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A STRATEGIC APPROACH TO ASSESS THE BUNDLE OF ECOSYSTEM SERVICES PROVIDED BY *POSIDONIA OCEANICA* MEADOWS IN THE BAY OF MARSEILLE

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STATE-AND-TRANSITION MODELS
TRIAGE METHOD
DELPHI PROCESS
ECOSYSTEM SERVICE ASSESSMENT
ECOSYSTEM BASED QUALITY INDEX

ABSTRACT. – The aim of the European program Life Integrated Project Environment (IPE) MarHa (2018-2025) is to restore and sustain the favorable conservation status of marine natural habitats in French Natura 2000 sites. In this context, Ecosystem Service Assessments (ESA) are carried out at various French sites including the Bay of Marseille (Provence, France). First, we applied the TRIAGE methodology: a strategic assessment of the issues with experts of the area (local MPA managers and scientists). TRIAGE raises two main concerns: (i) the intensification of recreational uses (by both residents and visitors), and (ii) the conservation of *Posidonia oceanica* (Linnaeus) Delile, 1813 seagrass meadows. In order to address both issues, we selected two adapted methodologies based on the strategic assessment: (i) a study oriented toward understanding the demand for ecosystem services (focused on recreational activities), and (ii) a study of the capacity of *P. oceanica* meadows to deliver ecosystem services using state-and-transition modeling. The objective of this work is to present the ESA process, from the strategic assessment to the analysis results. We focus on the study of the capacity of *P. oceanica* seagrass meadows to provide ecosystem services. State and transition models consist in defining alternative states of the habitat based on ecological indicators, identifying the bundle of services associated with each state and identifying transition vectors capable of explaining the shifts between each state. State-and-transition models can be very powerful frameworks for integrating multiple functions and services delivered by ecosystems while accounting for their temporal dynamics.

INTRODUCTION

Anthropogenic activities and climate change can deeply alter ocean productivity and food web dynamics, reduce the abundance of habitat-forming species, shift species distributions, and lead to a higher incidence of disease (Hoegh-Guldberg & Bruno 2010, Ceballos *et al*. 2015). The European Union (EU) established directives to designate strictly protected areas. An assessment of the conservation status of habitats is carried out periodically within the framework of the Habitat Directive (HD) on the conservation of natural habitats and of wild fauna and flora (HD, 92/43/EC). In 2012, the conservation status of most of the Natura 2000 marine habitats was assessed as "unfavorable" throughout the French Atlantic and Mediterranean biogeographical regions (Bensettiti & Puissauve 2015, Meinesz & Blanfuné 2015). Consequently, restoring and maintaining the favorable conservation status of marine habitats now appears as: (i) a moral duty, consisting in managing the common good for present and future generations, (ii) a legal duty, with regard to European and international biodiversity commitments, and (iii) a socio-economic duty, which takes into account and sustains the maintenance and restoration of Ecosystem Services (ES).

The ES concept seeks to account for the dependence of human societies on ecosystems and is commonly defined as the contributions of ecosystem structures and functions to human well being (MA 2005). The ES conceptual framework was initiated in the 1970s by the conservation biology movement (SCEP 1970) and is perfectly aligned with the biodiversity conservation paradigm. The publication of the Millennium Ecosystem Assessment report (MA 2005) consolidated this conceptual framework and represented the culmination of an institutionalization process of the concept by science, politics and law (Mongruel *et al*. 2016). This report opened the door to other initiatives at the international (*e.g*., TEEB 2010), regional (*e.g*., Maes *et al*. 2013) and national scales (*e.g*., EFESE program in France[1]).

ES science is an interdisciplinary field, mainly resulting from the meeting of ecological and economic approaches. It is also operational and effective, since it supports and facilitates biodiversity management policies. The Ecosystem Service Assessment (ESA) is now a common method used in public environmental policies and is relatively well known by environmental stakeholders. Nevertheless, ESA is far from being a unified set of scientific practices. The epistemological foundations that support our economic approaches are those of strong sustainability[2]. The choice of this paradigm led us to reject systematic and large-scale monetary valuation. In this perspective we rely on a strategic approach to valuation. We consider that, since we cannot assess everything, the best strategy is to choose "what" and "how" it deserves to be assessed in terms of ES.

The objective of this paper is to present the process implemented to produce the ESA in the Bay of Marseille, with the objective of providing the managers of the Marine Protected Areas (MPA) of this sector with a useful and effective tool to identify appropriate levers to restore and maintain the favorable conservation status of natural marine habitats in the site they manage. This work was carried out at the scale of the Bay of Marseille, which includes two Natura 2000 sites designated under HD 92/43/EC. The strategic approach used for the ESA in this study allowed us to use different methods: the TRIAGE approach to ESA (Pendleton *et al*. 2015) combined with a Delphi process (Rowe & Wright 1999) and then a state-and-transition model (Lavorel *et al*. 2015).

MATERIALS AND METHODS

Case study: the Bay of Marseille: The Bay of Marseille (Provence, France) has been a good model to illustrate the complex interactions between ecological and socio-economic issues since antiquity. Located on the northwestern Mediterranean seafront, its coastline has been greatly impacted by anthropic activities, mostly associated with urbanization[3], the harbor[4] and both freight and passenger traffic. Despite this accumulation of pressures, the bay shelters several marine habitats listed in HD, notably *Posidonia oceanica* (Linnaeus) Delile, 1813 seagrass meadows, coralligenous reefs, and sea caves. The Bay of Marseille is bounded by two MPAs which are Natura 2000 Special Areas of Conservation[5] (SAC): the Côte-Bleue Marine Park (CBMP) and the Calanques National Park (CNP). In these two MPAs, the *Posidonia* meadows cover a surface area of 1,198 ha in CBMP and 1,186 ha in CNP.

In the northwest, the Côte-Bleue Marine Park (CBMP) is a public structure created in 1983, resulting from the merging of five coastal municipalities. It extends over an area of 98.7 km^2. It includes notably two no-take-zones (2.95 km^2 in total surface area) established at the initiative of local fishermen and their representatives[6]. The CBMP is managing the Natura 2000 SAC 'Côte Bleue Marine' (FR9301999) since 2009.

In the southeast, the Calanques National Park (CNP) was created in 2012 and includes the Natura 2000 SAC "Calanques et îles marseillaises – Cap Canaille et massif du Grand Caunet" (FR9301602). The Park covers both terrestrial and marine areas, and includes several peri-urban sectors. At sea, a marine surface area of about 435 km^2 makes up the "core" area, in which the objective of protection is stricter and human activities are regulated in order to ensure the efficient conservation of fauna, flora, the natural environment and landscape. The sea core extends 10 nautical miles from the coast and includes seven No-Take zones, accounting for almost 11% of its surface area (46.5 km^2). The "adjacent marine area", which is the part of the park's territory where activities are not subject to specific regulations (although they must conform to a reference in terms of sustainable development), extends over a marine surface area of 977 km^2.

In the centre of the Bay of Marseille, in front of the Prado beaches, a 2-km^2 reserve managed by the municipality of Marseille has been equipped with more than 400 artificial reefs in 2007-2008 (Cresson *et al*. 2019). All activities are banned inside the reserve, with the exception of scientific experiments and monitoring with the aim of supporting artisanal fisheries and sustaining and improving the ecological quality of adjacent natural habitats (*via* fish biomass exportation). With a gross volume of 27,300 m^3, the Prado reef is the biggest artificial reef in Europe and the Mediterranean Sea (Charbonnel *et al*. 2011).

[1] https://www.ecologique-solidaire.gouv.fr/levaluation-francaise-des-ecosystemes-et-des-services-ecosystemiques

2 In economic analysis the key question regarding sustainable development is whether natural and human capitals can be substituted by manufactured capital (weak sustainability), or whether each should be maintained (strong sustainability). Under the strong sustainability paradigm, economic analysis goes beyond optimizing the substitution of capitals to examine the means of achieving their conservation (Dietz & Neumayer 2007).

[3] The collectivity of Aix-Marseille-Provence has a population of more than 1.8 million.

[4] The harbor of Fos-Marseille is the most important commercial harbor in France with traffic amounting to 78 million tons of cargo and 3,276,902 passengers in 2014 (Bas & Kalaydjian 2018)

[5] Special Areas of Conservation is a designation for natural sites representing a strong interest regarding the restoration or maintenance of a favorable state of conservation of the habitats or species of the HD.

[6] The regional committee of fisheries and marine cultures of Provence-Alpes-Côte d'Azur (CRPMEM PACA) and the '*Prud'homie des Pêcheurs*'.

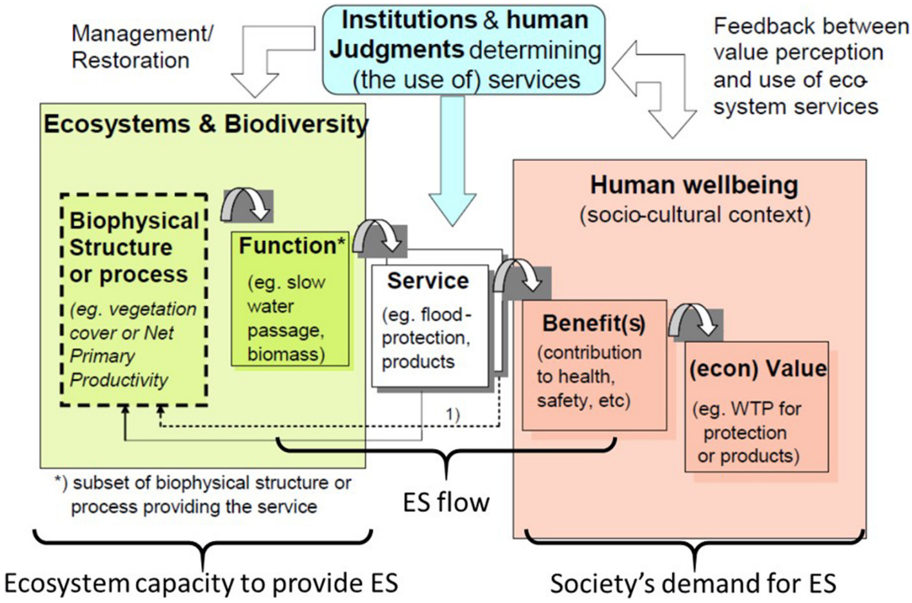

Fig. 1. – The Ecosystem Service "cascade" (Source: TEEB (2010) adapted from Haines-Young & Potschin (2010)).

Ecosystem services assessment: ES are defined as the benefits society acquires from the functioning of ecosystems. They allow establishing a link between the functioning of ecosystems and their real benefits to society (Fig. 1). We can highlight three dimensions to assess ecosystems (Villamagna *et al*. 2013, Burkhard *et al*. 2014): (i) the capacity of an ecosystem to provide an ES or its potential defined as the hypothetical maximum production of a given ecosystem; (ii) the flow of ES is the bundle of ES and other outputs effectively selected at a given place and period; and (iii) the demand for ES is defined as the quantity of ES required or desired by society. The ESA method and ES indicators differ according to the dimension we want to focus on. In this study, this choice is based on a strategic analysis of the management issue conducted with a TRIAGE process.

The triage method: The TRIAGE method guides the ESA by identifying and specifying the objective, scale, methods and tools required for its implementation. It is a preliminary step to the ESA and allows perceiving the latter in strategic (the scope is circumscribed as it is not realistic to assess everything) and operational (according to the availability of knowledge and means, and consistent with the site management framework) ways. The TRIAGE method is composed of a three-stage sequence. The first step defines the scope of the ESA: (i) identify the purpose of the ESA: is it to provide information on the ES (informative use), to contribute to the implementation of a measure (technical use) or to help the manager to carry out trade-offs (decisive use)? (ii) identify the management issues that will most influence the ES in order to situate the ESA in local reflections related to the issues at stake; (iii) identify the components of the socio-ecosystem (ecological compartments, functions, ES, actors) that will be the most influenced by these management issues. The second step selects the key ES based on their prioritization regarding three criteria: (i) the importance of the different ES; (ii) the exposure of ES to drivers of change; (iii) the possibility for local managers to act on the ES (based on a ranking between 1 and 5). The more an ES is considered important, the more it is exposed to changes and it is possible to act on it, then the more it will be useful to evaluate the ES (Pendleton *et al*. 2015). The third step consists in: (i) choosing the type of indicators (biophysical, economic and/or based on social perceptions) that are most usable by the MPA manager; (ii) choosing the methods and tools that can be used to inform these indicators; (iii*)* assessing the resources required and the availability of data for the ESA.

The exchanges with MPA managers began in January 2019, while the TRIAGE process was implemented in May 2019 during a workshop bringing together 11 local MPA managers and scientists, experts of the Bay of Marseille.

The Delphi process: the Delphi process is an approach that reveals and refines the judgment of a group and whose core principle is the fact that the judgment of a group is more relevant when uncertainty is high (Kaynak & McCauley 1984). As a result, it is perfectly coherent with the TRIAGE method, which aims to prioritize assessment issues based on stakeholders' expertise. We used a limited number of iterations to maximize response rates, considering the number of experts interviewed.

The Delphi process was applied in the TRIAGE method. The local MPA managers and scientists, experts of the Bay of Marseille, were contacted by email following their participation in the workshop in May 2020. We sent the first report of the workshop allowing them to return to the concepts and questions related to ES assessment, to step back from the first results of the ES prioritization process and to allow them to review their judgments and therefore modify the ES prioritization (step 2 of the TRIAGE). The results of the TRIAGE are thus the fruit of an individual and collective reflection that leads to consensus.

State-and-transition models: State-and-transition models provide an operational and conceptual framework for organizing and providing information about ecosystem dynamics and management outcomes, describing how communities respond to pressures and management (Briske *et al*. 2005, Bestelmeyer 2015). They were developed by Westoby *et al*. (1989) for rangeland ecological sites in southern Arizona (United States of America). While their scientific application is widespread for certain terrestrial habitats (*e.g*., McIntyre & Lavorel 2001, Quétier *et al*. 2007, Tarrasón *et al*. 2016), they have very rarely been applied to marine environments.

In this study, the evolution of *P. oceanica* seagrass meadows was described at the scale of the French Mediterranean with respect to different pressures. The first step has consisted in identifying and describing the different ecological states of the *P. oceanica* seagrass meadows in the French Mediterranean and then describing the transition drivers (*e.g*., natural and anthropogenic pressures) that make *P. oceanica* seagrass meadows switch from one state to another. This exercise was initiated during workshops in May and December 2019, supplemented by bilateral meetings with several local MPA managers and scientific experts of *P. oceanica* meadows.

RESULTS

A triage of management issues and key ES for ESA

The first step of TRIAGE is the definition of the scope of the ESA. We reviewed 28 social-ecological issues that were hierarchized consensually by the participants to the workshop. We identified two primary management issues at stake: (i) the intensification of recreational activities and (ii) the conservation of *P. oceanica* meadows. We also identified four secondary issues: fishing (both recreational and professional), tourism, chemical pollution and governance. We then conducted a preliminary definition of the socio-ecosystem that led to identifying a list of 24 relevant ES in connection with these issues. We observed a small decrease in ranking after the second round of the Delphi process (mean decrease of 0.35, max 0.78 and mean 0.02). Table I presents the final results of the ES hierarchization process. The final scores are relatively homogeneous, the main ES is the provision of fish and to a lesser extent the maintenance ES of shelter, the provision ES of sea urchins and octopuses and the recreational ES of observation, education and recreational fishing. However, we can see bigger differences in the ranking of each criterion. Then, we conducted a Principal Component Analysis to help visualizing the different groups of ES (Fig. 2). The two first axes explain 92.25 % of the variance of data. First, on the positive part of axis 1 that explains 56.26 % of the variance of data, we find the services more at stake regarding the global score. Second, on the positive part of axis 2 are positioned the important ES for which a low possibil-

Table I. – Result of the hierarchization of the ES provided by the ecosystems of the bay of Marseille.

Ecosystem services		A : Importance	B : Exposition	C : Possibility of action	SCORE (A+B+C)/3
Maintenance and support services	Trophic network	4.33	3.78	2.22	3.44
	Nursery	4.00	3.67	2.78	3.48
	Shelter	3.67	3.89	3.11	3.56
	Reproduction	3.67	3.56	3.00	3.41
Provision services	Urchins	3.11	4.11	3.78	3.67
	Octopuses	3.00	4.22	4.00	3.74
	Fishes	4.44	4.33	3.67	4.15
	Crustaceans	2.13	3.88	3.50	3.17
	Shellfish (mussels and limpets)	2.33	3.44	3.33	3.04
Regulation services	Climate regulation	3.56	3.78	1.89	3.07
	Purification capacity	3.50	2.63	2.00	2.71
	Coastal protection	3.56	3.78	3.00	3.44
Cultural services	Marine landscape	4.33	3.22	2.56	3.37
	Sub-marine landscape	4.22	3.89	2.33	3.48
	Acoustic landscape (feeling of well-being)	2.78	3.00	2.78	2.85
	Wrecks (abiotic)	3.22	2.00	2.33	2.52
	Observation of flagship species	4.22	4.33	3.00	3.85
	Education	3.44	3.50	3.89	3.61
	Research	3.00	2.63	2.89	2.84
	Recreational fishing	3.89	3.78	3.67	3.78
	Arts (*e.g.*, photography)	2.56	2.38	2.25	2.39
Heritage dimensions	Historical dimension	3.11	2.13	2.50	2.58
	Natural Capital (common good)	3.67	3.33	2.67	3.22
	Cultural anchoring (*e.g.*, toponymy)	2.67	2.13	2.00	2.26

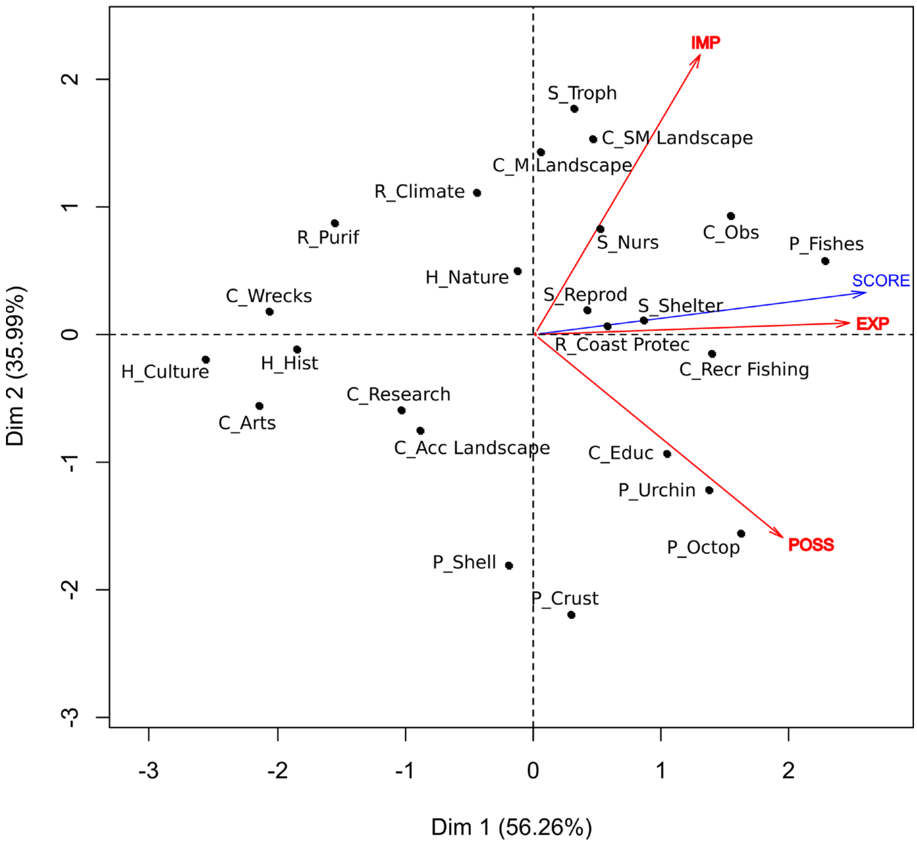

Fig. 2. – Result of a PCA conducted on the ranking of the three criteria of Importance (IMP), Possibility of action (POSS) and Exposure (EXP) as explicative variables and the global score (SCORE) as illustrative variable.

ity of action exists (*e.g.*, landscapes and seascapes, nursery role, etc.) in the top right square (1st category) and on the negative part of axis 2, the ES that are less important but for which a high possibility of action exists (*e.g.*, education, urchins, octopuses, etc.) (2nd category).

This ES ranking can be linked to the two main issues revealed by the TRIAGE. The question of the conservation of *P. oceanica* is more associated with the services of the 1st category (notably support services and coastal protection) while the question of the massification of recreational activities is more transversal as cultural services are present in the two categories. In terms of management purposes, a low possibility of action implies that the ESA should be focused on an informative use. In this perspective the ESA is built to widen the scope of possibilities for future action. On the other hand, when the possibility of action is high, the ESA can be useful to support decision-making in the arbitration between different management measures or in their design. The TRIAGE method led us to choose two different ESA methods. First, an assessment focused on the ecological importance of the *P. oceanica* ecosystem in the provision of ES based on the state-and-transition model. This method is adapted to the question regarding the conservation of *P. oceanica*; it will highlight its importance in the provision of ecosystem services (notably support services). In addition, it presents a good opportunity to integrate existing knowledge on ecology in the operational framework of the ESA. Second, an assessment of the demand for ES associated with the evolution of recreational and touristic practices. This method will allow us to investigate the question of the intensification of recreational activities with retrospective and prospective objectives. The current work is focused on the first analysis.

A state and transition model for **P. oceanica** *meadows*

The first result of the workshop and bilateral interviews we conducted with experts on *P. oceanica* was to adjust the list of ES from the TRIAGE (relevant at the scale of the entire Bay of Marseille in all its dimension, *i.e.*, diversity of habitats, uses and management objectives) to a list that is more adapted to deal with *P. oceanica* in the French Mediterranean. We identified a list of 18 ES[7].

Fig. 3 presents the different states (S) of the *P. oceanica* seagrass meadows identified in the model and the dif-

[7] During the TRIAGE, 24 ES were identified for the Bay of Marseille (Table I), with the focus placed on the *P. oceanica* ecosystem. We refined this list to 18 ES: 6 support ES (primary production, secondary production, nursery, shelter, reproduction, biomass exportation); 3 provision ES (sea urchins, fish and cephalopods, crustaceans); 4 regulation ES (climate regulation, contaminant sequestration, coastal protection, production and sequestration of sediment), and 5 cultural ES (landscape and emblematic species, preservation of archeological resources, education, research, recreational fishing).

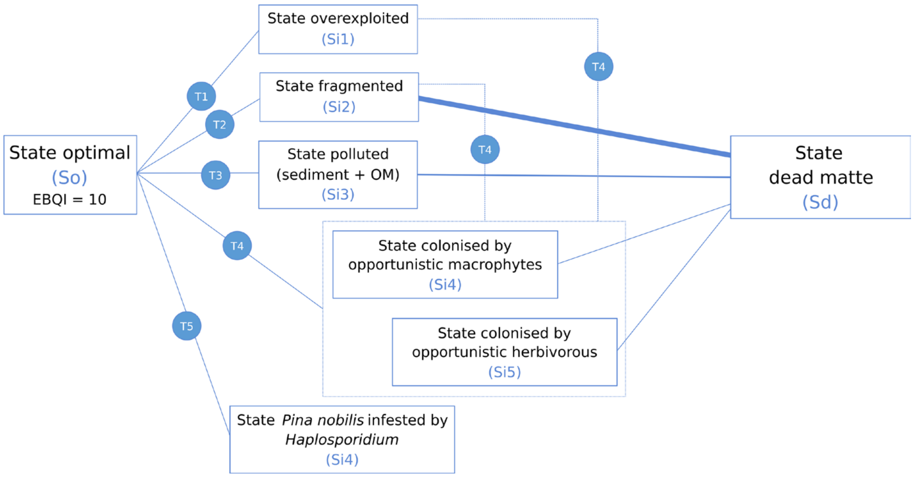

Fig. 3. – Ecological states of the *P. oceanica* meadows and transition factors.

ferent transition factors (T) capable of explaining the shift from one state to another. The optimal state (So) represents the reference state of the *P. oceanica* seagrass meadows. In this state, the functioning of the habitat is optimal. From this state, *P. oceanica* seagrass meadows can reach different intermediary states (Si1 through Si6) that are described as transition factors (T1 through T5) regarding the pressures on the ecosystem. The decline of the *P. oceanica* meadow is generally indicated by the appearance of areas of 'dead matte'. The matte is the structure composed of live and dead parts of rhizomes and roots, together with the sediment, which fills the interstices. 'Dead matte' areas are areas where *P. oceanica* dies, leaving the matte uncovered by shoots of living leaves (Mateo *et al.* 1997, Boudouresque *et al.* 2016). The matte (living matte beneath the shoots of leaves and dead matte) may persist for decades and even centuries. The dead-matte patches are occupied by macroalgae that do not at all play the same ecological role as *P. oceanica*, which is an ecosystem engineer.

First, in the overexploited state (Si1), fish stocks are depleted (especially predatory and piscivorous teleosts). This depletion can lead to the proliferation of the herbivorous species such as sea urchins *Paracentrotus lividus* (Lamarck, 1816) and *Arbacia lixula* (Linnaeus, 1758) and salema porgy *Sarpa salpa* (Linnaeus, 1758) and to overgrazing of the seagrass meadow (Ferrari *et al.* 2008, Boudouresque *et al.* 2017). *P. oceanica* can be dragged into this state from the good state due to overfishing (T1). In the French Mediterranean Sea, 80 % of fishing activities are performed in coastal ecosystems (with one third in coastal lagoons), with a wide range of trades (Mongruel *et al.* 2019). At the scale of *P. oceanica* seagrass meadows of the Côte-Bleue Marine Park, artisanal small-scale fishing (*i.e.*, boats smaller than 12 m length) mainly target gilthead seabream *Sparus aurata* Linnaeus, 1758, European seabass (*Dicentrarchus labrax* (Linnaeus, 1758), red mullet *Mullus surmuletus* Linnaeus, 1758 and scorpion fish *Scorpaena* spp. (Leleu *et al.* 2014) while coastal trawling (*i.e.*, boats between 12 m and 19 m length) also catch non targeted species (Boudouresque *et al.* 2017). Current knowledge does not allow us to define a maximum sustainable yield (MSY) beyond which we would shift from sustainable exploitation to over-exploitation.

The second intermediate state is a fragmented state (Si2) in which the surface area and connectivity of *P. oceanica* seagrass meadows is interrupted by patches or extensive areas of dead matte. The corresponding transition factor (T2) is the qualitative or quantitative degradation of habitats due to fishing gears (active or lost), boats anchoring and extreme events as well as to the natural dynamics of the meadow (Boudouresque *et al.* 2009). First, *P. oceanica* is particularly vulnerable to trawling (Boudouresque *et al.* 2009). A standard trawler can uproot between 99,000 and 363,000 plants per hour (Martin *et al.* 1997). In order to limit this impact, trawling within the 3 nautical miles (5.6 km) zone is forbidden. However, this regulation is often not observed. Trawling is responsible for the loss of 12 % of the surface area of *P. oceanica* seagrass meadows of Corsica (Pasqualini *et al.* 2000). The time needed for *P. oceanica* to recover from trawling is estimated at 100 years (González-Correa *et al.* 2005), but depends on the surface area destroyed. The second is the impact of anchoring. Major threats come from large ships, notably cruise ships. For example, close to Porquerolles Island, anchoring is responsible for scars between 1 and 2 meters wide and up to 296 meters length that has generated 4.2 hectares of dead matte (Ganteaume *et al.* 2005, Montefalcone *et al.* 2006, Boudouresque *et al.* 2009). To a lesser extent, the anchoring of small pleasure boats can also lead to uprooting *P. oceanica* (*e.g.*, 68,000 shoots per hectare in a 1.4 ha zone in Corsica). However, impacted seagrass meadows can still produce new leaves in the next year if some shoots stay alive. Sustainable pressure from small boat anchoring is theoretically estimated to 2 moorings per hectare per day (as a yearly mean) and should not exceed 10 moorings per hectare per day (Boudouresque *et al.* 2012). Finally, on coasts exposed to extreme events such as strong winds and storm surges, sediment movements can bury sprouts, expose roots and rhizomes and even uproot entire plants (Gera *et al*. 2014). Infantes *et al* (2011) estimated that *P. oceanica* sprouts need to have more than half of their roots anchored in the sediment.

The third intermediate state is the polluted state (Si3): *P. oceanica* seagrass meadow is disturbed by terrigenous inputs, hypersedimentation, eutrophication and turbidity. We identified two drivers that can induce the transition factor associated with this state (T3): pollution from urban and industrial activities or from aquaculture (Boudouresque *et al*. 2009, 2012, 2020). A loss of *P. oceanica* meadows is observed close to Mediterranean urban centers and sewage outlets, notably in the Bay of Marseille (Boudouresque *et al*. 2009). Increased eutrophication, hypersedimentation and turbidity explain a large part of this loss. This pollution has been decreasing since the 1970s thanks to the improvement of wastewater treatment (Jackson *et al*. 2006). As a result, a *P. oceanica* seagrass meadow in recovery has been identified in the Bay of Marseille (Pergent-Martini *et al*. 1995); however, the recovery process is very slow (a few centimeters per year when good environmental conditions are restored). In the French Mediterranean Sea as elsewhere, aquaculture also generates pollution associated with food leftovers and fish feces that accumulate under cages (Boudouresque *et al*. 2020). In addition, shade generated by cages and turbidity leads to a decrease in the light intensity necessary for *P. oceanica* development (Boudouresque *et al*. 2009, 2020).

In the fourth and fifth intermediate state (Si4 and Si5), the transition factor is the presence of non-indigenous invasive species (NIS) (T4) that compete with *P. oceanica* and other species of the ecosystem. The impacts of invasive species can be different depending on whether NIS competes for space or if they are predatory/herbivorous species (Giakoumi *et al*. 2015). In this way, we distinguished two intermediary states: a state colonized by NIS macrophytes (Si4) and a state colonized by the herbivorous rabbitfishes *Siganus luridus* (Rüppell, 1829) and *S. rivulatus* (Forsskål, 1775) (Si5). Macrophytes (Si4) such as *Caulerpa* species (*Caulerpa taxifolia* (Vahl) C. Agardh and *C. cylindracea* Sonder)[8] compete with *P. oceanica*. When meadows are vulnerable, this competition can lead to (i) chlorosis, (ii) necrosis, (iii) decrease in the number, length, thickness and longevity of leaves, and (iv) the death of sprouts (Klein & Verlaque 2008). Colonization by macrophytes is more difficult within a dense and healthy meadow. *Siganus* spp. (Si5) has not yet settled on the French Mediterranean coasts, however it is now become very common in the eastern Mediterranean where it strongly interacts with native herbivorous fish species through competition for food resources and habitat (Bariche *et al*. 2004, Boudouresque *et al*. 2017). It also modifies marine vegetation when it is abundant. One individual of *S luridus* was fished for the first time in the Côte Bleue Marine Park in 2009 (Daniel *et al*. 2009). A second species of rabbit fish (*S. rivulatus*) was also caught by artisanal fishers close to CBMP in 2018 (Iglésias *et al*. 2020). These fish species constitute a potential threat in French seas.

In the last and sixth intermediate state (Si6), the meadows are infected by *Haplosporidium pinnae* sp. nov. (Si6), a pathogenic protozoan of the noble pen shell (*Pinna nobilis* Linnaeus, 1758), inducing mass mortality of this species with no impact on the other compartments of the ecosystem (Catanese *et al*. 2018). *Pinna nobilis* is a large bivalve endemic to the Mediterranean, threatened with extinction and providing important ecosystem services linked to its high heritage value.

Finally, when pressures are too high, the *P. oceanica* seagrass meadow shifts into the dead matte state (Sd) (Montefalcone *et al*. 2007). The dead matte is the ultimate degraded facies of the *P. oceanica seagrass* meadow on which can develop certain macroalgae and invertebrates although it has lost most of its ecological functions. The substrate is composed of an entanglement of roots and rhizomes clogged by sediments of various grain sizes, that are particularly compact and favorable to the establishment of a relatively specialized fauna.

DISCUSSION

In view to producing an ESA, the TRIAGE method is a useful process for increasing stakeholders' involvement, allowing their appropriation of the concepts and of the results obtained which in turn increase the chance of identifying scientific knowledge that fit into their management policies. This is important as there is a risk of discrepancy between the production of 'more knowledge' and its actual utilization by decision makers (Jordan & Russel 2014). Moreover, a strategic analysis prior to ESA allows us to be sure that knowledge is produced, integrated and aligned with the needs of the users and their perception (Honey-Rosés & Pendleton 2013). However, TRIAGE implies a shift in the construction of projects regarding ESA as it makes work planning difficult. Finally, ESA is the outcome of a trade-off between the management needs and the capacity (in terms of skills and means) of the assessors.

In the state-and-transition model, we have not selected climate change as a transition factor that can lead to

[8] Five species of macrophytes have been identified as competitors of *P. oceanica* (Boudouresque *et al*. 2009): two species of Australian chlorophytes (*Caulerpa taxifolia* et *Caulerpa racemosa* var. *cylindracea*) and three species of Indo-Pacific rhodophytes (*Acrothamnion preissii*, *Lophocladia lallemandii* and *Womersleyella lallemandii*). We will focus on the two caulerpas as they have strongly impacted French Mediterranean coasts (Verlaque & Fritayre 1994, Piazzi *et al*. 2003).

a well-identified intermediate state. Indeed, most of the consequences of climate change on coastal and marine ecosystems are still uncertain. Moreover, its effects are multiple and associated with different factors (marine water warming, acidification, sea level rise, increase in the frequency and intensity of extreme events, etc.) (Pergent *et al.* 2014). For example, different hypotheses can be made regarding the evolution of *P. oceanica* due to water heating. First, other Mediterranean seagrasses are good candidates in the succession, notably *Cymodocea nodosa* (Ucria) Asch and, to a lesser extent, *Zostera noltei* Hornemann (Montefalcone *et al.* 2007, Boudouresque *et al.* 2012). Second, *P. oceanica* could also be threatened by NIS such as *Halophila stipulacea* (Forsk.) Asch (Pergent *et al.* 2014), generally less structuring species that can trigger deep changes in associated communities and ecological functioning. Thirdly, *P. oceanica* could also adapt by modifying its thermic optimum, a phenomenon already observed for terrestrial plants (Koch *et al.* 2013). These hypotheses highlight the uncertainty associated with the impact of climate change on *P. oceanica* ecosystems and the concomitant difficulty regarding the definition of intermediate state. In this study, climate change is considered as an aggravating factor as it can increase the intensity of transition factors: (i) increasing the occurrence of extreme events (Lejeusne *et al.* 2010) and their associated fragmentation impacts (Gera *et al.* 2014); (ii) increasing exposure to NIS that are more resilient to changes in environmental conditions whether they are thermophilic NIS such as rabbit fish *Siganus* spp. or non-calcareous NIS such as *Caulerpa* spp. that are more resilient to water acidification (Hall-Spencer *et al.* 2008). But on the other hand, the rise in temperature can benefit the plant, promoting flowering and sexual reproduction, as was observed everywhere in autumn 2018.

In order to establish a link between states of *P. oceanica* and the potential bundle of ES it provides, we propose to move the research agenda forward by relying on the analysis conducted and by calculating the EBQI (Ecosystem-based Quality Index, Personnic *et al.* 2014). EBQI is an index based on a set of representative functional compartments, the weighting of these compartments and the assessment of the ecological status of each compartment by comparison to a supposed 'good' baseline. We propose to adopt a similar approach to determine the potential bundle of ES by assessing the contribution of each compartment to the provision of each ES. Using this approach, we need to follow several of the steps summarized in Table II. For step 1, we'll ask experts to determine the potential ES bundle. Steps 1 and 2 are based on expert judgments gathered during workshops and bilateral interviews, for step 1 we'll ask experts of Mediterranean habitats to assess the bundle of ES provided by *P. oceanica* meadows. Step 3 is based on the identification of existing meadows illustrative of each state for which a measure of EBQI is available. This work is still ongoing.

Thus, in the ESA process, we propose to base the assessment of the *P. oceanica* ecosystem's capacity to provide ES by establishing a linear relation with EBQI. Such a relation is useful as EBQI is used in ecological monitoring to assess the conservation status of seagrass meadows in the framework of several European Directives. EBQI allows the accumulation of large amounts of data that will allow comparison between *P. oceanica* seagrass meadows. In addition, EBQI is a well-known indicator that reinforces the appropriation of the ESA by decision makers. However, this may raise several problems. First, EBQI may not be a good indicator of the ES. For example, regarding the climate regulation service, a better indicator could be the mean thickness of the matte as it is where carbon is stored (up to 1,500 t/ha/y, Pergent *et al.* 1997, 2014). Secondly, the relation between ES and the quality of the ecosystem may be not linear. For example, we can discuss the question of the provision of sea urchins. According to EBQI, sea urchins (*P. lividus* and *A. lixula*) are part of the functional compartment called "herbivorous", based on the density of sea urchins. The highest EBQI rank for this compartment is 4 when the density of urchins is between 1 and 5 individuals per m^2, EBQI is decreased to 2 and to 0 if the number of urchins exceeds 5 and 10, respectively, as it shows a dysfunction of the ecosystem. However, in the perspective of the ES corresponding to the provision of sea urchins, a higher score should be given to a higher density of urchins. Assuming that ES and EBQI follow the same dynamic tends towards the demand assessment as we are presuming that we should give higher ranking to ES that are provided sustainably regarding the global state of the *P. oceanica* ecosystem. Thirdly, the weight attributed

Table II. – Summary of the step associated to the assessment of the ecosystem services bundle of *Posidonia oceanica* ecosystem.

Step	Method
1 – Determination of the potential bundle of ES associated to the optimal state of the ecosystem	Expert judgment
2 – Identification of the compartments of *P. oceanica* ecosystem involved in the provision of each service	Expert judgment with bibliographic support
3 – Establishment of a direct link between EBQI and the ES bundle	Expert judgment with bibliographic and field data support
4 – Determination of the EBQI of *P. oceanica* ecosystem in each state	Expert judgment and field data
5 – Calculation of the ES bundle of *P. oceanica* in each state	Calculation

to each compartment to take into account its importance in the good functioning of the *P. oceanica* ecosystem may be different when it comes to assessing the provision of ES. In order to overcome these issues, we have initiated a discussion with experts in order to identify the best compromise.

Finally, linking the state-and-transition model to EBQI data from specific sites allows changing the focus we made, *i.e.*, to move from a general model (at the French Mediterranean scale) towards a smaller scale, consistent with an existing management framework (*i.e.*, the Bay of Marseille).

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