions, and ecological indicators across a series of marine ecosystems

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ABSTRACT

Understanding how external pressures impact ecosystem structure and functioning is essential for ecosystem-based approaches to fisheries management. We quantified the relative effects of fisheries exploitation and environmental conditions on ecological indicators derived from two different data sources, fisheries catch data (catch-based) and fisheries independent survey data (survey-based) for 12 marine ecosystems using a partial least squares path modeling approach (PLS-PM). We linked these ecological indicators to the total biomass of the ecosystem. Although the effects of exploitation and environmental conditions differed across the ecosystems, some general results can be drawn from the comparative approach. Interestingly, the PLS-PM analyses showed that survey-based indicators were less tightly associated with each other than the catch-based ones. The analyses also showed that the effects of environmental conditions on the ecological indicators were predominantly significant, and tended to be negative, suggesting that in the recent period, indicators accounted for changes in environmental conditions and the changes were more likely to be adverse. Total biomass was associated with fisheries exploitation and environmental conditions; however its association with the ecological indicators was weak across the ecosystems. Knowledge of the relative influence of exploitation and environmental pressures on the dynamics within exploited ecosystems will help us to move towards ecosystem-based approaches to fisheries management. PLS-PM proved to be a useful approach to quantify the relative effects of fisheries exploitation and environmental conditions and suggest it could be used more widely in fisheries oceanography.

1. Introduction

There are two main mechanisms controlling the trophodynamics of marine ecosystems: (1) bottom–up control from plankton species that are directly influenced by ocean climate (e.g., Richardson and

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Schoeman, 2004; Ware and Thomson, 2005; Conti and Scardi, 2010); and (2) top–down control from upper-level predators and fisheries exploitation (e.g., Jennings et al., 2001) that directly impact fisheries production. In the past few decades, ecosystems globally have witnessed climate regime shifts (e.g., Gedalof and Smith, 2001) and boom-bust fisheries exploitation (e.g., Jennings et al., 2001). The difficulty of disentangling cumulative effects of fishing from ocean climate processes poses problems in the management of marine living resources (Conti and Scardi, 2010; Kirby et al., 2009). Analyzing patterns of community and ecosystem variations across a number of ecosystems with contrasting anthropogenic pressures and environmental conditions should provide new insights into how these factors interact and influence the structure and functioning of marine ecosystems (Link et al., 2010; Rouyer et al., 2008). This will help inform ecosystem-based approaches to fisheries management (Sissenwine and Murawski, 2004; de Young et al., 2008; Link, 2011).

Ecosystem indicators are quantitative physical, chemical, biological, social, or economic measurements that serve as proxies for ecosystem attributes and are increasingly used to inform ecosystem status (e.g., Cury and Christensen, 2005; Rochet and Trenkel, 2003; Shannon et al., 2010; Shin and Shannon, 2010; Shin et al., 2010b). Multiple indicators are needed to reflect the complexity of ecosystems, effects of different drivers, and management objectives (Fulton et al., 2005; Jennings, 2005; Rochet and Trenkel, 2009). Hundreds of ecosystem indicators have been proposed, including environmental, species-based, size-based, trophic-based, and integrated indicators (Rochet and Trenkel, 2003; Fulton et al., 2005; Cury and Christensen, 2005; Shin et al., 2010b).

However, the application of multiple indicators presents two major challenges: (1) interpreting different or even conflicting signals from different ecosystem indicators; and (2) understanding potential correlations among indicators either through functional or sampling dependencies (Cotter et al., 2009; Petitgas and Poulard, 2009). Principal component analysis (PCA), dynamic factor analysis (DFA), and partial least squares regression (PLSR) approaches have been used to combine different ecosystem indicators (Cotter et al., 2009; Fu et al., 2012; Petitgas and Poulard, 2009). These approaches are useful when indicators refer to a single dimension, such as one facet of the ecosystem functioning, which has been termed the latent concept (Trinchera and Russolillo, 2010). When indicators cover different dimensions, each referring to a different latent concept, then single dimension approaches are difficult to interpret. The framework of partial least squares path modeling (PLS-PM, Esposito Vinzi et al., 2010) is more suited to these problems and allows investigation of relationships among latent concepts and their relationships with their corresponding indicators.

The basic idea behind PLS-PM (Fig. 1) is that the complexity inside a system can be addressed through a relational network among latent concepts, called Latent Variables (LVs), each measured by several observed variables defined as Manifest Variables (MVs) (Esposito Vinzi et al., 2010; Sanchez, 2013; Wold, 1980). Here we defined external pressure LVs for fisheries exploitation and environmental conditions. We explored how these LVs are related to the ecological LVs represented by various ecological indicators.

Each ecological indicator responds differently to fishing and environmental pressures (Link et al., 2010). Consequently, we considered a suite of seven ecological indicators that were divided into two groups (catch-based and survey-based indicators) to represent two LVs, reflecting trophic and community structure of landed fish and of surveyed fish, respectively. We investigated how the two ecological LVs were connected with fishing and environmental variables. As a further step, we explored how these two ecological LVs were related to the resource potential reflected by total system biomass. While we do not claim to achieve causal relationships, we quantified the relationships among the LVs through correlations (i.e., path coefficients) provided by PLS-PM.

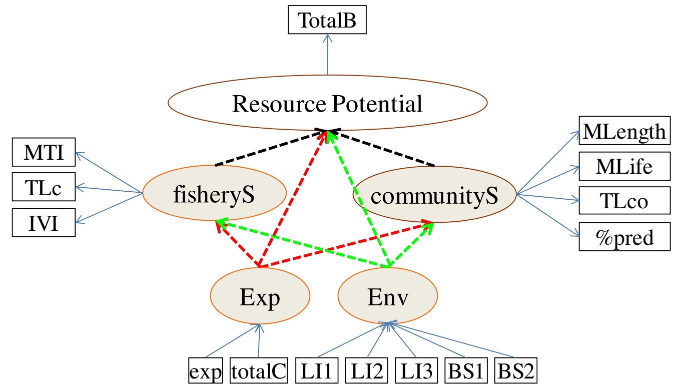

Fig. 1. Diagram of the partial least squares path model, showing in dashed arrows relationships among latent variables (LVs) of environment (Env) and fisheries exploitation (Exp), trophic structure and species composition of landings (fisheryS) and of the surveyed fish community (communityS), as well as system resource potential. Each of the LVs is related to its own manifest variables (MVs) shown as solid arrows: the LV Env is related to three local variables (LI1, LI2, and LI3) and two basin-scale variables (BS1 and BS2), and the LV Exp is related to total landings (totalC) and exploitation rate (exp); fisheryS is reflected by marine trophic index (MTI), mean trophic level of landings (TLc), and intrinsic vulnerability index of landings (IVI), and communityS by mean length (MLength), mean life span (MLife), trophic level (TLco) and proportion of predatory fish (%pred) in the community; system resource potential is represented by the total biomass time series (totalB). For simplicity, LVs with lagged time series are not shown.

Here we analyze 12 exploited marine ecosystems using the PLS-PM approach. These data form part of the IndiSeas collaborative program (Shin et al., 2012; www.indiseas.org) developed under the auspices of EUROCEANS and IOC/UNESCO. The aim of IndiSeas is to perform comparative analyses of ecosystem indicators for quantifying the impact of fishing on marine ecosystems and providing useful information in the context of decision support for ecosystem-based approaches to fisheries management. The aim of the comparative analysis was to contribute to an improved understanding of fishing and climate impacts on the structure and functioning of exploited marine ecosystems.

2. Methodology

2.1. Ecosystems and indicators

The 12 marine ecosystems that we explored were the Barents Sea, Gulf of Cadiz, eastern English Channel, Guinean EEZ, Ionian Sea Archipelago, New Zealand Chatham, North Sea, Portuguese EEZ, eastern Scotian Shelf, western Scotian Shelf, Northeast USA and West Coast Canada. These ecosystems have different species compositions, fishery exploitation histories, and environmental influences (Shin et al., 2010b; www.indiseas.org). The period covered by the data for each ecosystem is listed in Table 1. They all have the complete set of indicator time series (>10 year duration) described below. An example of the data time series is provided in Table A.1 of Appendix A to show how data were structured. Environmental variables both at local (e.g., sea surface temperature) and basin scales (e.g., Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO)) can be important drivers of ecosystem dynamics (e.g., Hare and Mantua, 2000; Wells et al., 2008; Link et al., 2010; Molinero et al., 2013; Alheit et al., 2014). For each ecosystem, regional experts were asked to provide two global and up to three local environmental indices that were considered important to biological production and ecosystem processes, based on published and unpublished information. These local- and basin-scale environmental indices (Table 1) were used for the environmental latent variable (LV), provided that there was at least 10 years of data that overlapped with the ecological indicator data. Total landings and exploitation rate (defined as the ratio of total landings to biomass of all landed species) were used for the exploitation LV.