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An ecosystem-based approach to evaluate the ecological quality of Mediterranean undersea caves

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A B S T R A C T

A theoretical model of structure and functioning was constructed for the Mediterranean undersea cave ecosystem. This model integrates almost all representative components of the cave ecosystem and gives an idea of their faunal compositions, characteristics and related interactions.

This model constitutes the basis of the Ecosystem-Based Quality Index (EBQI) of the European Union's Marine Strategy Framework Directive, which aims at evaluating the ecological quality of an ecosystem. It is based on four crucial complementary elements: (i) each component was weighted in accordance with its importance in determining the structure and functioning of the cave ecosystem; (ii) a suite of relevant parameters were defined to assess the ecological state of each component of the cave ecosystem; (iii) these parameters were aggregated into one relevant index, the Cave EBQI (CavEBQI), to summarize the quality evaluation for each cave site; (iv) each value of ecological state is accompanied by a Confidence Index as a measure of its reliability.

The CavEBQI was used on 22 Mediterranean undersea caves of France and Italy. Disparities of ecological quality were found among caves but most of them ranged from moderate to high ecological quality. For some caves, no conclusion can be drawn when our method predicts a poor reliability of the evaluation of their ecological quality.

This ecosystem-based evaluation of the quality of undersea caves seems to be a powerful tool, with the advantage of being based on almost all its components, rather than just on a few species. It is accompanied by a measure of its reliability, hence it provides a reliable idea of the ecological state of the entire ecosystem at each cave site. Monitoring the ecological state of caves and the effects of disturbances over large geographic and temporal scales is made possible with CavEBQI. Applying the same method to other ecosystems, can provide an integrated view of a marine region, which is essential when addressing questions about protection, conservation and restoration.

1. Introduction

Ecosystems and associated biodiversity have a double value: intrinsic (stand-alone value regardless to human) and instrumental (goods and services provided; Ghilarov, 2000; Groom et al., 2005). Threatened by anthropogenic activities, this natural heritage calls

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for an urgent need of conservation plans, particularly in coastal areas, which concentrate three times the average global population density (Small and Nicholls, 2003). In Europe, about 200 millions of people (almost half the population of maritime countries) concentrate along the coasts (Eurostat, 2009). This is reinforced in the Mediterranean which welcomes 200 millions of tourists each summer (Airoldi and Beck, 2007; Halpern et al., 2008; Coll et al., 2010).

Some of the management and conservation challenges are to detect changes in biodiversity within an ecosystem and to explain their causes. Ecological indicators are usually considered the most appropriate tools to address such questions, because they constitute a link between scientists, who produce scientific knowledge on ecosystem structure and functioning, and managers, who use scientific knowledge for protection and conservation measures (Dale and Beyeler, 2001; Turnhout et al., 2007).

The difficulty of defining and using ecological indicators is that they must give a simplified picture of highly complex, dynamic, spatially heterogeneous and temporally fluctuating natural systems (Turnhout et al., 2007). The best strategy to deal with this whole complexity appears to use a suite of parameters, indicative of the current and/or desired ecological quality of the system, which can be aggregated into one index to provide an assessment of the entire system (Dale and Beyeler, 2001; Turnhout et al., 2007). When they are characteristic, representative and specific enough of an ecosystem, this suite of parameters can constitute the ecosystem-based approach for the evaluation of ecological quality. The relevance of this integrative approach relies on the fact that it takes into account a wide variety of components to avoid focusing only on sentinel species.

This ecosystem-based approach is the keystone for the European Union's (EU) Marine Strategy Framework Directive (MSFD 2008/56/EC) for evaluating the ecological quality of an ecosystem. The MSFD established a framework for conservation in the field of marine environmental policy (Personnic et al., 2014) whose main goal is to make Member States take measures to achieve or maintain Good Environmental Status (GES) of EU marine waters by 2020.

According to the MSFD, "*Good Environmental Status means that the different uses made of the marine resources are conducted at a sustainable level, ensuring their continuity for future generations*". It implies that "*ecosystems, including their hydro-morphological (i.e. the structure and evolution of the water resources), physical and chemical conditions, are fully functioning and resilient to human-induced environmental change*". Consequently, "*noise from human activities is compatible with the marine environment and its ecosystems" and "the decline of biodiversity caused by human activities is prevented and biodiversity is protected*".

Personnic et al. (2014) have developed a method to assess the quality of a marine ecosystem based on (i) an aggregation of multiple parameters into one index, the Ecosystem-Based Quality Index (EBQI), indicating the status of the ecosystem and (ii) a confidence value that indicates the reliability of each value of the parameters and of the summarizing index. When reliability is low, the method helps to identify the cause of the flaw. This method uses a model of ecosystem functioning based on how experts think it is structured and how it functions under natural conditions (Dale and Beyeler, 2001). This model-based method has several advantages. It allows to define what the 'Good Environmental Status' of an ecosystem is, by taking into account all the components of an ecosystem as well as their interactions with each other and the relative importance of each descriptor of the ecosystem health. Eventually, it allows identifying the need of prospects to better understand the structure and functioning of the ecosystem.

This method has been developed for *Posidonia oceanica* (Linnaeus) Delile, 1813 seagrass meadows, a remarkable habitat of the Mediterranean Sea, listed by the EU Habitats Directive (92/43/CEE), a European regulation that defines areas ('Natura 2000 sites') where species and habitats must be protected (Personnic et al., 2014).

Undersea caves[1] are also remarkable habitats (listed by the EU Habitats Directive 92/43/EEC, Habitat type 8330) widespread throughout the Mediterranean Sea. They often originate from the marine flooding of limestone karstic networks during the last transgression. Hence, the rocky coast of the Mediterranean Sea is rich in undersea caves ranging from small crevices to large cavities where SCUBA divers can access (Bianchi et al., 1996). Undersea caves are of great importance because prevailing harsh environmental conditions lead to the establishment of a peculiar fauna whose composition significantly differs from the outside littoral zone. Caves harbour specialized and often also Mediterranean endemic species (Harmelin et al., 1985). Some of these species are regular bathyal and abyssal inhabitants, which find there, to some extent, environmental conditions similar to those of the deep sea (Harmelin et al., 1985; Vacelet et al., 1994; Vacelet and Boury-Esnault, 1995; Calado et al., 2004; Janssen et al., 2013). Moreover, caves constitute a naturally fragmented habitat, which can act as refuges or ecological islands. They are a biodiversity reservoir displaying poorly resilient communities (Harmelin et al., 1985; Chevaldonné and Lejeusne, 2003; Lejeusne and Chevaldonné, 2006; Gerovasileiou and Voultsiadou, 2012).

The high aesthetic value and richness in biological peculiarities of undersea cave communities can be degraded by several threats: mechanical disturbance (deleterious water movements, divers), water warming, sediment deposit, commercial species harvesting, urbanization, and waste outflows (Chevaldonné and Lejeusne, 2003; Parravicini et al., 2010; Giakoumi et al., 2013).

Undersea caves are ecologically connected with several other ecosystems such as infra- and circalittoral communities of hard substrata outside, including the coralligenous assemblages, rocky reefs, seagrass beds (Harmelin et al., 2003), and sandy bottoms. They are also connected with the pelagic system due to water movement, which brings food and propagules into caves. Detritus accumulated in the floor of caves contain materials transported from various other ecosystems that are more or less remote. In recent years, numerous studies focused on the contribution of cave assemblages to the overall coastal biodiversity (Todaro et al., 2006; Bussotti and Guidetti, 2009; Parravicini et al., 2010; Gerovasileiou and Voultsiadou, 2012) and/or assessed human impacts, like those related to unregulated underwater activities (Di Franco et al., 2010; Guarnieri et al., 2012). Abdulla et al. (2008) have shown that about 66% of the Mediterranean marine protected areas include marine caves. A good strategy of management, protection and conservation should be more integrative than focusing on a single ecosystem by taking into account ecosystems coupling. This is emphasized in the marine realm due to advection. It will be useless, or at least less effective, to protect an ecosystem if adjacent ecosystems suffer from destructive pressures. Integrating more ecosystems and their connections in strategies of biodiversity management, protection and conservation would be more effective especially when recognized factors altering ecosystems are common and controlled throughout their whole geographic range of influence. From this point of view, a common methodology to identify the ecological quality of various connected ecosystems shall be very useful.

The ecosystem-based approach is here applied to evaluate the ecological quality of the Mediterranean undersea caves. Hence we (i) propose a model of cave composition, structure and functioning, (ii) define what a 'Good Environmental Status' represents for this

[1] The term "undersea cave" is preferred in the present paper to avoid any misleading confusion. It encompasses marine caves that are totally submerged underwater.