Ecosystem-based quality indices: valuable tools for environment management

Charles F. Boudouresque, P. Astruch, D. Bănaru, Aurelie Blanfuné, B. Belloni, T. Changeux, Pierre Chevaldonné, Catherine Fernandez, J. G. Harmelin, Thierry Pérez, et al.

VIE ET MILIEU - LIFE AND ENVIRONMENT, 2020, 70 (3-4): 3-15

ECOSYSTEM-BASED QUALITY INDICES: VALUABLE TOOLS FOR ENVIRONMENT MANAGEMENT

C. F. BOUDOURESQUE[1], P. ASTRUCH[2], D. BĂNARU[1], A. BLANFUNÉ[1], B. BELLONI[2], T. CHANGEUX[1], P. CHEVALDONNÉ[3], C. FERNANDEZ[3], J. G. HARMELIN[2], T. PEREZ[3], G. PERGENT[4], C. PERGENT-MARTINI[4], S. RUITTON[1], T. THIBAUT[1]*

[1] Aix-Marseille University and University of Toulon, MIO (Mediterranean Institute of Oceanography), CNRS, IRD, Campus de Luminy, Marseille, France
[2] GIS Posidonie, OSU Pythéas, Campus de Luminy, Marseille, France
[3] IMBE (Institut Méditerranéen de Biodiversité et d'Écologie Marine et Continentale), CNRS, IRD, Aix-Marseille Université et Université d'Avignon, France
[4] FRES 3041 – UMR 6134, Coastal Ecosystems Team, University of Corsica, 20250 Corte, France
** Corresponding author: charles.boudouresque@mio.osupytheas.fr*

ECOLOGICAL INDICATORS
ECOSYSTEMS
ECOSYSTEM-BASED APPROACH
MANAGEMENT
MEDITERRANEAN SEA

ABSTRACT. – Environmental issues have been addressed on the basis of three different approaches. (i) The earliest is the 'Human-centered' approach; it was characterized by the dichotomy between 'useful' species (for Man) and pests (competitors of humans). (ii) The species-centered approach was characteristic of the 20th century and remains the most common approach adopted in many countries and by several international agencies. It is based upon the notion of outstanding species, which are designated as deserving appropriate management, in contrast to 'ordinary' species. (iii) Finally, the 21st century ecosystem-based approach is the one that can best meet the challenges driven by global change and ensure the proper management of natural habitats. In contrast with indices based upon a species, or a group of species belonging to a given taxon, that may not detect a strong impact on the ecosystem, and even erroneously suggest a 'good ecological status', indices based on the functioning of the entire ecosystem, from primary producers to top predators, such as Ecosystem-Based Quality Indices (EBQIs), provide a realistic assessment of the ecological status. EBQIs have already been established for northwestern Mediterranean marine ecosystems: the *Posidonia oceanica* seagrass meadow, underwater marine caves and infralittoral reef macroalgal forests. They are currently being developed for coralligenous habitats, saltmarshes and circalittoral coastal detritic bottoms. The ecosystem-based approach can be applied to all types of ecosystem and it is important now to extend this approach to other ecosystems and regions. Ecosystem-based management and EBQIs are not incompatible with specific management measures based upon certain iconic species, which are also part of an ecosystem. The interest of ecosystem-based management is that it is not limited to the accumulation of specific management measures for iconic species, which can be mutually incompatible.

INTRODUCTION

To put things simply, we may consider that environmental issues have been addressed, successively over time or simultaneously, on the basis of three different approaches (Boudouresque *et al.* 2020). (i) The earliest is the 'human-centered' approach; this was characterized by the dichotomy between 'useful' species (for man) and pests (competitors of humans). The concept of ecosystem goods and services can be considered as a modern form of this approach (Balmford & Bond 2005, Pesche *et al.* 2013, Nordlund *et al.* 2016, Paoli *et al.* 2017). (ii) The species-centered approach (or species-by-species approach) was characteristic of the 20th century and remains the most common approach adopted in many countries and by several international agencies; it is supported by groups of experts working on a given taxon ('taxonomic lobbies'). It is based upon outstanding species (a fuzzy concept, including iconic species), which are designated as deserving appropriate management for a variety of reasons (attractive in appearance, rare, emblematic, threatened, etc.), in contrast to 'ordinary' species. (iii) Finally, the 21st century ecosystem-based approach, although still rarely used, is the one that can best embrace the challenges driven by global change and ensure the proper management of natural habitats (see below).

In order to assess the quality of the natural environment, the measurement of the physical-chemical parameters is necessary, but very insufficient and often meaningless: it is not the content in the water of a contaminant (*e.g.*, mercury) which is important *per se*, but its possible impact on individuals, populations or ecosystems (Alava *et al.* 2018, Outridge *et al.* 2018). It is for this reason that biological indicators, describing the state of environmental health on the basis of species, have been developed. In addition, the species integrate the characteristics of the environment over their entire lifespan (from a few months to several decades); their presence or absence is therefore easier to interpret, and less costly in terms of time and money, than physical-chemical measurements which are extraordinarily variable from one hour to the next, from one day to the next, etc. (*e.g.*, Pergent 1991, Casazza *et al.* 2002, Dauvin *et al.* 2010, Romero *et al.* 2015).

Ideally, a biological indicator should be (i) sufficiently sensitive to provide an early warning of change, (ii) based on species distributed over a broad geographical area, (iii) capable of providing a continuous assessment over a wide range of stress, (iv) relatively independent of sample size, (v) easy and cost-effective to measure, (vi) able to differentiate natural cycles or trends from those induced by humans, and (vii) relevant to ecologically significant phenomena (Noss 1990, Rombouts *et al.* 2013).

Here, we retrace the history of biological indicators, based on one or more taxa (taxon-based indicators), or on all of the taxa and their interactions in the framework of the ecosystem (ecosystem-based indicators) in the Mediterranean. Without questioning the usefulness of indicators based on a single taxon, which perfectly meet the objective assigned to them, we show the leap forward represented by indicators based on the ecosystem, in terms of management of natural environments and particularly coastal marine habitats.

THE AGE OF TAXON-BASED INDICATORS

In the framework of European Union (EU) directives, mainly the Habitats Directive of 1992 (HD: 92/43/ECC), the Water Framework Directive of 2000 (WFD: 2000/60/EC) and the Marine Strategy Framework Directive of 2008 (MSFD: 2008/56/EC), a number of biological indices have been developed. Their aim is to assess the water quality, at local scale or at the scale of large water bodies. Some of them are particularly efficient and are today widely used to monitor the water quality and to assess its required improvement at the scale of the EU coastline and that of some neighboring countries. They can be grouped into three main categories. (i) Indices based on morpho-functional groups of macroalgae; the EEI (Ecological Evaluation Index) compares opportunistic (r) *vs* K strategist groups; it has been developed and steadily improved by Orfanidis *et al.* (2001, 2003, 2011) and Simboura *et al.* (2005) (but see Iveša *et al.* 2009). (ii) The CARLIT index is based upon a dozen species and groups of species thriving in the upper infralittoral and in the midlittoral stages (stages *sensu* Pérès & Picard 1964), *e.g., Cystoseira* spp. (brown algae), *Ulva* sp. (green algae), articulated corallines (red algae) and the mussel *Mytilus galloprovincialis*. The very shallow or above sea level habitat of the taxa taken into account enables the exhaustive mapping of the coastline over hundreds and even thousands of kilometers (Ballesteros *et al.* 2007, Bermejo *et al.* 2013, Nikolić *et al.* 2013, Blanfuné *et al.* 2016, Torras *et al.* 2016, Blanfuné *et al.* 2017, De la Fuente *et al.* 2018). (iii) A number of biological indices are based on the seagrass *Posidonia oceanica* (Linnaeus) Delile, which plays a pivotal role in the functioning of Mediterranean coastal areas, and is sensitive to a wide range of human impacts (Molinier & Picard 1952, Boudouresque *et al.* 2006, 2009, 2012, Bonhomme *et al.* 2013, Giakoumi *et al.* 2015, Boudouresque *et al.* 2016). The BiPo index (Biotic Index based on *Posidonia oceanica*) combines four metrics: maximum depth of the meadow, declining or progressing trend of the depth limit, shoot density and leaf surface area at 15 m depth (Lopez y Royo *et al.* 2010). The PREI index (*Posidonia oceanica* Rapid Easy Index) includes the same metrics plus a fifth, the ratio between epiphyte biomass and leaf biomass (Gobert *et al.* 2009). The POMI index (*Posidonia oceanica* Multivariate Index) combines 11 metrics at the physiological level (*e.g.*, nitrogen, phosphorus and carbohydrate content in rhizomes), the individual level (*e.g.*, leaf surface area per shoot), the population level (shoot density, % of plagiotropic rhizomes, meadow cover) and the contamination level (nitrogen content of leaf epibionts and trace metals) (Romero *et al.* 2007). These indices are robust, with congruent results when compared with each over (Bennett *et al.* 2011, Lopez y Royo *et al.* 2011, Mascaró *et al.* 2012, Gerakaris *et al.* 2017). Other taxon-based indicators have been proposed: Conservation Index (CI) (Moreno *et al.* 2001), Substitution Index (SI) (Montefalcone *et al.* 2007a), Phase Shift Index (PSI) (Montefalcone *et al.* 2007b, Montefalcone 2009, Rigo *et al.* 2019). According to Boudouresque *et al.* (2012), CI, SI and PSI can be relevant to assess changes over time in *P. oceanica* seagrass meadows linked to global change (warming, anthropogenic impact, community shift, etc.). Finally, the content in phenolic compounds increases with stress and represents a generic indicator of different environmental stressors (Mannino & Micheli 2020).

The relevance of these biological indices has been validated by putting them in correlation with some of the anthropogenic pressures impacting the study area (*e.g.*, land area covered by urbanization, industrial and agricultural activities, particulate organic matter and nitrogen input), *via* pressure indices such as LUSI (Land Use Simplified Index) and HAPI (Human Activities and Pressure Index) (Flo *et al.* 2011, Bacci *et al.* 2013, Blanfuné *et al.* 2017). The MCAI (Multi-criteria Anchoring Index) measures the impact of anchoring on *Posidonia oceanica* meadows (Rouanet *et al.* 2013, Schohn *et al.* 2019). The relevance of these biological indices has also been validated through their ability to detect changes over time; these changes reflect the effectiveness of the EU water quality improvement policy (establishment of sewage treatment plants, reduction of air pollution, a major source of sea water contamination, etc.) (Blanfuné *et al.* 2017, De la Fuente *et al.* 2018, Shin *et al.* 2018).

THE AGE OF ECOSYSTEM-BASED INDICATORS

The MSFD is considered to be the environmental pillar of the Integrated Maritime Policy adopted in 2010 by the European Commission (IMP: 2010/477/EU). This directive established eleven criteria, to determine 'good environmental status' (GES): (i) biological diversity is maintained; (ii) introduced species are at levels that do not adversely alter the ecosystems; (iii) populations of all exploited fish and shellfish are safely within biological limits; (iv) all elements of the food webs are maintained at adequate levels to ensure the long-term abundance of the species; (v) human-induced eutrophication is at a minimum; (vi) sea-floor integrity is at a level that ensures that the structure and functions of the ecosystems are safeguarded; (vii) permanent alteration of hydrographical conditions does not adversely affect marine ecosystems; (viii) concentrations of contaminants are at levels that do not give rise to pollution effects; (ix) contaminants in fish and other seafood do not exceed levels established by Community legislation; (x) properties and quantities of marine litter do not cause harm to the coastal and marine environment; and (xi) inputs of energy are at levels that do not adversely affect the marine environment.

The MSFD includes a major innovation: the ecosystem-based approach (Laffoley *et al*. 2004, Bryhn 2020); it appears in particular in criteria ii, iv, vi and vii. This approach is not to the taste of supporters of the species-by-species approach nor of the taxonomic lobbies, who seek to promote their beloved taxon (marine mammals, sea turtles, etc.), confuse habitat and ecosystem, and find it difficult to reflect at the level of the ecosystem. However, taxon-based indicators and ecosystem-based indicators are neither mutually exclusive, nor in opposition to each over, but simply complementary: they just do not measure the same thing (see below).

Fisheries managers were the pioneers of the ecosystem-based approach, under the names of EAF (Ecosystem Approach to Fisheries), EAFM (Ecosystem Approach to Fisheries Management) and EBFM (Ecosystem-Based Fishery Management) – Hereafter EBFM (Ward & Hegerl 2003, Pikitch *et al*. 2004, Turrell 2004, Rice 2005, Tudela & Short 2005). According to Turrell (2004), "*1. All aspects of the ocean are interrelated and should be treated as an integral whole. 2. In order to achieve a more rational management of resources and thus to improve the environment, States should adopt an integrated and co-ordinated approach to their development planning so as to ensure that development is compatible with the need to protect and improve environment for the benefit of their population*". But in fact, the real pioneers and promoters of the ecosystem-based approach were the authors of the Ecopath, the Ecopath with Ecosim and the Osmose models and their subsequent users (*e.g*., Christensen & Pauly 1992, 1993, Polovina 1993, Opitz 1996, Walters *et al*. 1997, Bănaru *et al*. 2013, Coll *et al*. 2015, Piroddi *et al*. 2017, Bănaru *et al*. 2019, Hermosillo-Núñez 2020).

The taxon-based indicators do not provide information on the quality of the ecosystem, but on the quality of the water bodies: water transparency, nutrient and contaminant content, etc. It is, moreover, for this latter objective that they were designed. The quality of the ecosystem naturally depends on the quality of the water, but other parameters can be more important: habitat destruction, overfishing, biological invasions, etc. This obvious point was illustrated in a diagram, in a somewhat caricatural way, by Boudouresque *et al*. (2015) (Fig. 1).

MEDITERRANEAN ECOSYSTEM-BASED INDICATORS

The rationale governing the EBQIs (Ecosystem-Based Quality Indices) is based on (i) attempting to quantify and assess some compartments (*e.g*., boxes 1 through 13 for the *Posidonia oceanica* ecosystem – EBQI/Pos; Fig. 2) of the conceptual model by means of a set of parameters, (ii) determining their relative weight and (iii) by using a

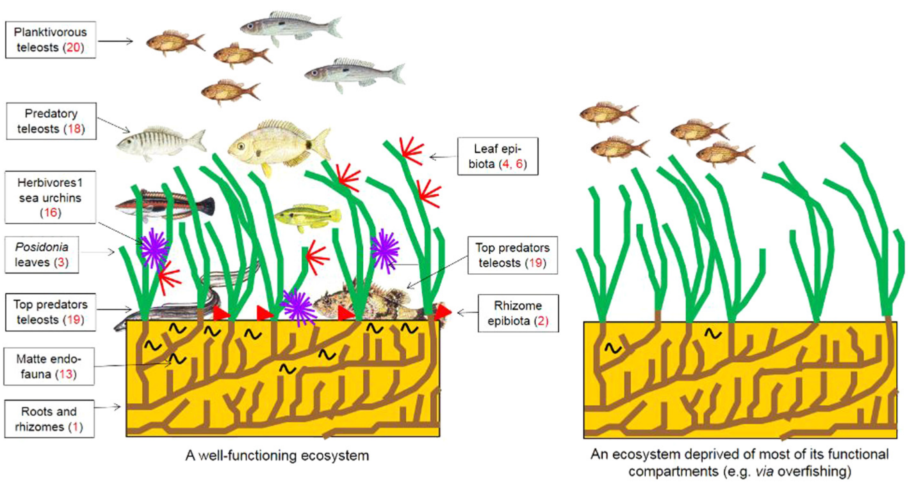

Fig. 1. – *Left*. A pristine *Posidonia oceanica* ecosystem, with species belonging to all functional compartments (for compartment numbers, see Fig. 2). *Right*. A *P. oceanica* meadow deprived of most of its functional compartments (*e.g*., *via* overfishing), which could be considered as healthy on the basis of taxon-based indicators, based upon metrics such as shoot density and meadow coverage. From Boudouresque *et al*. (2015), modified and redrawn).

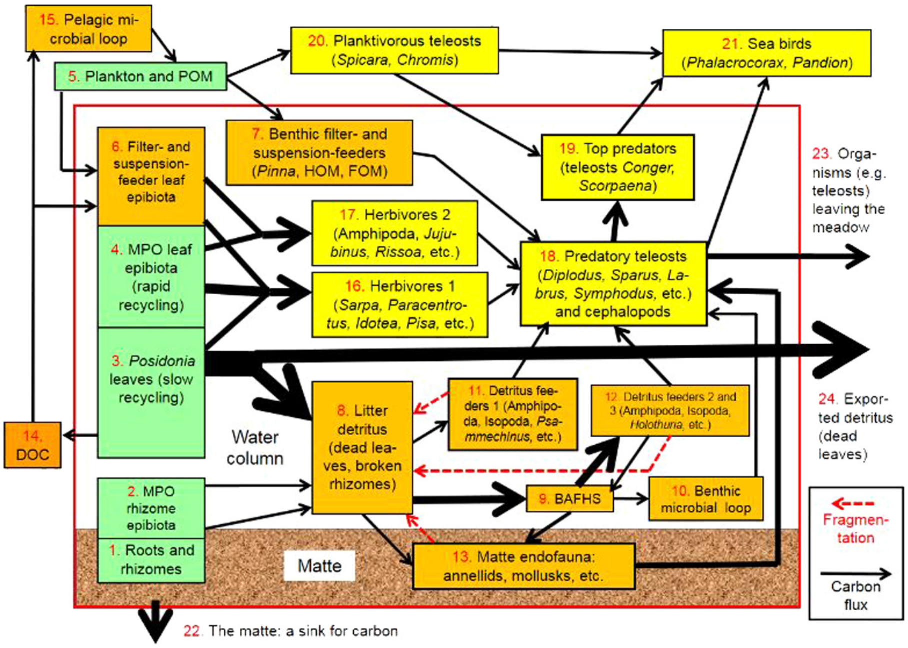

Fig. 2. – A conceptual model of the functioning of the *Posidonia oceanica* seagrass ecosystem. Functional compartments *(boxes)*: primary producers are in *green*; filter feeders, suspension feeders, litter, detritus feeders, dissolved organic carbon (DOC) and microbial loops are in *orange*; predators (including herbivores) are in *yellow*. POM: particulate organic carbon. BAFHS (bacteria, archaea, fungi and heterotrophic stramenopiles) are involved in the litter degradation. The width of the arrows roughly represents the volume of the carbon flow. The *P. oceanica* ecosystem properly speaking is included within the red rectangle. Boxes 1 through 13 correspond to the compartments *(boxes)* taken into account by the EBQI/Pos. From Boudouresque *et al.* (2015), adapted.

simple algorithm, calculating a rank for the ecosystem status within a given area, matching the five classes of the ecological status of the EU Water Framework Directive (WFD), from bad to high. In addition, (iv) it should be based on metrics that are easy to measure, species that do not require great taxonomic expertise for determination, and therefore able to be implemented routinely by managers; this implementation may require that a training course be organized for managers. EBQIs are a compromise between the completeness of the assessment and the need for an approach that is not too time-consuming (*e.g*., less than one day for 4 divers per site for EBQI/Pos) (Ruitton *et al*. 2013, Personnic *et al*. 2014, Boudouresque *et al*. 2015, Ruitton *et al*. 2017).

The status of each functional compartment (box) is assessed by means of a semi-quantitative scale (4 through 0), from very good (4) to very bad (0). Calibration of the scale is based upon the available literature. Compartments are weighted according to their relative importance in the ecosystem functioning, from 5 (highest weighting) to 1 (lowest weighting). The grade for each compartment is determined by its status (0 through 4), multiplied by its weighting (1 through 5), and is therefore graded from 0 to 4 and 0 to 20 (depending upon the weighting of the considered compartment). The grades of all compartments are added up to give the final grade for the ecosystem status (EBQI) at a given site. For practical purposes, the EBQI is converted to a scale from 0 to 10 (*e.g*., Table I for EBQI/Pos) (Personnic *et al*. 2014, Boudouresque *et al*. 2015, Ruitton *et al*. 2017). In the case of the EBQI/Pos, which considers 13 functional compartments:

$$EBQI = \left[\sum_{i=1}^{13} (W_i \times S_i) / \sum_{i=1}^{13} (W_i \times S_{max}) \right] \times 10$$

where: W_i is the weighting of the box i, S_i the status of the box i, S_{max} the highest possible grade (= 4) for a box and i is the number of the box (1 through 13).

For each box, each value of the box status and each site, a Confidence Index (CI) is proposed (Table II). The reason for the CI is (i) that data for one or several compartments may be missing or of poor quality at some sites, (ii) the reliability of available data may be different between boxes and sites, and (iii) it is worth drawing the attention of managers and scientists to those boxes (compartments) that are poorly known and which merit further field studies. The grade of each considered box is given by its CI (0 through 4) and by its weighting (1 through 5), and they are therefore graded from 0 through 20 (for EBQI/Pos). The grades of all considered boxes are added up, which gives the final grade for the CI at a given site. For practical purposes, the CI was converted to a scale from 0 to 4 (Personnic *et al*. 2014, Ruitton *et al*. 2017). In the case of the EBQI/Pos, which considers 13 functional compartments:

$$CI_{EBQI} = \left[\sum_{i=1}^{13} (W_i \times CI_i) / \sum_{i=1}^{13} (W_i \times CI_{max}) \right] \times 4$$

where W_i is the weighting of the box i, CI_i the Confidence Index of the box i, CI_{max} the highest possible Confidence Index (= 4) for a compartment (box) and i is the number of the box (1 through 13).

The first attempt to build an EBQI concerned the *Posidonia oceanica* ecosystem (EBQI/Pos) (Personnic *et al*. 2014, Boudouresque *et al*. 2015, Ruitton *et al*. 2017), one of the Mediterranean ecosystems for which the data available on the functioning and the different compartments are the most extensive (*e.g*., Bell & Harmelin-Vivien 1983, Mazzella *et al*. 1992, Pergent *et al*. 1994, 1997, Boudour-

Table I. – Conservation status of the *Posidonia oceanica* ecosystem (EBQI/Pos) in Balearic Islands, Spanish and French Catalonia, West and East Provence, French Riviera and Corsica. For each compartment (see Fig. 2): the weighting (1 through 5) and the status grade (0 through 4) at the 17 studied localities. EBQI ranges from 0 to 10. SRDI: Specific Relative Diversity Index of fish. Ecological status classes: high (deep blue), good (light blue), moderate (green), poor (orange) and bad (red). From Boudouresque *et al.* (2015), adapted.

	Compartment	1	2	3-4	5	6	7	8	9	10	11	12	SRDI	13	EBQI.Pos
	Weight	3	5	4	2	2	2	2	5	5	5	3	3	1	
	Espardell (Balearic Islands)	4	4	3	3	3	3	3	3	1	1	1	3	2	6.4
	Sitges (Spanish Catalonia)	2	0	0	0	2	2	2	3.5	0	0	1	0	0	2.3
	Tossa de Mar (Spanish Catalonia)	2	3	4	0	2	2	4	3	2	0	2	3	1	5.6
L	Medes Islands (Spanish Catalonia)	2	3.5	4	3	2	2	2	2.5	4	4	3	4	2	7.9
O	Peyrefite Bay (French Catalonia)	2	3.5	2	4	2	2	2	2	3	1	1.5	4	0	5.8
C	Niolon (West Provence)	2	2.5	2	0	1.5	1	3	2	1	0	2	2	1	3.9
A	Prado Bay (West Provence)	2	2.5	2	0	2.5	2	3	2.5	3	1	1.5	3	2	5.3
L	Plateau des Chèvres (West Provence)	2	2.5	4	0	1.5	2	3	2.5	2	1	0.5	2	2	5.0
I	Saint-Cyr Bay (East Provence)	1	3	2	1	2	2	2	2	2	2	2	2	0.5	4.9
T	Gulf of Giens (East Provence)	3	4	2	2	2	1	3	1.5	1	0	1	1	0.5	4.3
I	Porquerolles North (East Provence)	3	2	3	2	2	0	1	1.5	1	1	2	2	1	4.3
E	Porquerolles South (East Provence)	3	4	4	3	3	3	2	2	2	2	3	3	1	6.9
S	Bagaud Pass (East Provence)	4	3	2	4	3	4	4	3	3	2	3	4	1	7.6
	Port-Cros South (East Provence)	4	4	4	4	3	4	3	3.5	4	4	3	4	1.5	9.3
	Villefranche Bay (French Riviera)	2	1.5	2	1	3	0	0	2	3	2	1.5	4	0	4.8
	Elbu Bay, Scàndula (Corsica)	4	3	1	4	3	2	2	2	2	1	1.5	3	4	5.7
	Valincu Gulf (Corsica)	4	3	2	2	2	2	3	2	2	2	2	2	1	5.4

Table II. – Criteria to assess the Confidence Index (CI) of the status of a compartment.

CI	Criteria
4	Field data available, recent and suitable with the recommended methods
3	Field data recent, partially completed with expert judgment
2	No quantitative field data but recent expert judgment
1	No quantitative field data, but non-recent expert judgment
0	No quantitative field data and no suitable expert judgment

esque *et al.* 2006, 2012, Deudero *et al.* 2014, Giakoumi *et al.* 2015, Ourgaud 2015, Ourgaud *et al.* 2015, Boudouresque *et al.* 2016).

Subsequently, the concept of EBQI was generalized and theorized (Ruitton *et al.,* 2013, 2017): (i) construction of a conceptual model of the ecosystem on the basis of existing literature; (ii) evaluation of carbon and/or nutrient flows between compartments, with weighting of their volume when possible (Fig. 3); (iii) choice of compartments that can be taken into account routinely (minimization of the sampling effort); (iv) weighting of these compartments (on a scale of 1 to 5) (Fig. 3); (v) assessment of the ecological status of the compartments taken into account (Fig. 4); (vi) calculation of the EBQI and CI for each locality. The decisions concerning all these steps are made through an expert meeting and a Delphi process (see Dalkey & Helmer 1963 for the Delphi process).

EBQIs were proposed for the Mediterranean undersea cave ecosystem, EBQI/Caves (Rastorgueff *et al.* 2015, Ruitton *et al.* 2017) (Fig. 5) and for shallow rocky reefs dominated by macroalgae, EBQI/Reefs (Ruitton *et al.* 2017, Thibaut *et al.* 2017) (Fig. 6). Undersea caves are remarkable infralittoral and circalittoral habitats widespread throughout the Mediterranean Sea (*e.g.*, Marseille area, Croatia) (Chevaldonné & Lejeusne 2003; Surić *et al.* 2010). They often originate from the marine flooding of karstic networks during the post-glacial maximum transgression; they harbor specialized species, which are often Mediterranean endemics; some of them are regular bathyal and abyssal dwellers, which find in these caves environmental conditions similar to those of the deep sea (Harmelin *et al.* 1985, Vacelet *et al.* 1994, Bianchi *et al.* 1996, Janssen *et al.* 2013, Rastorgueff *et al.* 2015). Shallow rocky reefs dominated by macroalgae are also an infralittoral ecosystem. The ecosystem is characterized by *Cystoseira* (long-living brown algae – Stramenopiles; *Cystoseira sensu lato*) forests which can shift to barren grounds when herbivorous sea urchins (such as *Paracentrotus lividus* (Lamarck, 1816) proliferate; this proliferation is related to a disturbance of the ecosystem, such as overfishing of fish predators of sea urchins and organic pollution (Sala & Zabala 1996, Bonaviri *et al.* 2011, Boudouresque & Verlaque 2013, Ling *et al.* 2015, Thibaut *et al.* 2017).

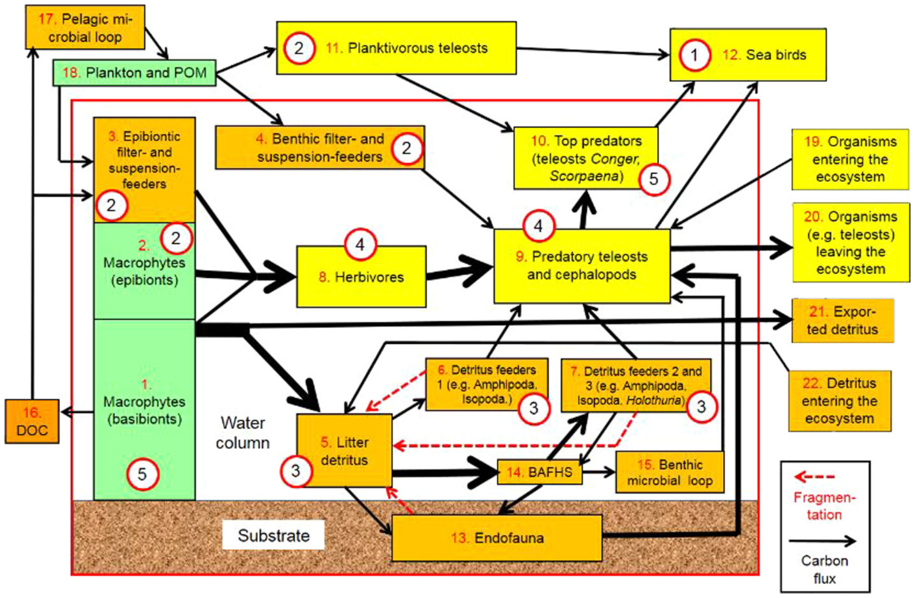

Fig. 3. – Conceptual model of a theoretical ecosystem (fictitious data). Compartments 1 through 12 are taken into account for designing the EBQI. Their weight (numbers in red circles) is established *via* expert judgement by means of a Delphi process. Primary producers are in green; filter feeders, suspension feeders, litter, detritus feeders, dissolved organic carbon (DOC) and microbial loops are in orange; predators (including herbivores) are in yellow. POM: Particulate Organic Matter). BAFHS: bacteria, archaea, fungi and heterotrophic stramenopiles involved in the litter degradation. The width of the arrows roughly represents the volume of the carbon flow. The ecosystem properly speaking is included within the red rectangle. From Ruitton *et al.* (2017), adapted and redrawn.

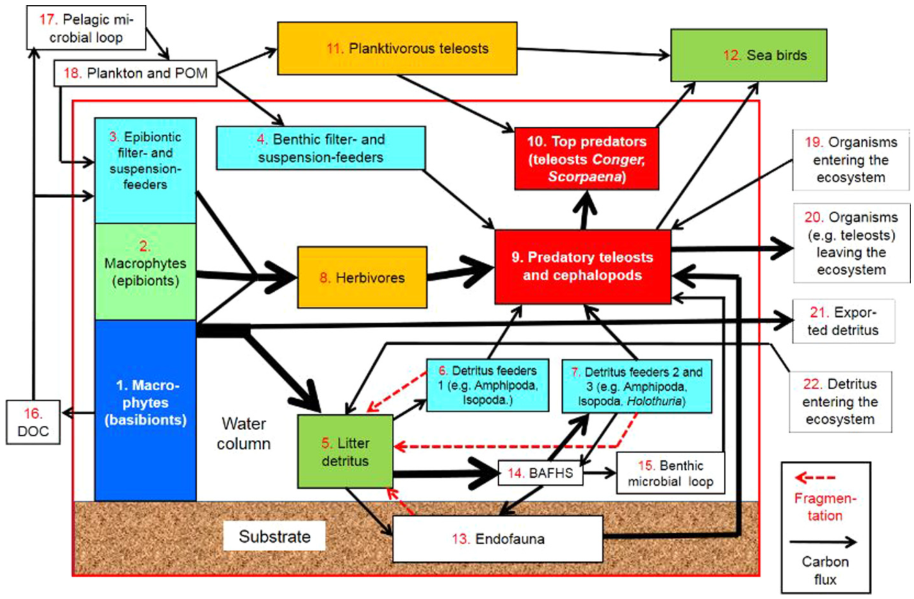

Fig. 4. – Conceptual model of a theoretical ecosystem (fictitious data). Assessment of the ecological status of the compartments taken into account: high (deep blue), good (light blue), moderate (green), poor (orange) and bad (red). From Ruitton *et al.* 2017, adapted and redrawn.

EBQIs are being developed for the coralligenous ecosystem (EBQI/Cor) (Ruitton *et al*. 2014, 2017), salt marshes and coastal lagoons (EBQI/sm) (Massinelli *et al*. 2017, Astruch *et al*. 2019a) and circalittoral coastal detrital sandy bottoms (EBQI/cd) (Astruch *et al*. 2019b). They are at the conceptual model development stage, choosing the compartments that can be used routinely and testing the metrics. The EBQI/Cor is even ready for publication (Ruitton *et al*. 2017).

Certain works, although they do not lead to the calculation of an EBQI, can clearly be referred to as exemplifying an ecosystem-based approach. For example, Bănaru *et al*. (2010) show in the Black Sea the switch from a complex top-down and bottom up functioning pattern of the coastal ecosystem (1965-1970) to a bottom-up pattern (2001-2005). The end-to-end model of the Gulf of Lions ecosystem (NW Mediterranean) is also referable to an ecosystem-based approach (Bănaru *et al*. 2019). They explicitly detail trophic flows between food web compartments, highlight the main primary producers and successive consumers as well as dominant and key species. Fisheries pressure on food web compartments and their direct and indirect effects may also be highlighted (Bănaru *et al*. 2013). These models allow depiction the combined effects of both climate and fisheries on the system functioning (Bănaru *et al*. 2019, Diaz *et al*. 2019). Astruch *et al*. (2019a) highlighted the need for an EBA within the saltmarshes of Hyères (Provence, France) as a way to make the management system more appropriate, evolving from a previous species-centered approach (*e.g.*,

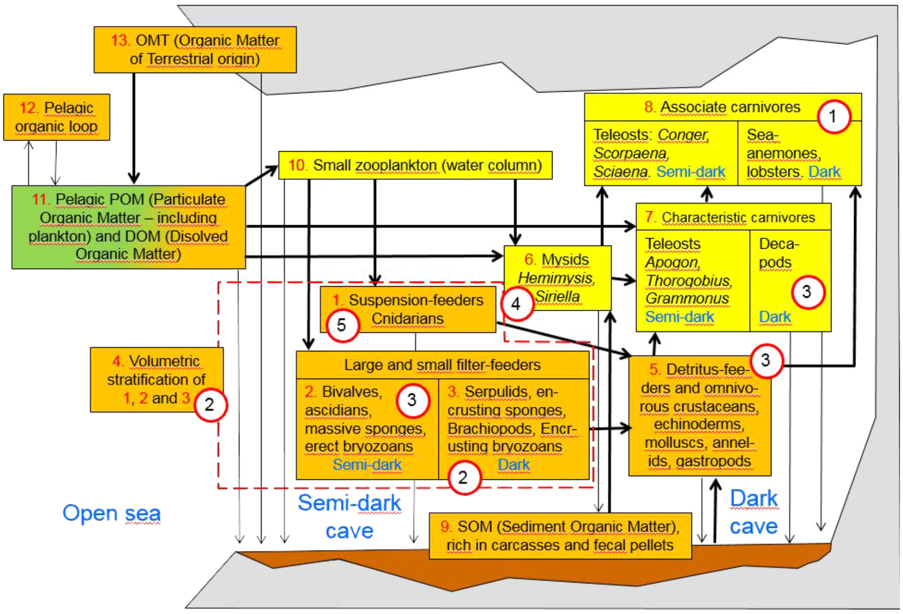

Fig. 5. – Conceptual model of structure and functioning of the Mediterranean undersea cave ecosystem. Compartments 1 through 8 are taken into account for designing the EBQI/Caves. Their weight is indicated by numbers in red circles. Primary producers are in green; filter feeders, suspension feeders, litter, detritus feeders, dissolved organic carbon (DOC) and microbial loops are in orange; predators (including herbivores) are in yellow. Distinction between semi-dark and dark caves appears in the bottom of concerned compartments. Arrows represent the intensity of the flux of organic matter between compartments (wide *vs* narrow arrows). From Rastorgueff *et al.* (2015) and Ruitton *et al.* (2017). Adapted and redrawn.

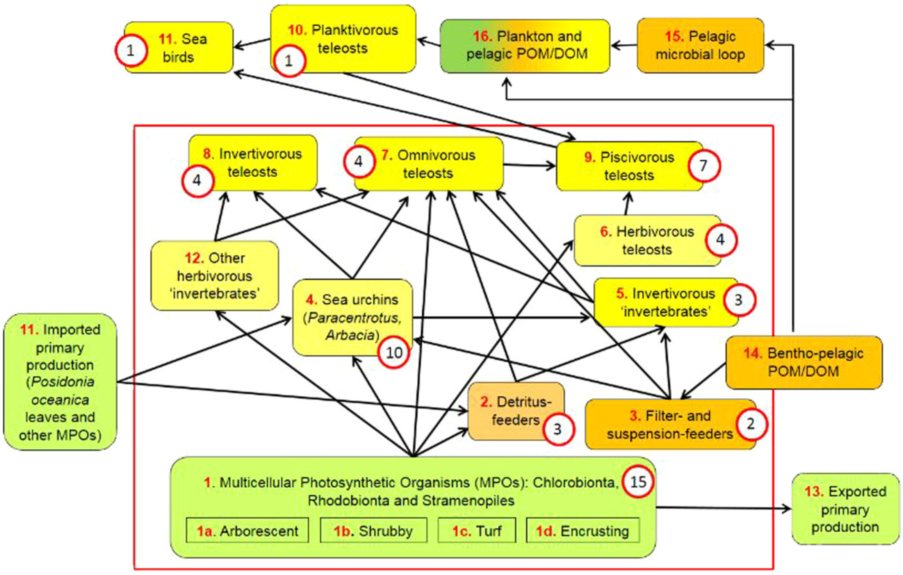

Fig. 6. – Conceptual model of structure and functioning of the Mediterranean shallow rocky reefs dominated by macroalgae. Compartments 1 through 10 are taken into account for designing the EBQI/Reefs. Their weight is indicated by numbers in red circles. Primary producers are in green; filter feeders, suspension feeders, litter, detritus feeders, dissolved organic carbon (DOC) and microbial loops are in orange; predators (including herbivores) are in yellow. The ecosystem properly speaking is included within the red rectangle. Arrows represent the flux of organic matter between compartments. From Thibaut *et al.* (2017) and Ruitton *et al.* (2017). Adapted and redrawn.

waterfowl enhancement, fight against so-called 'harmful species' such as the red fox *Vulpes vulpes*, etc.).

ECOSYSTEM-BASED INDICATORS: VALUABLE TOOLS FOR COASTAL MANAGEMENT

Environmental management is often perceived by managers and the general public as 'firefighter's work', which consists of putting out fires, running from one fire to another. A 'fire' is a species of which the abundance increases, or on the contrary decreases, a changing landscape, etc. This management approach is also deeply biased by taxonomic lobbies: a species of dolphin or bird, even if nothing indicates a decline, is the subject of multiple management programs, while a species of insect or macroalga, seriously threatened or even on the brink of extinction, is of little interest to NGOs and the general public (Boudouresque 2002, Thibaut *et al.* 2016, Verlaque *et al.* 2019). It is significant that (since 1992) 46 % of the European programs intended for the protection of the environment are dedicated to birds, against 26 % to mammals, 8 % to 'invertebrates' 8 % to flowering plants and 6 % to 'fish'; insects and macroalgae are not even mentioned (Tempier 2018, Mammides 2019). Members of a taxonomic lobby are not aware of this, because they are really attached to their preferred taxon, but management based on taxa is sometimes akin to a *millefeuille* (a French multi-layered cake): a layering of taxon-focused protection measures, the addition of measures to enhance

Table III. – Comparison between EBQI/Pos (from Personnic *et al*., 2014) with taxon-based indices based mainly upon *Posidonia oceanica* (the organism itself) and aimed at establishing the ecological status of a seawater body. Ecological status: high (deep blue), good (light blue), moderate (green), poor (orange) and bad (red). From Personnic *et al*. (2014) and Boudouresque *et al*. (2015), adapted. EBQI/Pos ranges from 0 (lowest ecological status) to 10 (highest ecological status. PREI, POMI and BiPo indices, based upon distinct but similar metrics, range from 0 (lowest ecological status) to 1 (highest ecological status). * See text for the metrics of PREI, POMI and BiPo.

Locality (region)	EBQI/Pos	Taxon-based index	Type of taxon-based index	Reference
Port-Cros Island, south (East Provence)	9.3	0.80	PREI*	Gobert *et al.* (2009)
Medes Islands (Spanish Catalonia)	7.9	0.75	POMI*	Romero *et al.* (2007)
Elbu Bay, Scàndula (Corsica)	5.7	0.80	BiPo*	Lopez y Royo *et al.* (2010)
Tossa de Mar (Spanish Catalonia)	5.6	0.68	POMI	Romero *et al.* (2007)
Valincu Gulf (Corsica)	5.4	0.39	PREI	Gobert *et al.* (2009)
	5.4	0.73	BiPo	Lopez y Royo *et al.* (2010)
Prado Bay, Marseilles (West Provence)	5.3	0.64	PREI	Gobert *et al.* (2009)
Plateau des Chèvres, Marseille (West Provence)	5.0	0.48	PREI	Gobert *et al.* (2009)
Saint-Cyr Bay (East Provence)	4.9	0.68	PREI	Gobert *et al.* (2009)
Villefranche-sur-Mer Bay (French Riviera)	4.8	0.28	PREI	Gobert *et al.* (2009)
Gulf of Giens (East Provence)	4.3	0.71	PREI	Gobert *et al.* (2009)
Porquerolles North (East Provence)	4.3	0.82	PREI	Gobert et al. (2009)
Niolon, Côte Bleue (West Provence)	3.9	0.47	PREI	Gobert et al. (2009)
Sitges (Spanish Catalonia)	2.3	0.24	POMI	Romero *et al.* (2007)

a declining species or to hinder another species which is proliferating, regardless of the fact that the latter may be the predator of the former. The indices based on a taxon were not designed to manage taxa, but to assess the quality of a water body, and the effectiveness of measures intended to improve this quality, for example the establishment of sewage treatment plants. But for many stakeholders, if the indices based on *Posidonia oceanica* show positive results, it means that *P. oceanica* is fine, and if *P. oceanica*, an ecosystem engineer, is fine, the whole environment is fine. However, this is not always the case, as shown in Fig. 1: *P. oceanica* can thrive in a highly degraded ecosystem.

There is no significant correlation between taxon-based indices and ecosystem-based indices, as shown by the comparison between the EBQI/Pos and taxon-based indices (PREI, POMI, BiPo) for the same localities (Table III) (Personnic *et al*. 2014, Boudouresque *et al*. 2015). This is logical, since the two categories of indicators were designed to highlight different things, respectively the quality of the functioning of an ecosystem and the quality of a water body, but it is important to emphasize it again. The contrasting ranking of Porquerolles Island (north coast) from EBQI (poor) to PREI (high, first rank) (Table III), together with those of the Gulf of Giens, may be due to impacts other than the water quality, such as artisanal and recreational overfishing.

Ecosystem-based management and EBQIs are not incompatible with specific management measures based upon certain iconic species, which are also part of an ecosystem. The interest of ecosystem-based management is that it is not limited to the accumulation of specific management measures for iconic species, which can be mutually incompatible when, for example, an iconic species proliferates at the expense of other iconic species in the same habitat.

The spread of invasive species is considered as one of the most worrying environmental issues in the 21st century (Schmitz & Simberloff 1997, Canning-Clode 2015, Maxwell *et al*. 2016). The Mediterranean Sea is the region worldwide most severely hit by invasive species, with more than 800 non-indigenous species (Verlaque *et al*. 2015, Zenetos *et al*. 2017, Galil *et al*. 2018). Invasive species can deeply alter the food webs and the functioning of marine ecosystems (Vitousek *et al*. 1996, Boudouresque *et al*. 2005, Thomsen *et al*. 2016, Boudouresque *et al*. 2017a; David *et al*. 2017). Although an index accounting for invasive species has been proposed (ALEX – Alien Biotic Index) (Piazzi *et al*. 2015, 2018), food web approach (see *e.g*., David *et al*. 2017) and EBQIs are the most effective tools for tracking their overall impact on the ecosystem.

Overfishing is also one of the major environmental pressures that affect marine ecosystems, *via* extirpation of target species, reducing the top predators compartment, reducing the mean trophic level ('fishing down the food web') and increasing the abundance of herbivorous sea urchins (Pauly *et al*. 1998, Sala *et al*. 1998, Pauly & Palomares 2005, Myers *et al*. 2007, Sala *et al*. 2012, Boudouresque & Verlaque 2013, Boudouresque *et al*. 2017a, Bryhn *et al*. 2020). Obviously, EBQIs tackle fishery pressure better than taxon-based indices in coastal areas. On a larger scale, offshore ecosystem functioning indices are proposed to highlight the state of ecosystems and relate it to the pressure of fisheries (Coll *et al*. 2016, www.indiseas.org).

The ecosystem-based approach can be applied to all types of ecosystems and it is important now to extend this approach to the pelagic ecosystems and their coupling with benthic ecosystems, infralittoral sandy bottoms, the beach-dune-*Posidonia oceanica banquette* ecosystem (see Boudouresque *et al*. 2017b, Otero *et al*. 2018), the deep sea and terrestrial ecosystems. Obviously, application perspectives of the EBA must reach areas away from the northwestern Mediterranean: eastern, central and southern Mediterranean, and worldwide coastal areas.

CONCLUSIONS

Ecosystem-based indices are the natural tools required for ecosystem-based management. They allow a comprehensive approach to the management of natural coastal areas, in particular Marine Protected Areas. They provide answers to different questions compared to taxon-based indices and are therefore not in opposition to them. It is obvious that the management of an ecosystem is much more complex than that of a single species or group of species. However, ecosystem-based management, and therefore ecosystem-based indices, represents the future. It will take time for stakeholders and the general public to understand that the complexity of the functioning of ecosystems can lead to responses which, at times, are counter-intuitive, but much more realistic and effective.

There is ever-increasing evidence of global change occurring. For example, in the eastern Mediterranean Sea, community-shift is dramatically altering ecosystem functions and services, leading to new ecosystems, most often less effective than the native ones. Monitoring and combating these major challenges must be undertaken at ecosystem scale, taking into account the whole functioning of the impacted ecosystems.

ACKNOWLEDGEMENTS. – The authors are indebted to B Daniel and A Pibot (Office Français de la Biodiversité) for the stimulating discussions we had, M Perret-Boudouresque for documentation assistance, and to M Paul, a native English speaker, for proofreading the text.

REFERENCES

Alava JJ, Cisneros-Montemayor AM, Sumaila UR, Cheung WWL 2018. Projected amplification of food web bioaccumulation of MeHg and PCBs under climate change in the Northeastern Pacific. *Sci Rep* 8(13460): 1-12.

Astruch P, Boudouresque C., Changeux T, Faget D, Lascève M, Le Diréach L, Massinelli L, Moussy F 2019a. From a species-centred to an ecosystem-based management approach, a case study of the saltmarshes of Hyères (Provence, France). *In* Gargiulo C, Zoppi C Eds, Planning, Nature and Ecosystem Services. FedOAPress, Naples: 29-38.

Astruch P, Goujard A, Rouanet É, Boudouresque CF, Verlaque M, Berthier L, Daniel B, Harmelin JG, Peirache M, Peterka A, Ruitton S, Thibaut T 2019b. Assessment of the conservation status of coastal detrital sandy bottoms in the Mediterranean Sea: an ecosystem-based approach in the framework of the ACDSEA project. *In* Langar H, Ouerghi A Eds, Proceedings of the 3rd Symposium on the Conservation of Coralligenous and other Calcareous Bio-constructions, Antalya, Turkey, 15-16 January 2019. RAC/SPA, Tunis: 23-29.

Bacci T, Rende SF, Penna M, Trabucco B, Montefalcone M, Cicero AM, Giovanardi F 2013. A methodological approach to understand functional relationships between ecological indices and human-induced pressures: the case of the *Posidonia oceanica* meadow. *J Environ Manage* 129: 540-547.

Ballesteros E, Torras X, Pinedo S, García M, Mangialajo L, de Torres M 2007. A new methodology based on littoral community cartography dominated by macroalgae for the implementation of the European Water Framework Directive. *Mar Pollut Bull* 55: 172-180.

Balmford A, Bond W 2005. Trends in the state of nature and their implications for human well-being. *Ecol Lett* 8: 1218-1234.

Bănaru D, Harmelin-Vivien M, Boudouresque CF 2010. Man induced change in community control in the north-western Black Sea: the top-down bottom-up balance. *Mar Environ Res* 69 (4): 262-275.

Bănaru D, Mellon-Duval C, Roos D, Bigot JL, Souplet A, Jasaud A, Beaubrun P, Fromentin JM 2013. Trophic structure in the Gulf of Lions marine ecosystem (north-western Mediterranean Sea) and fishing impacts. *J Mar Syst* 111-112: 45-68.

Bănaru D, Diaz F, Verley P, Campbell R, Navarro J, Yohia C, Oliveros-Ramos R, Mellon-Duval C, Shin YJ 2019. Implementation of an end-to-end model of the Gulf of Lions ecosystem (NW Mediterranean Sea. I. Parametrization, calibration and evaluation. *Ecol Modell* 401: 1-19.

Bell JD, Harmelin-Vivien ML 1983. Fish fauna of French Mediterranean *Posidonia oceanica* seagrass meadows. 2. Feeding habits. *Tethys* 11(1): 1-14.

Bennett S, Roca G, Romero J, Alcoverro T 2011. Ecological status of seagrass ecosystems: an uncertainty analysis of the meadow classification based on the *Posidonia oceanica* multivariate index (POMI). *Mar Pollut Bull* 62: 1616-1621.

Bermejo R, De La Fuente G, Vergara JJ, Hernández I 2013. Application of the CARLIT index along a biogeographical gradient in the Alboran Sea (European coast). *Mar Pollut Bull* 72: 107-118.

Bianchi CN, Cattaneo-Vietti R, Cinelli F, Morri C, Pansini M 1996. Lo studio biologico delle grotte sottomarine: conoscenze attuali e prospettive. *Bol Mus Ist Biol Univ Genova* 60-61: 41-69.

Blanfuné A, Boudouresque CF, Verlaque M, Beqiraj S, Kashta L, Nasto I, Ruci S, Thibaut T 2016. Response of rocky shore communities to anthropogenic pressures in Albania (Mediterranean Sea): Ecological status assessment through the CARLIT Method. *Mar Pollut Bull* 109(1): 409-418.

Blanfuné A, Thibaut T, Boudouresque CF, Mačić V, Markovic L, Palomba L, Verlaque M, Boissery P 2017. The CARLIT method for the assessment of the ecological quality of European Mediterranean waters: relevance, robustness and possible improvements. *Ecol Indic* 72: 249-259.

Bonaviri C, Vega Fernández T, Fanelli G, Badalamenti F, Gianguzza P 2011. Leading role of the sea urchin *Arbacia lixula* in maintaining the barren state in southwestern Mediterranean. *Mar Biol* 158: 2505-2513.

Bonhomme P, Bonhomme D, Frachon N, Boudouresque CF, Borocco S, Bricout R, Schohn T, Imbert M, Ruitton S 2013. A method for assessing anchoring pressure. *Rapp Comm Int Mer Médit* 40: 845.

Boudouresque CF 2002. Protected marine species, prevention of species introduction and the national environmental agencies of Mediterranean countries: professionalism or amateurishness? *In* Actes du congrès international 'Environnement et identité en Méditerranée', Corte, 3-5 July 2002, Université de Corse Pascal Paoli 4: 75-85.

Boudouresque CF, Verlaque M 2013. *Paracentrotus lividus*. *In* Lawrence JM Ed, Sea Urchins: Biology and Ecology, Third Edition. Elsevier: 297-327.

Boudouresque CF, Ruitton S, Verlaque M 2005. Large-scale disturbances, regime shift and recovery in littoral systems subject to biological invasions. *In* Velikova V, Chipev N Eds, Large-Scale Disturbances (Regime Shifts) and Recovery in Aquatic Ecosystems: Challenges for Management Towards Sustainability. Unesco, Paris: 85-101.

Boudouresque CF, Mayot N, Pergent G 2006. The outstanding traits of the functioning of the *Posidonia oceanica* seagrass ecosystem. *Biol Mar Medit* 13(4): 109-113.

Boudouresque CF, Bernard G, Pergent G, Shili A, Verlaque M 2009. Regression of Mediterranean seagrasses caused by natural processes and anthropogenic disturbances and stress: a critical review. *Bot Mar* 52(5): 395-418.

Boudouresque CF, Bernard G, Bonhomme P, Charbonnel E, Diviacco G, Meinesz A, Pergent G, Pergent-Martini C, Ruitton S, Tunesi L 2012. Protection and conservation of *Posidonia oceanica* meadows. RAMOGE and RAC/SPA, Tunis: 202 p.

Boudouresque CF, Personnic S, Astruch P, Ballesteros E, Bellan-Santini D, Bonhomme P, Botha D, Feunteun E, Harmelin-Vivien M, Pergent G, Pastor J, Poggiale JC, Renaud F, Thibaut T, Ruitton S 2015. Ecosystem-based versus species-based approach for assessment of the human impact on the Mediterranean seagrass *Posidonia oceanica*. *In* Ceccaldi H, Hénocque Y, Koike Y, Komatsu T, Stora G, Tusseau-Vuillemin MH eds, Marine Productivity: Perturbations and Resilience of Socio-Ecosystems. Springer International Publishing, Switzerland: 235-241.

Boudouresque CF, Pergent G, Pergent-Martini C, Ruitton S, Thibaut T, Verlaque M 2016. The necromass of the *Posidonia oceanica* seagrass meadow: fate, role, ecosystem services and vulnerability. *Hydrobiologia* 781: 25-42.

Boudouresque CF, Blanfuné A, Fernandez C, Lejeusne C, Pérez T, Ruitton S, Thibault D, Thibaut T, Verlaque M 2017a. Marine Biodiversity – Warming vs. biological invasions and overfishing in the Mediterranean Sea: Take care, 'One train can hide another'. *MOJ Ecol Environ Sci* 2(4): 1-13.

Boudouresque CF, Ponel P, Astruch A, Barcelo A, Blanfuné A, Geoffroy D, Thibaut T 2017b. The high heritage value of the Mediterranean sandy beaches, with a particular focus on the *Posidonia oceanica* '*banquettes*': a review. *Sci Rep Port-Cros Natl Park* 31: 23-70.

Boudouresque CF, Astruch P, Bănaru D, Blanchot J, Blanfuné A, Carlotti F, Changeux T, Faget D, Goujard A, Harmelin-Vivien M, Le Diréach L, Pagano M, Perret-Boudouresque M, Pasqualini V, Rouanet É, Ruitton S, Sempéré R, Thibault D, Thibaut T 2020. The management of Mediterranean coastal habitats: a plea for a socio-ecosystem-based approach. *In* Ceccaldi HJ, Hénocque Y, Komatsu T, Pouzet P, Sautour B, Yoshida J eds, Evolution of Marine Coastal Ecosystems Under the Pressure of Climate Change. Springer Nature, Switzerland: 297-320.

Bryhn A, Kraufvelin P, Bergström U, Vretborn M, Bergström L 2020. A model for disentangling dependencies and impacts among human activities and marine ecosystem services. *Environ Manage* 65(5): 575-586.

Canning-Clode J 2015. General introduction – aquatic and terrestrial biological invasions in the 21st century. *In* Canning-Clode J Ed, Biological Invasions in Changing Ecosystems. Vectors, Ecological Impacts, Management and Predictions. De Gruyter, Warsaw, Berlin: 13-20.

Casazza G, Silvestri C, Spada E 2002. The use of bio-indicators for quality assessments of the marine environment: examples from the Mediterranean Sea. *J Coast Conserv* 8: 147-156.

Chevaldonné P, Lejeusne C 2003. Regional warming-induced species shift in north-west Mediterranean marine caves. *Ecol Lett* 6(4): 371-379.

Christensen V, Pauly D 1992. Ecopath II – A software for balancing steady-state ecosystem models and calculating network characteristics. *Ecol Modell* 61(3-4): 169-185.

Christensen V, Pauly D Eds 1993. Trophic models of aquatic ecosystems. ICLARM, Conference proceedings, 26.

Coll M, Akoglu E, Arreguín-Sánchez F, Fulton EA, Gascuel D, Heymans JJ, Libralato S, Mackinson S, Palomera I, Piroddi C, Shannon LJ, Steenbeek J, Villasante S, Christensen V 2015. Modelling dynamic ecosystems: venturing beyond boundaries with the Ecopath approach. *Rev Fish Biol Fish* 25: 413-424.

Coll M, Shannon LJ, Kleisner KM, Juan-Jordá MJ, Bundy A, Akoglu AG, Banaru D, Boldt JL, Borges MF, Cook A, Diallo I, Fu C, Fox C, Gascuel D, Gurney LJ, Hattab T, Heymans JJ, Jouffre D, Knight BR, Kucukavsar S, Large SI, Lynam C, Machias A, Marshall KN, Masski H, Ojaveer H, Piroddi C, Tam J, Thiao D, Thiaw M, Torres MA, Travers-Trolet M, Tsagarakis K, Tuck I, Van Der Meeren GI, Yemane D, Zador SG, Shin YJ 2016. Ecological indicators to capture the effects of fishing on biodiversity and conservation status of marine ecosystems. *Ecol Indic* 60: 947-962.

Dalkey N, Helmer O 1963. An experimental application of the Delphi method to the use of experts. *Manage Sci* 9: 458-467.

Dauvin JC, Bellan G, Bellan-Santini D 2010. Benthic indicators: from subjectivity to objectivity – Where is the line? *Mar Pollut Bull* 60: 947-953.

David P, Thébault E, Anneville O, Duyck PF, Chapuis E, Loeuille N 2017. Impacts of invasive species on food webs: a review of empirical data. *Adv Ecol Res* 56: 1-60.

De La Fuente G, Chiantore M, Gaino F, Asnaghi V 2018. Ecological status improvement over a decade along the Ligurian coast according to a macroalgae based index (CARLIT). *PLoS ONE* 13(12): e0206826.

Deudero S, Box A, Vázquez-Luis M, Arroyo NL 2014. Benthic community responses to macroalgae invasions in seagrass beds: diversity, isotopic niches and food web structure at community level. *Estuar Coast Shelf Sci* 142: 12-22.

Diaz F, Bănaru D, Verley P, Shin YJ 2019. Implementation of an end-to-end model of the Gulf of Lions ecosystem (NW Mediterranean Sea). II. Investigating the effects of high trophic levels on nutrients and plankton dynamics and associated feedbacks. *Ecol Modell* 405: 51-68.

Flo E, Camp J, Garcés E 2011. Appendix B. BQE phytoplankton – assessment pressure methodology: land uses simplified index (LUSI). In: UNEP/MAP. Review of the methods, criteria and limit values for the assessment of eutrophication (Biological Quality Element Phytoplankton) as developed in the framework of the Intercalibration exercise of the MED GIG (Mediterranean Eco-region) Water Framework Directive 2000/60 EC. NEP(DEPI)/MED WG.365/Inf.7, Athens: 41 p.

Galil BS, Marchini A, Occhipinti-Ambrogi A 2018. East is east and West is west? Management of marine bioinvasions in the Mediterranean Sea. *Estuar Coast Shelf Sci* 201: 7-16.

Gerakaris V, Panayotidis P, Vizzini S, Nikolaidou A, Economou-Amilli A 2017. Effectiveness of *Posidonia oceanica* biotic indices for assessing the ecological status of coastal waters in the Saronikos Gulf (Aegean Sea, Eastern Mediterranean). *Medit Mar Sci* 18(1): 161-178.

Giakoumi S, Halpern BS, Michel LN, Gobert S, Sini M, Boudouresque CF, Gambi MC, Katsanevakis S, Lejeune P, Montefalcone M, Pergent G, Pergent-Martini C, Sanchez-Jerez P, Velimirov B, Vizzini S, Abadie A, Coll M, Guidetti P, Micheli F, Possingham HP 2015. Towards a framework for assessment and management of cumulative human impacts on marine food webs. *Conserv Biol* 29(4): 1228-1234.

Gobert S, Sartoretto S, Rico-Raimondino V, Andral B, Chery A, Lejeune P, Boissery P 2009. Assessment of the ecological status of Mediterranean French coastal waters as required by the Water Framework Directive using the *Posidonia oceanica* Rapid Easy Index: PREI. *Mar Pollut Bull* 58(11): 1727-1733.

Harmelin JG, Vacelet J, Vasseur P 1985. Les grottes sous-marines obscures : un milieu extrême et un remarquable biotope refuge. *Téthys* 11: 214-229.

Hermosillo-Núñez BB 2020. Contribution of echinoderms to keystone species complexes and macroscopic properties in kelp forest ecosystems (northern Chile). *Hydrobiologia* 847(3): 739-756.

Iveša L, Lyons DM, Devescovi M 2009. Assessment of the ecological status of north-eastern Adriatic coastal waters (Istria, Croatia) using macroalgal assemblages for the European Union Water Framework Directive. *Aquat Conserv: Mar Freshw Ecosyst* 19: 14-23.

Janssen A, Chevaldonné P, Arbizu PM 2013. Meiobenthic copepod fauna of a marine cave (NW Mediterranean) closely resembles that of deep-sea communities. *Mar Ecol Prog Ser* 479: 99-113.

Laffoley D, Maltby E, Vincent MA, Mee L, Dunn E, Gilliland P, Hamer JP, Mortimer D, Pound D 2004. The Ecosystem Approach. Coherent actions for marine and coastal environments. A report to the UK government. Peterborough, English Nature: 65 p.

Ling SD, Scheibling RE, Rassweiler A, Johnson CR, Shears N, Connell SD, Salomon AK, Norderhaug KM, Péres-Matus A, Hernández JC, Clemente S, Blamey LK, Hereu B, Ballesteros E, Sala E, Garrabou J, Cebrian E, Zabala M, Fujita D, Johnson LE 2015. Global regime shift of catastrophic sea urchin overgrazing. *Philos Trans R Soc B* 370: 1-10.

Lopez y Royo C, Casazza G, Pergent-Martini C, Pergent G 2010. A biotic index using the seagrass *Posidonia oceanica* (BiPo), to evaluate ecological status of coastal waters. *Ecol Indic* 10: 380-389.

Lopez y Royo C, Pergent G, Alcoverro T, Buia MC, Casazza G, Martínez-Crego B, Pérez M, Silvestre F, Romero J 2011. The seagrass *Posidonia oceanica* as indicator of coastal water quality: experimental intercalibration of classification systems. *Ecol Indic* 11: 557-563.

Mammides C 2019. European Unions' conservation efforts are taxonomically biased. *Biodivers Conserv* 28(5): 1291-1296.

Mannino AM, Micheli C 2020. Ecological function of phenolic compounds from Mediterranean fucoid algae and seagrasses: an overvieuw on the genus *Cystoseira sensu lato* and *Posidonia oceanica* (L.) Delile. *J Mar Sci Eng* 8(18): 1-19.

Mascaró O, Bennett S, Marbà N, Nikolić V, Romero J, Duarte CM, Alcoverro T 2012. Uncertainty analysis along the ecological quality status of water bodies: the response of the *Posidonia oceanica* multivariate index (POMI) in three Mediterranean regions. *Mar Pollut Bull* 64: 926-931.

Massinelli L, Astruch P, Montagne G, Gimond F, Lascève M, Boudouresque CF 2017. *Ruppia spiralis* in a Mediterranean lagoon habitat (Hyères salt marshes, France): an ecosystem-based approach to management. *In* COAST Bordeaux 2017 & French-Japanese Oceanography Symposium. Systemic and biodiversity evolution of marine coastal ecosystems under the pressure of climate change, natural and anthropogenic local factors: 174.

Maxwell SL, Fuller RA, Brooks TM, Watson JEM 2016. The ravages of guns, nets and bulldozers. *Nature* 536: 143-145.

Mazzella L, Buia MC, Gambi MC, Lorenti M, Russo G, Scipione MB, Zupo V 1992. Plant-animal trophic relationships in the *Posidonia oceanica* ecosystem of the Mediterranean Sea: a review. *In* John DJ *et al*. Eds, Plant-Animal Interactions in Marine Benthos. Systematic Association special volume 46, Clarendon Press: 165-187.

Molinier R, Picard J 1952. Recherches sur les herbiers de Phanérogames marines du littoral méditerranéen français. *Ann Inst Océanogr* 27(3): 157-234.

Montefalcone M 2009. Ecosystem health assessment using the Mediterranean seagrass *Posidonia oceanica*: a review. *Ecol Indic* 9(4): 595-604.

Montefalcone M, Morri C, Peirano A, Albertelli G, Bianchi CN 2007a. Substitution and phase shift within the *Posidonia oceanica* seagrass meadows of NW Mediterranean Sea. *Estuar Coast Shelf Sci* 75(1-2): 63-71.

Montefalcone M, Albertelli G, Morri C, Bianchi CN 2007b. Urban seagrass: status of *Posidonia oceanica* facing the Genoa city waterfront (Italy) and implications for management. *Mar Pollut Bull* 54(2): 206-213.

Moreno D, Aguilera PA, Castro H 2001. Assessment of the conservation status of seagrass (*Posidonia oceanica*) meadows: implications for monitoring strategy and the decision-making process. *Biol Conserv* 102: 325-332.

Myers MA, Baum JK, Shepherd TD, Powers SP, Peterson CH 2007. Cascading effects of the loss of apex predatory sharks from a coastal ocean. *Science* 315: 1846-1850.

Nikolić V, Žuljević A, Mangialajo L, Antolić B, Kušpilić G, Ballesteros E 2013. Cartography of littoral rocky-shore communities (CARLIT) as a tool for ecological quality assessment of coastal waters in the Eastern Adriatic Sea. *Ecol Indic* 34: 87-93.

Nordlund LM, Koch EW, Barbier EB, Creed JC 2016. Seagrass ecosystem services and their variability across genera and geographical regions. *PLoS ONE* 11(10): e0163091.

Noss RF, 1990. Indicators for monitoring biodiversity: a hierarchical approach. *Conserv Biol* 4(4): 355-364.

Opitz S 1996. Trophic interactions in Caribbean coral reefs. ICLARM, Technical Report, 43.

Orfanidis S, Panayotidis P, Stamatis N 2001. Ecological evaluation of transitional and coastal waters: a marine benthic macrophytes-based model. *Medit Mar Sci* 2(2): 45-65.

Orfanidis S, Panayotidis P, Stamatis N 2003. An insight to the ecological evaluation index (EEI). *Ecol Indic* 3: 27-33.

Orfanidis S, Panayotidis P, Ugland KI 2011. Ecological Evaluation Index continuous formula (EEI-c) application: a step forward for functional groups, the formula and reference condition values. *Medit Mar Sci* 12(1): 199-231.

Otero MM, Simeone S, Aljinovic B, Salomidi M, Mossone P, Gerakaris V, Giunta Fornasin ME, Milano P, Heurtefeux H, Issaris Y, Guido M, Adamopoulou M 2018. POSBEMED: gouvernance et gestion des systèmes plages/dunes à posidonie. Rapport final. IUCN, Malaga: 66 p. + annexes.

Ourgaud M 2015. Influence des apports anthropiques sur les flux de carbone et de contaminants dans les réseaux trophiques de poissons de l'écosystème à *Posidonia oceanica*. Doctoral thesis, Aix-Marseille University, Marseille: 348 p.

Ourgaud M, Ruitton S, Bell J, Letourneur Y, Harmelin JG, Harmelin-Vivien M 2015. Response of a seagrass fish assemblage to improved wastewater treatment. *Mar Pollut Bull* 90: 25-32.

Outridge P, Mason R, Wang F, Guerrero S, Heimbürger LE 2018. Updated global and oceanic mercury budgets for the United Nations Global Mercury Assessment 2018. *Environ Sci Technol* 52(20): 11466-11477.

Paoli C, Montefalcone M, Morri C, Vassallo P, Bianchi CN 2017. Ecosystem functions and services of the marine animal forests. *In* Rossi S, Bramanti L, Gori A, Orejas C Eds, Marine Animal Forests. Springer International Publishing, Switzerland: 1271-1312.

Pauly D, Palomares ML 2005. Fishing down marine food web: it is far more pervasive than we thought. *Bull Mar Sci* 76(2): 197-211.

Pauly D, Christensen V, Dalsgaard J, Froese R, Torres Jr F 1998. Fishing down marine food webs. *Science* 279: 860-863.

Pérès JM, Picard J 1964. Nouveau manuel de bionomie benthique de la mer Méditerranée. *Rec Trav Stat Mar Endoume* 31(47): 3-137.

Pergent G 1991. Les indicateurs écologiques de la qualité du milieu marin en Méditerranée. *Océanis* 17(4): 341-350.

Pergent G, Romero J, Pergent-Martini C, Mateo MA, Boudouresque CF 1994. Primary production, stocks and fluxes in the Mediterranean seagrass *Posidonia oceanica*. *Mar Ecol Prog Ser* 106: 139-146.

Pergent G, Rico-Raimondino V, Pergent-Martini C 1997. Fate of primary production in *Posidonia oceanica* meadows of the Mediterranean. *Aquat Bot* 59: 307-321.

Personnic S, Boudouresque CF, Astruch P, Ballesteros E, Blouet S, Bellan-Santini D, Bonhomme P, Thibault-Botha D, Feunteun E, Harmelin-Vivien M, Pergent G, Pergent-Martini C, Pastor J, Poggiale JC, Renaud F, Thibaut T, Ruitton S 2014. An ecosystem-based approach to assess the status of a Mediterranean ecosystem, the *Posidonia oceanica* seagrass meadow. *PLoS ONE* 9(6): e98994.

Pesche D, Méral P, Hrabanski M, Bonnin M 2013. Ecosystem services and payments for environmental services: two sides of the same coin? *In* Muradian R, Rival L Eds, Governing the Provision of Ecosystem Services. Springer, Dordrecht: 69-87.

Piazzi L, Gennaro P, Ceccherelli G 2015. Suitability of the Alien Biotic IndEX (ALEX) for assessing invasion of macroalgae across different Mediterranean habitats. *Mar Pollut Bull* 97: 234-240.

Piazzi L, Gennaro P, Atzori F, Cadoni N, Cinti MF, Frau F, Ceccherelli G 2018. ALEX enables detection of alien macroalgae invasions across habitats within a marine protected area. *Mar Pollut Bull* 128: 318-323.

Pikitch EK, Santora C, Babcock EA, Bakun A, Bonfil R, Conover DO, Dayton P, Doukakis P, Fluharty D, Heneman B, Houde ED, Link J, Livingstone PA, Mangel M, McAllister MK, Pope J, Sainsbury KJ 2004. Ecosystem-based fishery management. *Science* 305: 346-347.

Piroddi C, Coll M, Liquete C, Macias D, Greer K, Buszowski J, Steenbeek J, Danovaro R, Chritensen V 2017. Historical changes of the Mediterranean Sea ecosystem: modelling the role and impact of primary productivity and fisheries changes over time. *Sci Rep* 7(44491): 1-18.

Polovina JJ 1993. Foreword: the first Ecopath. *In* Christensen V, Pauly D Eds, Trophic Models of Aquatic Ecosystems. ICLARM, Conference Proceedings, 26.

Rastorgueff PA, Bellan-Santini D, Bianchi CN, Bussotti S, Chevaldonné P, Guidetti P, Harmelin JG, Montefalcone M, Morri C, Perez T, Ruitton S, Vacelet J, Personnic S 2015. An ecosystem-based approach to evaluate the ecological quality of Mediterranean undersea caves. *Ecol Indic* 54: 137-152.

Rice JC 2005. Implementation of the Ecosystem Approach to Fishery Management – asynchronous co-evolution at the interface between science and policy. *Mar Ecol Prog Ser* 300: 265-270.

Rigo I, Montefalcone M, Morri C, Bianchi CN, Oprandi A, Vassallo P, Paoli C 2019. Use of ecological indices to assess the health status of *Posidonia oceanica* meadows in eastern Liguria. *In* Gargiulo C, Zoppi C Eds, Planning, Nature and Ecosystem Services. FedOAPress, Naples: 271-280.

Rombouts I, Beaugrand G, Artigas L, Dauvin JC, Gevaert E, Goberville E, Kopp D, Lefebvre S, Luczac C, Spilmont N, Travers-Trolet M, Villanueva MC, Kirby RR 2013. Evaluating marine ecosystem health: case studies of indicators using direct observations and modelling methods. *Ecol Indic* 24: 353-365.

Romero J, Martínez-Crego B, Alcoverro T, Pérez M 2007. A multivariate index based on the seagrass *Posidonia oceanica* (POMI) to assess ecological status of coastal waters under the Water Framework Directive (WFD). *Mar Pollut Bull* 55: 196-204.

Romero J, Alcoverro T, Roca G, Pérez M 2015. Bioindicators, monitoring, and management using Mediterranean seagrasses: what have we learned from the implementation of the EU Water Framework Directive? *In* Munné *et al*. Eds, Experiences from Ground, Coastal and Transitional Water Quality Monitoring: the EU Water Framework Directive Implementation in the Catalan River Basin District (Part II). Springer International, Switzerland: 161-182.

Rouanet É, Astruch P, Bonhomme D, Bonhomme P, Rogeau E, De Saint Martin T, Boudouresque CF 2013. Evidence of anchor effect in a *Posidonia oceanica* seagrass meadow under low anchoring pressure *via* a multi-criteria grid. *Rapp Comm Int Mer Médit* 40: 676.

Ruitton S, Boudouresque CF, Personnic S, David R *et al*. 2013. An ecosystem-based approach to evaluate the status of Mediterranean ecosystem habitats. *Rapp Comm Int Mer Médit* 40: 577.

Ruitton S, Personnic S, Ballesteros E, Bellan-Santini D, Boudouresque CF, Chevaldonné P, Bianchi CN, David R, Féral JP, Guidetti P, Harmelin JG, Montefalcone M, Morri C, Pergent G, Pergent-Martini C, Sartoretto S, Tanoue H, Thibaut T, Vacelet J, Verlaque M 2014. An ecosystem-based approach to assess the status of the Mediterranean coralligenous habitat. *In* Bouafif C, Langar H, Ouerghi A Eds, Proceedings of the 2nd Mediterranean Symposium on the Conservation of Coralligenous and Other Calcareous Bio-concretions. RAC/SPA, Tunis: 153-158.

Ruitton S, Boudouresque CF, Thibaut T, Rastorgeff PA, Personnic S, Boissery P, Daniel B 2017. Guide méthodologique pour l'évaluation écosystémique des habitats marins. MIO, Marseille: 1-161.

Sala E, Zabala M 1996. Fish predation and the structure of the sea urchin *Paracentrotus lividus* populations in the NW Mediterranean. *Mar Ecol Prog Ser* 140: 71-81.

Sala E, Boudouresque CF, Harmelin-Vivien M 1998. Fishing, trophic cascade and the structure of algal assemblages: evaluation of an old but untested paradigm. *Oikos* 83: 425-439.

Sala E, Ballesteros E, Dendrinos P, Di Franco A, Ferretti F, Foley D, Fraschetti S, Friedlander A, Garrabou J, Güçlüsoy H, Guidetti P, Halpern BJ, Hereu B, Karamanlidis AA, Kizilkaya Z, Macpherson E, Mangialajo L, Mariani S, Micheli F, Pais A, Riser K, Rosenberg AA, Sales M, Selkoe KA, Starr R, Tomas F, Zabala M 2012. The structure of Mediterranean reef ecosystems across environmental and human gradients, and conservation implications. *PLoS ONE* 7(2): e32742.

Schmitz DC, Simberloff D 1997. Biological invasions: a growing threat. *Issues Sci Technol* 13(4): 33-40.

Schohn T, Astruch P, Best P, Glotin H, Rouanet É, Le Diréach L, Dossmann L, Goujard A, Belloni B, Lyonnet A, Poupard M, Jehl C, Buchet L, François M, Ferrari M, Schluter J, Giraudet P, Arlotto P, Dominici JM 2019. Étude et caractérisation de la fréquentation maritime et de son impact sur l'herbier de posidonie, le peuplement de poissons et le balbuzard pêcheur (*Pandion haliaetus*) dans la réserve naturelle de Scandola. Rapport final – décembre 2019. Programme GIREPAM – Contrat Parc Naturel Régional de Corse – GIS Posidonie, Marseille: 231 p + annexes.

Shin YJ, Houle JE, Akoglu E, Blanchard JL, Bundy A, Coll M, Demarcq H, Fu C, Fulton EA, Heymans JJ, Salihoglu B, Shannon L, Sporcic M, Velez L 2018. The specificity of marine ecological indicators to fishing in the face of environmental change: a multi-model evaluation. *Ecol Indic* 89: 317-326.

Simboura N, Panayotidis P, Papathanassiou E 2005. A synthesis of the biological quality elements for the implementation of the European Water Framework Directive in the Mediterranean ecoregion: the case of Saronikos Gulf. *Ecol Indic* 5: 253-266.

Surić M, Lončarić R, Lončar N 2010. Submerged caves of Croatia: distribution, classification and origin. *Environ Earth Sci* 61(7): 1473-1480.

Tempier E 2018. Prud'homies de pêche, un modèle de gestion des communs. *In* Buti G, Faget D, Raveux O, Rivoal S Eds, Moissonner la Mer. Économies, Sociétés et Pratiques halieutiques méditerranéennes (XVe-XXIe siècle). Karthala, Maison méditerranéenne des sciences de l'homme, Aix-en-Provence: 239-251.

Thomsen MS, Wernberg T, South PM, Schiel D 2016. Non-native seaweeds drive changes in marine coastal communities around the world. *In* Hu ZM, Fraser C Eds, Seaweed Phylogeography. Springer Science-Business Media, Dordrecht: 147-185.

Thibaut T, Blanfuné A, Verlaque M, Boudouresque CF, Ruitton S 2016. The *Sargassum* conundrum: highly rare, threatened or locally extinct in the NW Mediterranean and still lacking protection. *Hydrobiologia* 781: 25-42.

Thibaut T, Blanfuné A, Boudouresque CF, Personnic S, Ruitton R, Ballesteros E, Bellan-Santini D, Bianchi CN, Bussotti S, Cebrian E, Cheminée A, Culioli JM, Derrien-Courtel S, Guidetti P, Harmelin-Vivien M, Hereu B, Morri C, Poggiale JC, Verlaque M 2017. An ecosystem-based approach to assess the status of Mediterranean algae-dominated shallow rocky reefs. *Mar Pollut Bull* 117: 311-329.

Torras X, Pinedo S, García M, Weitzmann B, Ballesteros E 2016. Environmental quality of Catalan coastal waters based on macroalgae: the interannual variability of CARLIT Index and its ability to detect changes in anthropogenic pressures over time. *In* Munné A *et al*. Eds, Experiences from ground, coastal and Transitional Water Quality Monitoring: The EU Water Framework Directive Implementation in the Catalan River Basin District (part II). *Hdb Environ Chem* 43: 183-200.

Tudela S, Short K 2005. Paradigm shifts, gaps, inertia, and political agendas in ecosystem-based fisheries management. *Mar Ecol Prog Ser* 300: 281-286.

Turrell B 2004. The policy basis of the "Ecosystem Approach" to fisheries management. EuroGOOS, Norrkóping, 21: 1-28.

Vacelet J, Boury-Esnault N, Harmelin JG 1994. Hexactinellid Cave, a unique deep-sea habitat in the scuba zone. *Deep-Sea Res I* 41: 965-973.

Verlaque M, Ruitton S, Mineur F, Boudouresque CF 2015. CIESM Atlas of Exotic Species. 4. Macrophytes. Briand F Ed, CIESM Publisher, Monaco: 362 p.

Verlaque M, Boudouresque CF, Perret-Boudouresque M 2019. Mediterranean seaweeds listed as threatened under the Barcelona Convention: a critical analysis. *Sci Rep Port-Cros Natl Park* 33: 179-214.

Vitousek PM, D'Antonio CM, Loope LL, Westbrooks R 1996. Biological invasions as global environmental changes. *Am Sci* 84: 468-478.

Walters C, Christensen V, Pauly D 1997. Structuring dynamic models of exploited ecosystems from trophic mass-balance assessments. *Rev Fish Biol Fish* 7(2): 139-172.

Ward T, Hegerl E 2003. Marine protected areas in ecosystem-based management of fisheries. Commonwealth of Australia, Canberra: 66 p.

Zenetos A, Çinar ME, Crocetta F, Golani D, Rosso A, Servello G, Shenkar N, Turon S, Verlaque M 2017. Uncertainties and validation of alien species catalogues: the Mediterranean as an example. *Estuar Coast Shelf Sci* 191: 171-187.