Ecological Indicators 73 (2017) 809–824

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Comparison of thermodynamic-oriented indicators and trait-based indices ability to track environmental changes: Response of benthic macroinvertebrates to management in a temperate estuary

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ARTICLE INFO

Article history:
Received 12 September 2016
Received in revised form 28 October 2016
Accepted 31 October 2016
Available online 14 November 2016

Keywords:
Ecological indicators
Management
Environmental disturbance
Estuaries

ABSTRACT

Reliable ecosystem status assessment of coastal and marine environments is key due to mounting pressures from human activities. Aiming at a successful management, a plethora of evaluation tools currently exist, but there is no consensus on what index or indices should be used by environmental managers in establishing benthic quality.

The main goal of this investigation was to evaluate the suitability of thermodynamic-oriented indicators (Eco-Exergy and Specific Eco-Exergy) and trait-based indices (Rao's Quadratic Entropy, Functional Redundancy and Community-Weighted Mean trait value) as tools to capture potential ecological changes, comprehending their utility for addressing specific management objectives. In order to do so, a long-term data set (1993–2012) from a southern European estuary (Mondego estuary, Portugal) was used to assess the responsiveness of macroinvertebrates assemblages to a large-scale management intervention, and the performance of thermodynamic-oriented indicators and trait-based indices was compared.

The results indicated that the undertaken management efforts were successful at improving the ecosystem state and confirmed that hydrodynamic conditions in the estuary have been the major drivers of the changes observed over the last three decades. Both Exergy-based and trait-based indices coherently reflected the ecological changes observed along the temporal disturbance-recovery gradient analysed. Indices response was congruent but of different nature and detail level. Trait-based indices provided a more detailed assessment of the benthic communities and informative picture than Exergy-based indices but the overall outcome of both types of indices was broadly convergent. Combining multiple indicators should thus be more likely to improve transparency and to provide a more robust assessment method.

1. Introduction

Unprecedented biodiversity loss on aquatic ecosystems with major consequences for ecosystems structure and functioning, resulting from human action and climatic drivers, has been documented on a global scale (Lotze et al., 2006; Halpern et al., 2015). Recognized as one of the cornerstones of healthy ecosystems, the issue of preserving biodiversity and the vital ecosystem services it supports has become a priority of current environmental policies including the European Water Framework Directive (WFD, 2000/60/EC) and the Marine Strategy Framework Directive (MSFD, 2008/56/EU) (Worm et al., 2006; Laurila-Pant et al., 2015).

Environmental management is committed with the safeguarding and improvement of ecosystems' environmental state through a science-based and integrated 'Ecosystem Approach' (CBD, 2000), in order to inform management planning effectively and regulate human pressures (Elliott, 2014). Aiming at ecosystems' long-term conservation and sustainable use, such an integrative assessment requires knowledge on the natural systems structure and functioning, and their response to human activities, crucial to perceive the effectiveness of management decisions (Borja et al., 2016).

The relationship between biodiversity and ecosystem functioning, which is complex and can take many forms, has been widely debated (Loreau, 2010; Gagic et al., 2014; Gamfeldt et al., 2015; Strong et al., 2015). There is, however, broad consensus that changes in biodiversity will result in altered ecosystem functions,

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http://dx.doi.org/10.1016/j.ecolind.2016.10.040
1470-160X/

with diverse areas presenting higher and efficient functioning rates, as species-rich communities are more likely to express a greater range of traits and environmental sensitivities, allowing for a more effective resource use and providing stability (Chapin et al., 2000; Strong et al., 2015). These findings have encouraged the use of biodiversity patterns as proxies of ecosystem function in decision-making (Mayfield et al., 2010). Although ecosystem functioning has become a priority research avenue over the last decades, quantifying it remains one of the 'grand challenges' in ecology without a simple or standardized measure to accomplish it (Borja, 2014).

Ecosystem functioning has been often approached through biomass, primary production or nutrient cycling measurements (e.g. Naeem and Wright, 2003; Raffaelli and Friedlander, 2012), but recent advances in applied ecology and environmental legislation (e.g. MSFD) have stressed the need for working measures of ecosystem function for use in the assessment of marine ecosystem status (Bremner 2008; Cadotte et al., 2011; Borja et al., 2016). Descriptors that account for the transfer of energy through food webs including the potential transfer/loss of genetic information, embracing ecosystem complexity rather than reducing it (as in thermodynamic approaches), may be a way forward to address ecosystem functioning (Jørgensen, 1995, 2000; Reyjol et al., 2014). In this sense, thermodynamic-oriented indicators such as Exergy, seen as a super holistic indicator (Jørgensen et al., 2016), appears to be suitable to capture ecosystems' development, constituting a system-oriented characteristic for natural tendencies. In ecology, Eco-Exergy is defined as 'a goal function which expresses the sum of energy (biomass) and information contained in a given system due to living organisms' (Bendoricchio and Jørgensen, 1997), and may act as an ecosystem quality indicator, providing reliable information on the structural development of a community (Marques et al., 1997; Fei-Jun et al., 2009). The energy stored in an ecosystem, which can be affected by changes in the system total biomass and species composition, is expressed through the Eco-Exergy and frequently complemented by the Specific Eco-Exergy (the ratio between Eco-Exergy and the total biomass of the system) (Bendoricchio and Jørgensen, 1997). Both measures are therefore suitable environmental indicators, able to account for the quantity and quality of the system's biomass, with an increase in their values reflecting enhanced ecosystem efficiency, quality and functioning (Bendoricchio and Jørgensen, 1997; Marques et al., 1997; Pusceddu and Danovaro, 2009; Silow and Mokry, 2013; Vassallo et al., 2013).

Another way to assess ecosystem functioning which has been given some consideration recently is the use of trait-based approaches. Promising methods have been applying biological traits (Violle et al., 2007), which are considered to assert explicit links with ecological functioning (Bremner, 2008). Traits influence ecosystem functioning and are relevant to species responses to the environment (Snelgrove, 1998; Díaz and Cabido, 2001; Bremner et al., 2006). Descriptors that include traits confer thus better representations of functioning over community structure parameters (e.g. species number, biomass) alone, by capturing the causal mechanisms underlying species-environment relationships (Griffin et al., 2009; Statzner and Bêche, 2010; Verberk et al., 2013). Trait-based indices are becoming increasingly applied to investigate systems functional changes when facing anthropogenic disturbance, since a species ability to deal with environmental disturbance is at some extent governed by its traits (Mouchet et al., 2010; Schleuter et al., 2010; Vandewalle et al., 2010; Mason et al., 2013; Mouillot et al., 2013; Verberk et al., 2013; Culhane et al., 2014; Van der Linden et al., 2016a,b).

In recent decades numerous ecological indices have been developed, in particular for benthic macroinvertebrates, driven by the need to assess marine environmental state under different legislation worldwide (Birk et al., 2012). Despite this overdevelopment, there is still no agreement on which index or indices should be used by environmental managers to establish benthic quality (Borja et al., 2015). An ecologically parsimonious approach favours the evaluation of the existing indices prior to developing new ones (Diaz et al., 2004). In the present-day scenario of crisis and limited budgetary resources this is wise advice to assist environmental managers in selecting indices to be used in monitoring programs (Borja and Elliott, 2013). Indices robust in space and time, and responsive to different pressures, should be desirable to communicate research information to managers and society (Borja and Dauer, 2008). In this way, studies testing ecological indices performance at different geographical regions, systems, and on single/multi-pressure scenarios, help strengthen evidence about their suitability, before they can be widely adopted as environmental assessment tools (Borja et al., 2009).This knowledge is key to consolidate information and to reach scientific consensus on the preferred indices, providing assistance to both managers and stakeholders in the selection of the most robust ones.

The Mondego estuary (Portugal), a well-documented estuarine system, was used as a case-study. The estuary has an eutrophication past which changed the macrophytes distribution and the benthic communities (e.g. Marques et al., 1993, 2003; Martins et al., 2007), followed by a phased restoration scheme implemented to reinstate the environmental quality. Initially, small-scale mitigation measures were undertaken which fostered the system partial recovery, followed by a more severe and large-scale intervention (the upstream reconnection between the North and the South arms of the estuary in 2006; Veríssimo et al., 2012a,b), used here as an adaptive management model.

The purpose of the present study was to test the suitability of thermodynamic-oriented and trait-based indices to capture potential ecological changes related to management and to understand their usefulness as ecological assessment tools. Initially, the effectiveness of the large-scale management intervention was reassessed. This study follows up on a previous evaluation of the response of the subtidal and intertidal macrobenthic communities, which covered a limited period until 2008 (Veríssimo et al., 2012a,b; Marques et al., 2013). The updated assessment is based on new intertidal monitoring data for the period 2008–2012, extending the coverage of those previous works by adding new data to the long-term series thus, broaden knowledge on the potential intervention success. In particular, we tested for differences in the structure and composition of the macrobenthic communities before and after management. Thereafter we applied two thermodynamic-oriented indicators (Eco-Exergy and Specific Eco-Exergy) and three trait-based indices (Rao's Quadratic Entropy – Rao, Community-Weighted Mean trait value – CWM, and Functional Redundancy – FRED) in order to compare their performance to detect ecological changes, before and after the large-scale management efforts.

Ultimately, it was intended to integrate the existing scientific knowledge on the Mondego estuary to support future sustainable management prescriptions to this system in particular, and provide insights that may serve as useful management guidelines to other estuarine systems undergoing similar problems.

2. Material and methods

2.1. Study site description and management context

The Mondego estuary (Portugal), a small transitional system (860 ha) on the SW Atlantic European Coast (40°08′N, 8°50′W) (Fig. 1), is under continuous anthropogenic pressure given its location next to an urban centre (Figueira da Foz city). It holds several small and medium-sized enterprises (salt-works, aquaculture farms, paper and canning industries), mercantile and fishing