Marine Pollution Bulletin xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

An ecosystem-based approach to assess the status of Mediterranean algae-dominated shallow rocky reefs

Thierry Thibaut [a,*], Aurélie Blanfuné [a], Charles F. Boudouresque [a], Sébastien Personnic [a], Sandrine Ruitton [a], Enric Ballesteros [b], Denise Bellan-Santini [c], Carlo Nike Bianchi [d], Simona Bussotti [e], Emma Cebrian [b], Adrien Cheminée [a,f], Jean-Michel Culioli [g], Sandrine Derrien-Courtel [h], Paolo Guidetti [e], Mireille Harmelin-Vivien [a], Bernat Hereu [i], Carla Morri [d], Jean-Christophe Poggiale [a], Marc Verlaque [a]

[a] Aix-Marseille University, Mediterranean Institute of Oceanography (MIO), CNRS/INSU, IRD, UM 110, Campus universitaire de Luminy, case 901, 13288 Marseille cedex 09, France
[b] Centre d'Estudis Avançats de Blanes - CSIC, 17300 Blanes, Spain
[c] Aix-Marseille University, Institut Méditerranéen de Biodiversité et d'Ecologie (IMBE), UMR 7263, Station Marine d'Endoume, rue de la batterie des lions, 13007 Marseille, France
[d] DiSTAV, Dipartimento di Scienze della Terra, dell'Ambiente e della Vita, Università di Genova, Corso Europa 26, 16132 Genova, Italy
[e] Université Nice Sophia Antipolis, CNRS, FRE 3729 ECOMERS, Parc Valrose, 28 avenue Valrose, 06108 Nice cedex 02, France
[f] Université de Perpignan, CNRS, Via Domitia, Centre de Formation et de Recherche sur les Environnements Méditerranéens, UMR 5110, 66860 Perpignan cedex 9, France
[g] Office de l'Environnement de la Corse, Riserva Naturali di i Bucchi di Bunifaziu, Rundinara, 20169 Bonifacio, Corsica, France
[h] Museum National d'Histoire Naturelle, Station Marine de Concarneau, 29900 Concarneau, France
[i] Departament d'Ecologia, Universitat de Barcelona, Diagonal 643, 08028 Barcelona, Spain

ARTICLE INFO

Article history:
Received 7 October 2016
Received in revised form 13 January 2017
Accepted 16 January 2017
Available online xxxx

Keywords:
Photophilic algae
Marine Strategy Framework Directive (MSFD)
Biological indicator
Mediterranean Sea

ABSTRACT

A conceptual model was constructed for the functioning the algae-dominated rocky reef ecosystem of the Mediterranean Sea. The Ecosystem-Based Quality Index (reef-EBQI) is based upon this model. This index meets the objectives of the EU Marine Strategy Framework Directive. It is based upon (i) the weighting of each compartment, according to its importance in the functioning of the ecosystem; (ii) biological parameters assessing the state of each compartment; (iii) the aggregation of these parameters, assessing the quality of the ecosystem functioning, for each site; (iv) and a Confidence Index measuring the reliability of the index, for each site. The reef-EBQI was used at 40 sites in the northwestern Mediterranean. It constitutes an efficient tool, because it is based upon a wide set of functional compartments, rather than upon just a few species; it is easy and inexpensive to implement, robust and not redundant with regard to already existing indices.

1. Introduction

Coastal regions are subject to multiple and massive anthropogenic and natural pressures that may result in major ecosystem-wide changes (e.g. Worm and Lotze, 2006; Halpern et al., 2008; Derrien-Courtel et al., 2013; Giakoumi et al., 2015). These changes can include the loss of biodiversity, and alterations of ecosystem functioning and related services of benefit to society. Managing the quality of coastal waters and their ecosystems has become a challenge for many countries and governments (Bianchi et al., 2012; Parravicini et al., 2012; Vacchi et al., 2014; Giakoumi et al., 2015). Since the early 1990s, the European Union (EU) has adopted framework legislation for regulating human activities in the marine environment in order to guide them towards greater sustainability, by protecting and, wherever necessary, restoring good environmental quality. In the EU, the Habitats Directive (Habitats Directive, 1992) established a list of habitats and species deserving protection, which provided a basis for designating areas in which these habitats and species had to be protected ('Natura 2000 sites'). The coverage of the marine realm by the Habitats Directive is insufficient, but more recently the EU Marine Strategy Framework Directive (MSFD, 2008) established a more comprehensive framework for the management and conservation of the marine environment. The MSFD is considered to be the environmental pillar of the Integrated Maritime Policy adopted in 2008 by the European Commission. The MSFD, with an Annex listing 11 descriptors, constitutes the basis for the assessment of 'Good Environmental Status' (GES) according to: (1) biodiversity; (2) non-indigenous species; (3) exploited fish and shellfish; (4) food webs; (5) human-induced eutrophication; (6) sea-floor integrity; (7) hydrographical conditions; (8) contaminants in water and sediment; (9) contaminants in fish and shellfish; (10) marine litter; and (11) introduction of energy/noise. The GES rating means that the marine environment is at the sustainable level, thus allowing uses and activities by current and future generations, i.e. the structure, functions and

* Corresponding author.
E-mail address: thierry.thibaut@univ.-amu.fr (T. Thibaut).

http://dx.doi.org/10.1016/j.marpolbul.2017.01.029
0025-326X/© 2017 Published by Elsevier Ltd.

processes of the marine ecosystems, together with the associated physio-geographical, geographical, geological and climatic factors, allow those ecosystems to function efficiently and to maintain their resilience in the face of human induced environmental changes. The EU MSFD established a framework within which Member States agreed to take the appropriate measures to achieve or maintain GES in the marine realm by the year 2020, at the latest.

Large canopy-forming species of kelp (Laminariales, Phaeophyceae, Stramenopiles) and fucoids (Fucales, Phaeophyceae, Stramenopiles) are dominant worldwide, in temperate areas, in most healthy shallow rocky reefs (Dayton, 1985; Steneck et al., 2002; Schiel and Foster, 2006; Derrien-Courtel, 2008; Harley et al., 2012; Derrien-Courtel et al., 2013). Kelps and fucoids are autogenic ecosystem engineers (Jones et al., 1994; Steneck et al., 2002). Their abundance and distribution are controlled by both top-down and bottom-up processes (Estes and Palmisano, 1974; Witman, 1987; Witman and Dayton, 2001; Steneck et al., 2002; Guidetti, 2006; Hereu et al., 2008; Vergés et al., 2009, 2014). A variety of human activities and global warming are responsible, directly or indirectly, for the worldwide decline of kelp and fucoid beds (e.g. Helmuth et al., 2006; Airoldi and Beck, 2007; Airoldi et al., 2008; Hawkins et al., 2008; Schiel, 2011; Lamela-Silvarrey et al., 2012; Thibaut et al., 2015; Vergés et al., 2016). Some taxa have even been driven to regional extinction (Thibaut et al., 2005; Coleman et al., 2008; Phillips and Blackshaw, 2011; Bianchi et al., 2014; Thibaut et al., 2015). A major consequence of these changes is a phase shift from a state with canopy forming species to alternative states, including barren grounds (e.g. Micheli et al., 2005; Sala et al., 2011, 2012; Boudouresque and Verlaque, 2013; Filbee-Dexter and Scheibling, 2014; Vergés et al., 2014). The shift from canopy forming states to barren ground states can present a hysteresis effect; this is the case for the extirpation of these forests by sea urchin overgrazing: the threshold in sea urchin density that induces the shift from canopy forests toward barren grounds is approximately one order of magnitude higher than the threshold density that allows the reverse shift from barren ground toward canopy forest (Ling et al., 2015).

Species of the genus *Cystoseira* (Fucales) are the main canopy-forming macroalgae on the Mediterranean Sea shallow rocky reefs (e.g. Boudouresque, 1971a, 1971b; Verlaque, 1987; Ballesteros, 1988, 1990a, 1990b; Giaccone et al., 1994; Sales et al., 2012). The loss of *Cystoseira* beds has been reported throughout the Mediterranean Sea due to habitat destruction, eutrophication, damage by fishing nets and overgrazing by herbivores, leading to a shift to less structurally complex benthic assemblages, such as turf-forming, filamentous or other ephemeral seaweed assemblages or barren grounds where the regular sea urchin compartment (*Paracentrotus lividus* and *Arbacia lixula*) is one of the major drivers of habitat homogenization (e.g. Guidetti, 2006; Guidetti and Dulčić, 2007; Fraschetti et al., 2011; Giakoumi et al., 2012; Bianchi et al., 2014). This alteration of the structural complexity may in turn impair the functions associated with forested rocky reefs (e.g. spawning or nursery grounds) (Cheminée et al., 2013; Thiriet, 2014; Cuadros, 2015).

Where the decline of these canopy-forming species has been observed, the Mediterranean photophilic rocky reef assemblages are currently generally characterised by low stands of shrubby macrophytes (e.g. *Cladostephus hirsutus*, *Corallina caespitosa*, *Dasycladus vermicularis*, Dictyotales, *Halopteris scoparia*, *Laurencia* spp., *Padina* spp.) or by barren grounds with encrusting macrophytes (e.g. *Aglaozonia* stages of *Cutleria* spp., *Lithophyllum incrustans*, *Neogoniolithon brassica-florida*, *Peyssonnelia rosa-marina*, *Pseudolithoderma adriaticum*), sea urchins (*P. lividus* and *A. lixula*) and *Patella caerulea* (e.g. Boudouresque, 1971a; Ballesteros, 1993; Bonaviri et al., 2011; Bianchi et al., 2012).

Environmental parameters, species composition and the ecosystem functioning can be profoundly altered by anthropogenic activities. Biological indicators are species or groups of species of which the distribution, function and abundance reflect possible alterations of the environment. A number of biological indicators are also adopted for monitoring biochemical, physiological or behavioural changes. The use of biological indicators concerns terrestrial, freshwater and marine habitats (e.g. White and Irvine, 2003; Diaz et al., 2004; Blanco et al., 2007; Martínez-Crego et al., 2010; Hoare et al., 2013).

In algae-dominated rocky reefs, macroalgae are commonly used as biological indicators to assess the ecological status of benthic assemblages. These indicators are multiple, using a panel of techniques ranging from quadrat sampling to *in situ* visual estimation of the assemblages (e.g. Díez et al., 2003; Ballesteros et al., 2007; Juanes et al., 2008; Orfanidis et al., 2011; Díez et al., 2012; Le Gal and Derrien-Courtel, 2015; Ar Gall et al., 2016; Blanfuné et al., 2016, and references therein). A further aim of seascape indicators using macroalgae is to provide information on the ecological status of the littoral zone (Cariou et al., 2013; Gobert et al., 2014). These indirect indicators are satisfactory for achieving specific goals (see above); however, their aim is not to reflect the structure and functioning of an ecosystem in pristine conditions or under anthropogenic stressors. Ecosystem-based indicators, taking into account the whole structure and functioning of the ecosystems, were recently developed for the meadows of the Mediterranean seagrass *Posidonia oceanica* (Personnic et al., 2014; Boudouresque et al., 2015a), underwater caves (Rastorgueff et al., 2015) and coralligenous habitats (Ruitton et al., 2014). This new category of indicators has been named 'Ecosystem Based Quality Indices' (EBQI).

The goal of the present study was not to develop a new method, nor to assess the relevance of the EBQI methodology, but to adopt it in the framework of a new category of ecosystem, the Mediterranean shallow, algae-dominated rocky reefs. Our aims here were to (i) establish a model of rocky reef composition, structure and functioning, (ii) identify the 'Good Environmental Status' for this ecosystem, (iii) define parameters and criteria needed for an ecosystem-based assessment of the quality of algae-dominated rocky reefs, (iv) propose an ecosystem-based index, and then (v) apply this method to multiple sites across the NW Mediterranean Sea.

2. Materials and methods

2.1. Conceptual model

The habitat considered here includes the so-called photophilic infralittoral rocky environments, as defined by Pérès (1982). The limits of our study zone range between 1 and 10 m depth. The uppermost part of the infralittoral zone (<1 m depth) is excluded here, because it harbours particular assemblages with species adapted to particular and extremely variable conditions in relation to water movement, humectation, irradiance, salinity and temperature (Cefalì et al., 2016). Here we also exclude the deepest part of the infralittoral zone subjected to <10% of the surface irradiance, because it is usually a transient zone to the circalittoral habitats and also because the key species of macro-herbivores are usually rare, resulting in low herbivore pressure (Boudouresque and Verlaque, 2013).

On the basis of information gathered from previous, generally quantitative, studies performed by the authors of this paper and others (e.g. Pérès, 1982; Verlaque and Nédelec, 1983; Sala and Boudouresque, 1997; Ruitton et al., 2000; Guidetti, 2004; Hereu et al., 2008; Bonaviri et al., 2009; Vergés et al., 2009; Agnetta et al., 2015; and references therein) and our own expert knowledge of algae-dominated rocky reefs, we constructed a conceptual model of the structure and functioning of north-western Mediterranean algae-dominated rocky reefs (Fig. 1), which encompasses the following compartments:

– Multicellular Photosynthetic Organisms (MPOs) (box 1).
– Imported primary production from adjacent ecosystems (mostly *Posidonia oceanica* leaves and other marine MPOs).
– Bentho-pelagic Particulate and Dissolved Organic Matter (POM and DOM).

Please cite this article as: Thibaut, T., et al., An ecosystem-based approach to assess the status of Mediterranean algae-dominated shallow rocky reefs, Marine Pollution Bulletin (2017), http://dx.doi.org/10.1016/j.marpolbul.2017.01.029