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Understanding relationships between conflicting human uses and coastal ecosystems status: A geospatial modeling approach

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ABSTRACT

Human use of ecosystem resources and services is increasing worldwide, generating pressures that alter ecosystem structure, functioning and provision of services. Unexpected ecosystem change is becoming frequent, and the complex ways through which multiple human pressures may interact leave conservation practitioners and natural resource managers faced with high uncertainty. We developed a geospatial approach for modeling the complex relationships between multiple human pressures and coastal ecosystems status. This framework was then used to produce maps of the expected status of marine coastal ecosystems resulting from variation in the cumulative human pressure. The geospatial modeling approach we developed was tested on an emblematic study case requiring marine spatial planning, i.e. a recently established marine protected area (MPA) that will have to coexist with the expansion of a close commercial harbor. In the study case presented, our modeling approach was used to predict the status of coastal ecosystems resulting from different management alternatives. Results showed that should Port Authority support MPA in reducing human pressures in the area, coastal ecosystems would not be expected to further deteriorate as a consequence of harbor expansion. Our approach proved effective in modeling complex interaction among multiple pressures (e.g. synergisms) and predicting potential future scenarios. The implementation of this approach into geographical information systems (GIS) allows managers to represent the expected outcomes of their planned conservation efforts, thereby representing an important decision-support tool for finding efficient management solutions in the face of complex interactions and high uncertainty.

1. Introduction

Marine ecosystems are challenged worldwide by a vast set of potentially interacting human uses. The human ‘footprint’ on the oceans is so pervasive that many scientists have proposed that no ocean region can still be considered pristine (Jackson and Sala, 2001; Stachowitsch, 2003; Halpern et al., 2008b). Human influence is particularly profound in coastal ecosystems (Vitousek et al., 1997; Halpern et al., 2008b). Here, conflicting human uses generate multiple pressures that act simultaneously often producing unexpected ecosystem responses (Crain et al., 2008; Darling and Côté, 2008; Doak et al., 2008; Halpern et al., 2008a).

The recognition of the necessity for increased marine conservation has motivated a worldwide establishment of marine protected areas (hereafter MPAs). Despite playing a pivotal role in marine ecosystem protection, MPAs may not be sufficient alone (Agardy, 1994; Montefalcone et al., 2009). Globally, MPAs rarely cover an adequate extent and representation of different ecosystems and in most cases are too small to protect adequate portions of habitats and populations (Mora et al., 2006). Moreover, MPAs do not address the multiplicity of human pressures along coastal zones and cannot prevent the impacts of coastal pollution or the expansion of invasive species (Agardy, 1994; Halpern, 2003). For these reasons, recent conservation literature calls for the implementation of ecosystem-based-management (hereafter EBM) emphasizing that multiple pressures have to be explicitly accounted and addressed in comprehensive, spatially explicit management plan (Ruckelshaus et al., 2008; Thrush and Dayton, 2010).

Human pressures and coastal ecosystems have, by definition, a spatial component. This is why cartography is traditionally considered essential for the analysis and management of natural environments (White et al., 1992; Bock et al., 2005). In the marine environment, however, cartography is less developed and less frequently applied compared to the land because of the

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reluctance to consider the sea as a 'territory' and the evident operational difficulties involved (Bianchi et al., 2004). Early approaches emphasized the need to integrate 'naturalistic' maps with 'socio-economic' maps for coastal zone management (Bianchi and Zattera, 1986). Modern tools for spatially-explicit planning stem from the long-standing cartographic tradition and use in environmental management and are viewed as fundamental for implementing EBM (Stelzenmuller et al., 2010a). Understanding the relationships between multiple human pressures and the status of ecosystems is crucial to develop spatial plans whose main goal is the cartographic visualization of the results of different management alternatives (Douvere, 2008).

Yet, understanding the relationships between multiple human activities and the status of ecosystems is difficult for two main reasons: (1) multiple pressures may interact in complex non-additive manners (Shears and Ross, 2010) and (2) spatial information on both ecosystem status and potential sources of impact is scarce (Halpern et al., 2008a; Fraschetti et al., 2009).

While disentangling complex interactions among multiple pressures (e.g. non-additive behaviors) can be effectively done in factorial experiments manipulating stressors both separately and in combination (Crain et al., 2008), this remains challenging in the real world, where pressures are typically more than two and their direct manipulation is often unfeasible. However, such information is needed and represents the base-knowledge to implement EBM (Thrush et al., 2008). In the real world, scientists are faced with a suite of information gaps and statistical challenges, including missing data, lack of normally distributed variables and with spatial correlation among different human pressures. Flexible approaches and modeling tools capable to highlight multiple stressors interaction and to cope with uncertainty are necessary to implement spatial plans; waiting for the ideal conditions to understand pressures/status relationships is a luxury that marine ecosystems and their managers can hardly afford (Parravicini et al., 2010).

In spite of the objective difficulties mentioned above, information on human pressures distribution by means of surrogates (e.g. presence/absence of relevant human activities or weighted distance from these activities) have been successfully used to mapping potential risks of human impact (Eastwood et al., 2007; Petrosillo et al., 2010; Stelzenmuller et al., 2010b; Mensa et al., 2011). In addition, gaps of knowledge of coastal ecosystem status are being, at least in part, filled by the huge amount of data made available by national and international initiatives (e.g. the Water Framework Directive and the Marine Strategy Directive of the European Union, and the Clean Water Act in the USA). All these instruments require the adoption of appropriate monitoring plans aimed at assessing ecosystems status through ecological indicators (Olsson et al., 2008; Hering et al., 2010).

We developed and tested a spatially-explicit and flexible modeling approach to quantifying and visually representing interactions between a suite of human pressures and the status of different ecosystem types across intensely-utilized coastal seascapes. Here, we use this approach to visualize the expected outcomes of alternative management scenarios for an emblematic case study from coastal Italy: a coastal zone where a newly established marine protected area will have to coexist with the planned extension of a close commercial harbor.

2. Methods

2.1. Conceptual framework

The primary goal of marine spatial planning is assessing the effects of different management alternatives on the state of coastal ecosystems (Douvere, 2008). Most techniques developed in this field are based on expert-judgment surveys or literature reviews. Both methods are used to assess the vulnerability of different habitats to selected human pressures (Selkoe et al., 2009; De Lange et al., 2010). If the spatial distribution of both marine habitats and human pressures is known, then a measure representing the potential risk of impact can be computed and represented on maps, thereby helping identify the most efficient management solution, i.e. the one capable to minimize the risk of impact (Halpern et al., 2009; Stelzenmuller et al., 2010b). These approaches have the invaluable advantage that spatial plans can be implemented when data on ecosystem status are missing or scarce, e.g. over large scales allowing a synoptic view of the territory to be managed (Bianchi, 2008). The main drawback of such approaches, however, is that multiple pressures are generally assumed arbitrarily to play additively (Halpern et al., 2009). This is a limitation when considering that almost three-quarters of studies on multiple pressures effects detected significant non-additive interactions (Crain et al., 2008; Darling and Côté, 2008). Without using data on ecosystem status, in fact, expert- or literature-based techniques can hardly detect and understand the complex interactions that may exist among pressures (e.g. synergisms or antagonisms). In addition, these behaviors are spatially variable and extremely site-specific, making it difficult, if not impossible, to extrapolate general rules to be used *a priori* over vast spatial scales (Crain et al., 2008).

Considering field data, our approach enables the modeling of the relationships between multiple pressures and ecosystem status and to use such information to predict the results of different management alternatives. The geospatial modeling tool presented comprises four main steps: (1) the GIS (geographical information system) mapping of human pressures and their intensities, (2) the GIS mapping of marine ecosystem status, (3) the modeling of the relationships between human pressures distribution and marine ecosystem status, (4) the use of the model calibrated in the step (3) to build maps of expected ecosystem status according to different management alternatives – i.e. expected or planned variations in human pressures distribution and intensities (Fig. 1). Within the framework of this geospatial approach, once a efficient solution is found, appropriate monitoring plans must be implemented to allow for future more accurate calibration of the model.

2.2. Study area and field data

We applied our geospatial modeling approach to the coastal zone surrounding the "Isola di Bergeggi" MPA, established in 2007 and located in the Ligurian Sea, NW Mediterranean (Fig. 2). This study case is emblematic of the importance that marine spatial planning and EBM may represent for conservation. The area is embedded within a human-dominated landscape, characterized by a twofold scenario of economic exploitation of the marine environment: westbound the area borders with the tourist center of Spotorno, eastbound with the commercial harbor of Vado Ligure. Although they are currently protected, the coastal ecosystems of the Bergeggi MPA pay the legacy of various past and ongoing human uses such as finfish fishing, date-mussels harvesting, coastal urbanization, SCUBA diving and anchoring (Parravicini et al., 2006, 2008, 2009; Montefalcone et al., 2009, 2010). In addition, the MPA is bordered by two large beaches, one of which was created *ex novo* between 1969 and 1971 (Fierro et al., 1975), and is maintained through almost annual nourishments. The area is an important tourist destination and, despite the presence of the commercial harbor nearby, belongs to the best water quality class according to WFD (water framework directive) standards (Asnaghi et al., 2009). Other protection measures include the presence of one SCI (site of community importance) whose management plan, implemented in 2009, prohibits anchoring and further coastal development within its boundaries. The MPA comprises three