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IMPROVING THE MANAGEMENT OF THE SALTMARSHES OF HYÈRES (PROVENCE, FRANCE) USING AN ECOSYSTEM-BASED APPROACH

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SALTMARSHES
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ABSTRACT. – The management of saltmarshes, the complex ecosystem constituted by coastal wetlands and lagoons (SME – Saltmarsh Ecosystem), is often centered on the so-called 'heritage species' (rare, threatened and charismatic species). This 'species-centered' or 'taxon-centered' approach, a legacy from the 20th century, is fully understandable in areas where definitely and critically endangered species occur. However, an ecosystem-based approach, of course including species and higher taxa, but based upon the whole functioning of the ecosystem, from primary producers to *e.g.*, detritus feeders and top predators, would present advantages of paramount importance. The ecosystem-based approach (EBA) involves the management of the interactions between functional compartments, and the search for equilibrium according to the supposed baseline, ecosystem services and management goals. This approach offers a basis for considering the current global change. A conceptual model of the whole saltmarsh ecosystem, including lagoon bottom, water body and terrestrial adjacent habitats, has been established. Taking into account the high diversity of saltmarsh environments physically and biologically as well, this model is a frame that should be adapted to each case study. Here, the authors focus on two case studies in Provence (Vieux Salins and Salin des Pesquiers), northwestern Mediterranean. The weaknesses of the traditional species-centered approach and the advantages of an ecosystem-based approach are highlighted through novel applications.

INTRODUCTION

Saltmarshes are a worldwide ecosystem, the origin and structure of which vary according to climate (boreal, temperate, sub-tropical, tropical) (Danin 1981, Ayyad & El-Ghareeb 1982, Peinado *et al*. 1995, Asri & Ghorbanli 1997, Costa *et al*. 2009, De Wit *et al*. 2019), precipitation rate and variability over years (Callaway & Sabraw 1994), and tide amplitude (from microtidal, *e.g*., Mediterranean Sea, to megatidal, *e.g*., Atlantic Ocean) (Long & Mason 1983, Adam 1990, Vernberg 1993, Mc Owen *et al*. 2017). A high degree of similarity can be observed worldwide between saltmarsh ecosystems (Costa *et al*. 2009, Peinado *et al*. 2009). In temperate microtidal areas, saltmarshes are a complex combination of both wetland and coastal lagoon or estuarian system with evapotranspiration deficit (Boutière 1974, Mesleard *et al*. 1995, Duarte *et al*. 2002); hereafter, we will name the complex ecosystem they constitute SME (saltmarsh ecosystem). They play an important role at the interface of continental-terrestrial ecosystems and coastal marine waters, and provide a variety of ecosystem services (Nordlund *et al*. 2016, Himes-Cornell *et al*. 2018, Newton *et al*. 2018, Sy *et al*. 2018, O'Higgins *et al*. 2019): (i) breeding and nesting area for a large number of migratory waterfowl and wintering bird species (Furness & Greenwood 1993, Del Hoyo *et al*. 1996, Birdlife International 2004, Isenmann 2004, Thorup 2006), (ii) heritage (historical, landscape) for exploited or non-exploited areas (Borel 1996, Hérault 2010), (iii) sediment retention and trapping (Li & Yang 2000, Wood & Hine 2007), (iv) protection against erosion and submersion (Sharma *et al*. 2016, Lo *et al*. 2017) of urbanized areas, receptacle of the watersheds (King & Lester 1995), (v) cleaning of continental pollutants and contaminants (Fisher & Acreman 2004, Bromberg-Gedan *et al*. 2009, Calvo-Cubero 2014, Calvo-Cubero *et al*. 2014), (vi) nursery habitat for marine fish species (Beck *et al*. 2001) of high economic and fishery interest (Minello *et al*. 2003) such as the seabass *Dicentrarchus labrax* (Linnaeus, 1758) and the gilthead bream *Sparus aurata*

Linnaeus, 1758, (vii) essential habitat for adult fish such as the European eel *Anguilla anguilla* (Linnaeus, 1758) (Kara & Quignard 2018a, 2019a), (viii) primary production by Magnoliophyta, macroalgae and phytoplankton (Quintana *et al.* 1998, Curcó *et al.* 2002, Menéndez 2002, Quintana & Moreno-Amich 2002), (ix) grazing areas for cattle (Duncan & D'Herbes 1982, Andresen *et al.* 1990), (x) sites for extensive and intensive aquaculture (Lumare 1983, Boudouresque *et al.* 2020a), (xi) and an important carbon sink (Sousa *et al.* 2017).

Saltmarshes are often ecosystems that have been more or less artificialized and impacted for centuries (Bertness *et al.* 2002, Bromberg-Gedan *et al.* 2009) and are exposed to numerous threats (Ganju *et al.* 2017): (i) Habitat destruction by urbanization, industry (including salt production) and agriculture (Andresen *et al.* 1990, Mesleard *et al.* 1995, Tourenq *et al.* 2001); (ii) eutrophication (Quintana & Moreno-Amich 2002, López-Flores *et al.* 2006, Moseman-Valtierra *et al.* 2016) including increased herbivory issues (Holdredge *et al.* 2008, Alberti *et al.* 2011); (iii) global change, including invasive species and community shift (Castillo *et al.* 2000, Occhipinti-Ambrogi 2000, Occhipinti-Ambrogi & Savini 2003, Boudouresque *et al.* 2005, Bianchi 2007, Occhipinti-Ambrogi 2007, Boudouresque *et al.* 2011, Boudouresque & Verlaque 2012, Bianchi *et al.* 2013, Lascève 2014, Al Hassan *et al.* 2016, Boudouresque *et al.* 2017, Curado *et al.* 2018), the rise of sea level (Laborel *et al.* 1994, Moseman-Valtierra *et al.* 2016, Valiela *et al.* 2018) with the decline of plant diversity induced by stronger competition (Noto & Shurin 2017), warming (Boyer *et al.* 2012, Monllor *et al.* 2018), inducing higher evaporation and consequently higher mean salinity (Mollema *et al.* 2013), (iv) use of insecticides against harmful mosquitoes with potential high impact on non-target fauna (Poulin 2012), (v) erosion (Lo *et al.* 2017), (vi) contamination from human activities in the watershed (Usero *et al.* 2002).

For those reasons, saltmarshes are ecosystems of high concern and high heritage value; many international agreements aim at their protection and sustainable management (*e.g.*, RAMSAR, Habitat Directive Natura 2000, 92/43/EEC) (Matthews 1993, Evans 2012). However, the management of saltmarsh ecosystems is heterogeneous and varies according to uses (De Wit *et al.* 2019): (i) still anthropized areas without conservation goals (Moomaw *et al.* 2018), (ii) management including conservation within an anthropized or industrialized site: *e.g.*, Camargue (Tamisier 1991), Tijuana Estuary (Southern California, Callaway & Zedler 1998, 2004), Ebro delta (Romagosa & Pons 2017), (iii) totally protected areas managed for their conservation (*e.g.*, saltmarshes of Hyères; Astruch *et al.* 2019, De Wit 2020). Furthermore, management plans with conservation priorities are based on a species-centered approach. Management goals rather target the maintenance or the enhancement of 'biodiversity' and 'high-level' species or taxon populations, namely those that are emblematic, rare, aesthetic, charismatic or threatened (Bougrain-Dubourg & Terrasse 2001, Bourgeois & Vidal 2005, Bourgeois *et al.* 2008, Boudouresque *et al.* 2020b), to the detriment of 'ordinary biodiversity' species and those considered harmful (De la Blanchère 1878, Boudouresque 2014). Biodiversity (Dasmann 1968, Soulé & Wilcox 1980, Wilson 1988, Boudouresque 2014) is often seen by managers and stakeholders as equivalent to the number of species, a high number of species being erroneously considered as a health index of the ecosystem. Disturbances and stress could in fact be conducive to an increase in the number of species (Hastwell & Huston 2001, Boudouresque 2014). Although this species-centered approach has allowed the protection and conservation of numerous heritage value and key species, it may be considered as inappropriate for an effective management, as it does not take into account the ecosystem functioning (Boudouresque *et al.* 2020b). Particularly for saltmarshes, an ecosystem-based approach is needed.

The aim of the present work is to apply the Ecosystem-based approach (EBA) to the saltmarsh ecosystem (SME), including wetlands and Mediterranean lagoons. We propose a conceptual model of the SME to understand its functioning and provide an efficient tool to improve its management. Here, we focus on the example of the Hyères saltmarshes. The development of the EBA and the conceptual model of the SME were based on analysis of the literature and the authors' expert judgment. Original data were collected within the saltmarshes of Hyères on macrophytes, fish assemblages and the plankton community to complete the available information.

MATERIAL AND METHODS

The case study of the saltmarshes of Hyères: The coastal wetlands and lagoons along the Bay of Hyères (Hyères, Provence, north-western Mediterranean Sea, France) have been deeply transformed by human activities since Antiquity. The spread of the city of Hyères (formerly named Olbia in Roman times) covered hundreds of hectares of wetlands, breaking up the ecological continuity from the peninsula of Giens to the eastern part of the bay. Since the Middle Ages, two distinct areas were delimited, Salin des Pesquiers and Vieux Salins (Fig. 1). The first was a coastal lagoon surrounded by wetland where an important local fishery was established, providing considerable revenue (Réveillon 2018). The second, smaller, had been exploited for salt production since Antiquity, but at an artisanal scale. From 1848 to 1995, these two areas were converted into an intensive salt production zone; they were transformed into a grid of several dozens of pans (ponds) used to evaporate brine, with a network of canals to exchange water between the pans, and to bring in or remove from water between the pans and the sea. The evaporation ponds and canals have remained in place, even after salt production was discontinued. In 2001, the whole site became the property of the *Conservatoire de l'Espace Littoral*

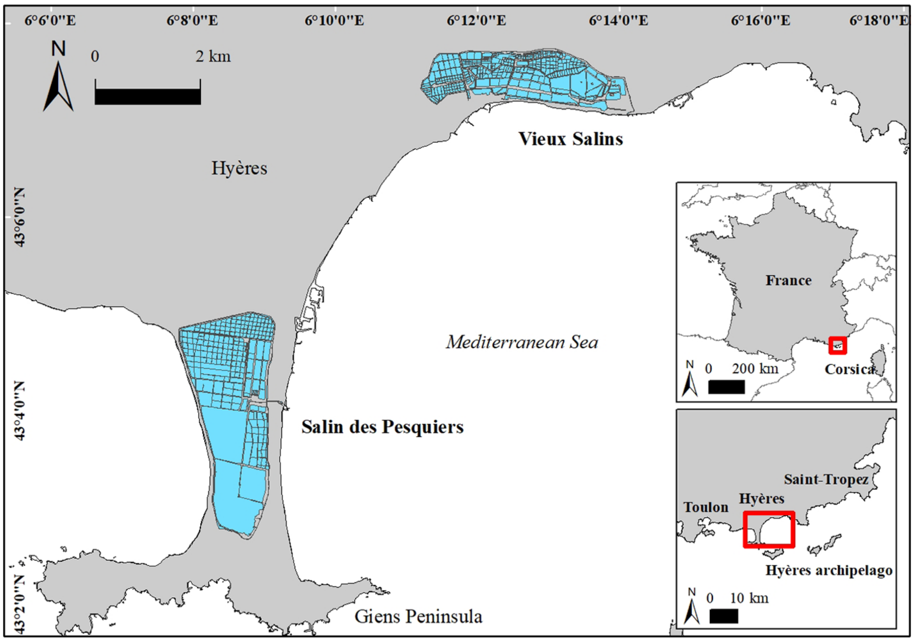

Fig. 1. – Location of the saltmarshes of Hyères (Salin des Pesquiers and Vieux Salins).

et des Rivages Lacustres (CERL) (coastal areas and lake shores conservation agency) and was managed by the *Toulon Provence Méditerranée* (TPM) local authority. During this period, the management goals and the water management planning were mainly focused on the historical heritage (salt production) and the conservation of waterfowl and wintering birds (Audevard 2017). A species-centered approach rather favored the so-called 'heritage taxa' (rare, threatened, charismatic). However, managers already identified the low connectivity between the saltmarshes (SME) and the open sea and related issues impacting fish assemblages (summer massive mortality, eutrophication) (Conservatoire du Littoral, Toulon Provence Méditerranée and Parc national de Port-Cros 2011, CREOCEAN 2011).

The concept of an ecosystem-based approach: The early concept of 'ecosystem' in ecology was proposed to understand and quantify flows (nutrients, carbon) in natural and anthropized ecosystems in the 1950s and earlier (Tansley 1935, Odum & Odum 1959, Odum 1998). Since then, saltmarshes, wetlands and lagoon ecosystems have been extensively studied (*e.g.*, Odum & Smalley 1959, Tamisier & Boudouresque 1994, Casagranda & Boudouresque 2007, De Wit *et al*. 2019), in part because of the aforementioned ecological services they fulfill. Since the seminal work of Teal (1962), several studies considering food webs and interactions between saltmarsh ecosystem functional compartments have been published (Nordström *et al*. 2015, Wang & Brose 2018). Today, the Ecosystem-based approach (EBA) is highlighted by the Marine Strategy Framework Directive (MSFD, 2008/56/EC) of the European Union (EU) (Laffoley *et al*. 2004, Halpern *et al*. 2010, Personnic *et al*. 2014) and is applied for fishery management worldwide (Turrell 2004, Rice 2005). It is regarded as an effective tool for the assessment and the management of an ecosystem corresponding to marine and coastal habitats of European interest (Habitat Directive Natura 2000, 92/43/EEC). In the framework of the MSFD, the EBA has been applied to four Mediterranean marine ecosystems to assess their quality: (i) *Posidonia oceanica* (Linnaeus) Delile seagrass meadow (Personnic *et al*. 2014), (ii) the coralligenous ecosystem (Ruitton *et al*. 2014); algae-dominated shallow rocky reefs (Thibaut *et al*. 2017) and underwater marine caves (Rastorgueff *et al*. 2015). An index, the Ecosystem-based Quality Index (EBQI), has been developed and tested to provide a standard tool for managers and stakeholders (Ruitton *et al*. 2017).

Hereafter, the conceptual model of the SME proposed is based on taxa from Mediterranean microtidal systems. The listed taxa are cited here as examples. The model itself is designed to be applied to non-Mediterranean SMEs encompassing other communities. The conceptual model was designed on the basis of expert judgment and the authors' knowledge, literature analysis and original data from the present study of the Hyères saltmarshes.

RESULTS

A conceptual model of the functioning of the saltmarsh ecosystem

Here, we propose a comprehensive conceptual model of the functioning of saltmarsh ecosystems (SME – wetland and lagoon). The conceptual model (Fig. 2) corresponds to an optimal functioning of the SME according to the management plan objectives (here, for the saltmarshes of Hyères). There is only one size of arrow. The goal of this scheme is not to assess the carbon flow between compartments (boxes) but to understand the fluxes between them. The description of the boxes in the conceptual

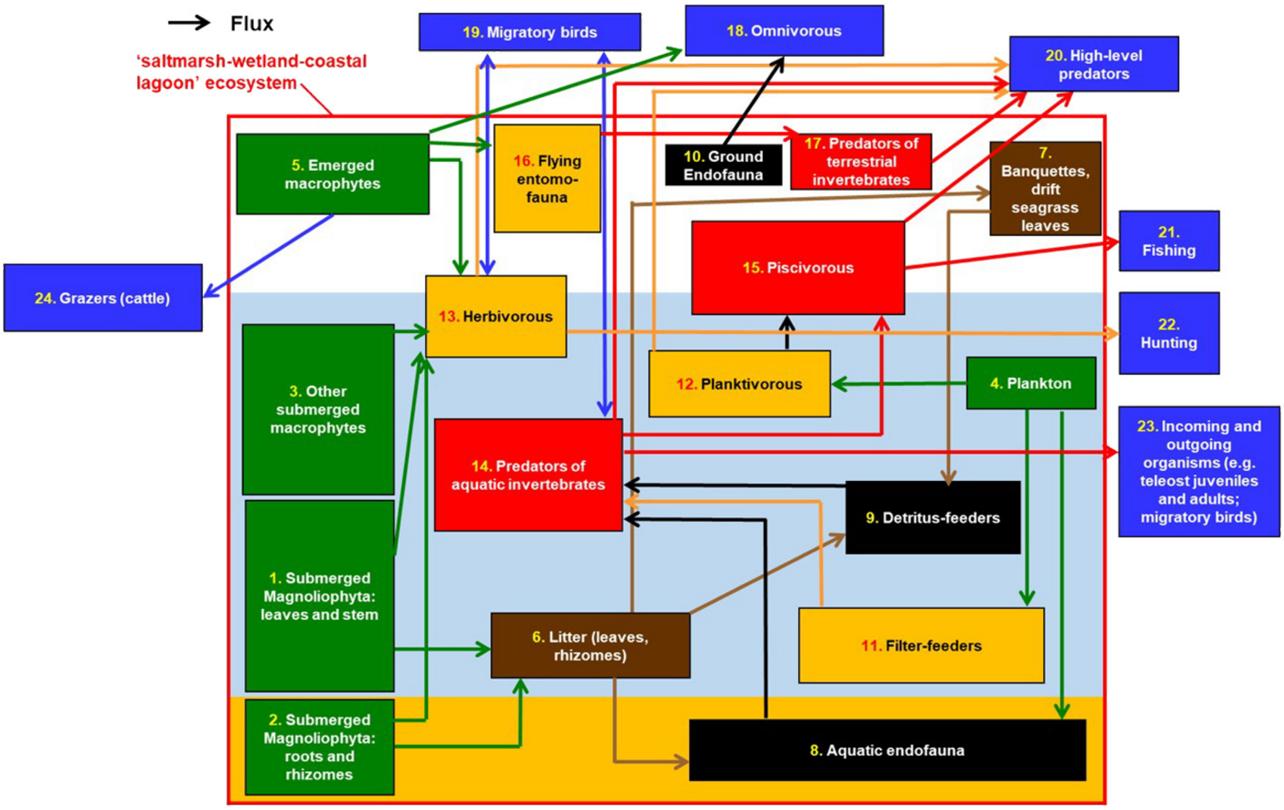

Fig. 2. – Conceptual model of the saltmarsh ecosystem (SME). Arrows correspond to the carbon flux between compartments (boxes). Box color: green: primary producers; yellow: primary consumers; red: predators; brown: detritus from primary producers; black: detritus-feeders and aquatic endofauna; blue: box out of the ecosystem but significantly interacting with it. The size of a box is not related to its 'weight' (importance).

model of SME is presented below. The cited taxa correspond to a northwestern Mediterranean context. The species or taxa described in the following boxes can belong to several of them according to trophic guilds.

(Box 1) Submerged Magnoliophyta

This box corresponds to the main aquatic primary producers of the ecosystem. These taxa are perennial, with maximum development between the end of spring and summer. Species occurrence in saltmarshes is strictly linked with the water salinity dependent on the connection with the open sea. *Ruppia spiralis* (Linnaeus) ex Dumortier (= *R. cirrhosa* (Petagna) Grande; Calado & Duarte 2000, Den Hartog & Kuo 2007, Ito *et al.* 2017) can tolerate euryhaline and hyperhaline conditions, from 0 to 106 g/kg (Verhoeven 1979, Mannino *et al.* 2015); *Stuckenia pectinata* (Linnaeus) Börner spreads in brackish or fresh water (Casagranda & Boudouresque 2007); *Zostera noltei* Hornemann can tolerate euryhaline conditions but less than *R. spiralis*; *Zostera marina* Linnaeus prefers marine-like conditions (Bernard *et al.* 2005); *Cymodocea nodosa* (Ucria) Asch. is an open sea species, widespread in the southern part of the Mediterranean, that can thrive in coastal lagoons (thermophilic, stenohaline) (Pergent *et al.* 2014). Two others marine Magnoliophyta are present in the Mediterranean Sea, *Posidonia oceanica* and *Halophila stipulacea* (Forssk.) Asch.; *P. oceanica* is strictly marine (Boudouresque *et al.* 2012) and *H. stipulacea* is an invasive Lessepsian species which can occur in brackish waters (Galil 2006). In this box, only leaves and stems are considered. Leaf and stem biomass can be driven by light availability, depth, nutrient availability and predation pressure. Low biomass or covering can be linked to inadequate environmental conditions while high biomass and maximum covering of the meadow could be explained by a relatively small population of herbivorous birds (*e.g.*, Anatidae). In both situations, it does not mean good ecosystem quality, the optimum corresponding to intermediate abundance (Gayet *et al.* 2012).

(Box 2) Buried parts of Magnoliophyta in the sediment

Roots and rhizomes are the buried part of the plant. Their biomass is related to the nutrient availability in the sediment. Even if the submerged part of the plant biomass is low, high endogenous biomass indicates a good state of health of the plant, which is adapted and able to accumulate reserves (Verhoeven 1980, Ferrat *et al.* 2003).

(Box 3) Other submerged macrophytes

Macroalgae can be abundant primary producers in SMEs. Most of them are Chlorobionta, mainly indicative of eutrophic conditions (*e.g.*, *Ulva* spp. Linnaeus, *Chaetomorpha linum* (O.F. Müller) Kützing, *Cladophora* spp. Kützing). The macroalgae assemblages are strictly linked with water conditions, light availability and eutrophication level. Compared to open sea macroalgae communities (*e.g.*, Infralittoral reefs with photophilous macroalgae), the species diversity is lower and is driven by annual changes of physical-chemical parameters (*e.g.*, salinity, dissolved oxygen, temperature) (Pérez-Ruzafa *et al*. 2008). In lagoons, which present a high connectivity with the open sea, Rhodobionta and Phaeophyceae can be more numerous, including perennial species such as *Cystoseira barbata* (Stackhouse) C. Agardh (Orfanidis *et al*. 2008, Réseau de Suivi Lagunaire 2011).

(Box 4) Plankton

Phytoplankton and zooplankton are key assemblages for the trophic network of the SME (Quintana *et al*. 1998). They constitute an important food supply for several boxes (planktivorous, detritus- and filter-feeders). Phyto- and zooplankton abundance are strongly correlated with a seasonal pattern (Riley & Bumpus 1946, Talling 2003). Species composition is linked to salinity and nutrient availability (Masmoudi *et al*. 2015). Status of plankton assemblages is a good indicator of the water column conditions. A high rate of Chlorophyll a could result from eutrophic conditions. The size of the organisms is also a good indicator that reflects the aging of the community. Extreme conditions can lead to the thriving of a single species (*e.g.*, *Artemia salina* Linnaeus, 1758 in hyperhaline conditions: Ollier 1964, Britton and Johnson 1987). Abundance of large individuals corresponds to an old stable population; abundance of small and young individuals indicates more unstable conditions. Early stages of Copepoda (nauplii) or Rotifera can be present in very high abundance, often corresponding to a rapid shift in water condition/circulation (Brucet *et al*. 2005, 2008).

(Box 5) Emerged macrophytes

e.g., *Salicornia* s.l. Linnaeus, *Spartina* Schreb (Molinier 1953, Molinier & Tallon 1970, Aboucaya *et al*. 2011). Biomass and specific richness depend on salinity (soil and water) and water control (flooding persistence) (García *et al*. 1993, Asri & Ghorbanli 1997, Curcó *et al*. 2002). Emerged vegetation (*e.g.*, *Spartina alterniflora* Loisel association) is considered as the main primary producer in the saltmarsh ecosystem (Teal 1962, Marañón 1998, Noble & Michaud 2016).

(Box 6) Litter

During the life span of aquatic Magnoliophyta, dead leaves usually shed from the summer. Rhizomes and roots can be uprooted by storms and herbivorous organisms. All these remnants constitute the litter. The abundance of the litter is correlated with the coverage and biomass of the living meadow. Litter is an important food supply for detritus-feeders, herbivores and part of the endofauna. It also can be exported to the *banquettes* (box 7). Litter increases when the salinity decreases (Curcó *et al*. 2002).

(Box 7) Banquettes

Composed of seagrass leaves and macroalgae detritus drifted onto the shore of the lagoon, *banquettes* provide habitat and trophic resources for detritus-feeders and part of the entomofauna. Thickness, taxonomic composition and abundance of the *banquette* are linked to seagrass meadow vitality and macroalgae abundance and can vary according to season (Virnstein *et al*. 1985).

(Box 8) Aquatic endofauna

Mainly represented by Annelida (*e.g.*, *Hedistes diversicolor* O.F. Müller, 1776) and Mollusca (*e.g.*, *Cerastoderma glaucum* Brugières, 1789, *Ruditapes* spp. Chiamenti, 1900), this box is composed of detritus- and filter-feeders. Abundance of individuals and species diversity are correlated with particle size of the sediment, dissolved oxygen rate, eutrophication and connection to the open sea (Ollier 1964, Lardicci *et al*. 1997, Breil 2014).

(Box 9) Detritus-feeders

The abundance of macro-invertebrates such as *Gammarus* spp. Fabricius, 1775, *Idotea chelipes* (Pallas, 1766), *Lekanesphaera hookeri* (Leach, 1814), *Carcinus maenas* (Linnaeus, 1758) and *C. aestuarii* Nardo, 1847 can be linked with seagrass biomass (Gravina *et al*. 1989, Casagranda *et al*. 2006, Özbek *et al*. 2012, Breil 2014). The mudsnail *Hydrobia* spp. Pennant, 1777 can be very abundant in saltmarshes and lagoons (Ollier 1964, Barnes 2005). This compartment, despite low biomass, has a key function, processing macrophyte matter to different trophic levels through fragmentation, thus accelerating the decomposition.

(Box 10) Ground endofauna

Mainly represented by Annelida, arachnids, and insects, it belongs to several trophic guilds (Chauliac 2005, Breil 2014).

(Box 11) Filter-feeders

This box is often represented by Mollusca such as *Mytilus galloprovincialis* Lamarck, 1819*, Ostrea edulis* Linnaeus, 1758*, Mya* sp. Linnaeus, 1758*, Ruditapes* spp.*, Cerastoderma* spp.*, Pinna nobilis* Linnaeus, 1758, Annelida such as *Ficopomatus enigmaticus* (Fauvel, 1923)*, Sabella spallanzanii* (Gmelin, 1791)*,* Ascidiascea such as *Phallusia mammillata* (Cuvier, 1815)*, Botryllus* spp. Gaertner, 1774*, Microcosmus* sp. Heller, 1878, *Ascidiella aspersa* (Müller, 1776), etc. (*e.g*., Perthuisot & Guélorget 1983, Gravina *et al*. 1989, Marchini *et al*. 2004, Soufi-Kechaou *et al*. 2019). Species diversity, abundance and size of individuals of the filter-feeder box depend on eutrophication level and food availability (see box 4). A high biomass could contribute to the eutrophication itself and leads to anoxic crises (Mayot *et al*. 2021). Oyster farming (mainly *Magallana gigas* (Thunberg, 1793) and *Mytilus galloprovincialis*) can contribute significantly to this box (Vaquer *et al*. 2000).

(Box 12) Planktivorous species

In coastal Mediterranean lagoon ecosystem and as well SME, the main taxa representing the Planktivorous box are *Atherina* spp. Linnaeus, 1758 (Le Diréach *et al*. 2013, 2021). This small sedentary teleost can be very abundant and can thrive in a wide range of abiotic conditions. *Atherina boyeri* Risso, 1810 spends its entire life cycle in SME (Maci & Bacet 2010, Kara & Quignard 2018b). This is a key taxon, which provides food for several higher trophic levels (*e.g*., box 15: piscivorous teleosts and birds) (Kara & Quignard 2018a). Depending upon the level of connectivity with the open sea, non-sedentary planktivorous species can also occur, such as the European anchovy *Engraulis encrasicolus* (Linnaeus, 1758) (Manzo *et al*. 2013). The pink flamingo *Phoenicopterus roseus* Pallas, 1811 can belong both to this compartment and to box 14.

(Box 13) Herbivorous species

This box is composed of Anatidae (*e.g*., *Tadorna tadorna* (Linnaeus, 1758)*, Anas Penelope* Linnaeus, 1758) and other herbivorous birds and the teleost *Salpa salpa* (Linnaeus, 1758). The latter species is the only indigenous herbivorous teleost in the Mediterranean Sea that can also be observed in brackish waters (Kara & Quignard 2019b). Some small crustaceans, terrestrial gastropods and insects are also to be included in this box (see Casagranda *et al*. 2006). Finally, the rare southwestern water vole *Arvicola sapidus* Miller, 1908, a rodent, and the European hare *Lepus europaeus* Pallas, 1778 can occur.

(Box 14) Predators of aquatic invertebrates

(from open water or sediment endofauna) Represented by: (i) Shoreline birds, most of them being migrators, which use the SME for breeding and nesting (*e.g*., the pied avocet *Recurvirostra avosetta* Linnaeus, 1758*,* the wood sandpiper *Tringa glareola* (Linnaeus, 1758)*,* the pink flamingo *Phoenicopterus roseus*); (ii) wintering birds such as the little stint *Calidris minuta* (Leisler, 1812) and the Dunlin *C. alpina* (Linnaeus, 1758) occur and can be abundant (Audevard 2019); (iii) teleost fishes (*e.g*., *Anguilla anguilla, Sparus aurata*, Soleidae, Mugilidae, etc.) (Kara & Quignard 2019a, b); and (iv) aquatic turtles, namely the European pond turtle *Emys orbicularis* (Linnaeus, 1758), and the red-eared slider turtle *Trachemys scripta* (Thunberg *in* Schoepff, 1792), even if their trophic regimes can be more diverse (Lascève 2014, Perrot *et al*. 2016).

(Box 15) Piscivorous species

Within the SME, piscivorous species are mainly birds: the lesser great cormorant *Phalacrocorax carbo* (Linnaeus, 1758), Laridae such as the little tern *Sternula albifrons* (Pallas, 1764)*,* and Ardeidae such as the little egret *Egretta garzetta* (Linnaeus, 1766) and the grey heron *Ardea cinerea* Linnaeus, 1758) (Audevard 2017). The teleost fish *Dicentrarchus labrax* is also a piscivorous species (Haffray *et al*. 2006, Kara & Quignard 2019a).

(Box 16) Flying entomofauna

This box is highly diversified. Chironomidae and the mosquitoes *Aedes* sp. (Meigen, 1818) and *Culex* sp. (Linnaeus, 1758) (Poulin 2012, Roiz *et al*. 2015) are among the most abundant. Species diversity and abundance of individuals of the flying entomofauna are strongly linked with landscape and vegetation structure within the saltmarsh (Chauliac 2005, Roiz *et al*. 2015; Orthoptera: Lemonnier-Darcemont 2004; Coleoptera: Ponel 2005; Lepidoptera: Varenne 2015).

(Box 17) Predators of terrestrial invertebrates

This box is composed of a variety of taxonomic groups: (i) Some species of Chiroptera use wetlands as shelters and food resource (Cosson 2005, Flaquer *et al*. 2009, Barataud 2012, Naturalia 2015); (ii) Reptilia such as lizards, the threatened Spanish psammodromus *Psammodromus hispanicus* Fitzinger, 1826, the common wall lizard *Podarcis muralis* (Laurenti, 1768), the western green lizard *Lacerta bilineata* Daudin, 1802 (Joyeux 2005, 2011) and a snake, the Iberian three-toed skink *Chalcides striatus* (Cuvier, 1829) (SOPTOM 2017); (iii) frogs, *e.g*., *Pelophylax* sp. Fitzinger, 1843 and the Mediterranean tree frog *Hyla meridionalis* Böttger, 1874 (Joyeux 2005); (iv) arachnids (Lycosidae Sundevall, 1833; and (v) Coleoptera Carabidae Latreille, 1802, *e.g*., *Scarites planus* Bonelli, 1813 and *Carabus morbillosus* Fabricius, 1792.

(Box 18) Omnivorous species

The wild boar *Sus scrofa* Linnaeus, 1758 is an opportunist species; it is often considered a pest by farmers, because of the damage it can cause to crops (Sáez-Royuela & Telleria 1986, Schley & Roper 2003, Corbobesse 2008); however, it plays an important role in the functioning of a natural ecosystem (see *e.g*., Barrios-García & Ballari 2012, Boudouresque *et al*. 2020b). The red fox *Vulpes vulpes* (Linnaeus, 1758) can be included in this box. The yellow-legged gull *Larus michahellis* Naumann, 1840, as an opportunistic species, is considered as omnivorous. The coleopter *Pimelia muricata* Olivier, 1795 is observed in sandy areas within the saltmarshes. Some fish species occurring in abundance within the lagoon habitats can belong to this box, such as *Chelon* spp. Artedi, 1793 and the flathead grey mullet *Mugil cephalus* Linnaeus, 1758 (Cardona 2006, Kara & Quignard 2019a).

(Box 19) Migratory birds

This box corresponds to migratory birds including waterfowl that can be listed in other boxes of the ecosystem (*e.g*., Herbivorous species, Predators of invertebrates, etc.). It highlights the inputs and outputs from and to the SME by avifauna. The maintaining of this compartment is one of the main goals of the managers of the saltmarshes of Hyères (Birdlife International 2004, Audevard 2017, 2019).

(Box 20) High-level predators

This box can be placed both inside and outside the SME. It includes species that mainly live outside but close to the SME: (i) mostly raptors such as the western marsh harrier *Circus aeruginosus* (Linnaeus, 1758) (Audevard 2017, 2019); and (ii) mammals such as the red fox *Vulpes vulpes,* traditionally considered as harmful (see the human-centered approach; Boudouresque *et al*. 2020b), and the domestic cat *Felis silvestris catus* (Linnaeus, 1758) (Tranchant & Vidal 2003). Some Reptilia belong to this compartment, such as the Montpellier snake *Malpolon monspessulanus* (Hermann, 1804) (SOPTOM 2017).

(Boxes 21 and 22) Fishing and Hunting

Human activities that exploit the SME must be considered for their impact on waterbird and fish populations (Mathevet & Tamisier 2002, Tamisier *et al*. 2003), even when those activities are prohibited (due to illegal fishing and hunting).

(Box 23) Incoming and outgoing organisms

The SME is an essential habitat for fish juveniles (settlement of post-larvae coming from open sea spawning areas), and for adults looking for trophic resources, shelter and suitable environmental conditions (Kara & Quignard 2019a, b). Similar ecological functions are provided for bird populations, mainly waterfowl, which find breeding and nesting areas and trophic resources mainly from spring to the end of summer. This box highlights some of the main ecological functions and services of the SME (Himes-Cornell *et al*. 2018, O'Higgins *et al*. 2019).

(Box 24) Grazers

Cattle (cows, sheep and horses) in grazed pastoral areas can find an important food supply in wetlands (Duncan & D'Herbes 1982), interacting with other herbivorous species belonging to the SME (box 13) and structuring emerged Magnoliophyta communities (box 5). This compartment is external to the ecosystem (SME).

Diagnosis on the conservation status of the saltmarshes of Hyères

The *Ruppia spiralis* seagrass meadow within the saltmarshes of Hyères presents a good conservation status (Massinelli *et al*. 2017, 2021). Its high mean biomass reflects the good health of this species, which finds favorable conditions for its development. However, *Ruppia spiralis* is a halophilous species, the only seagrass species that can thrive in such a range of salinity (*i.e*., 0-106 g/kg). The absence of other expected taxa such as *Zostera noltei* can be explained by both unsuitable conditions (*e.g*., high salinity, eutrophication) within the saltmarshes and the decline of its populations at regional scale (northwestern Mediterranean; Pergent *et al*. 2014). A number of aquatic compartments (boxes) of the saltmarshes of Hyères are not well connected with the open sea. Fish assemblages are dominated by sedentary taxa adapted to euryhaline or halophile conditions (Le Diréach *et al*. 2021): (i) *Atherina* spp., (ii) *Pomatoschistus* spp. Gill, 1863, (iii) *Syngnathus abaster* Risso, 1827 (Kara & Quignard 2018b). When the connection with the open sea is better established, *e.g*., within the belt channel of Salin des Pesquiers, a higher species diversity is observed, represented by: Mugilidae such as *Chelon* spp., *Mugil cephalus*, and migratory fish such as Sparidae (*Sparus aurata, Diplodus vulgaris* (Geoffroy Saint-Hilaire, 1817)*, Sarpa salpa*), *Dicentrarchus labrax*, *Anguilla anguilla* (Kara & Quignard 2019a, b). The occurrence of juvenile individuals from these taxa can be considered as indicative of that connectivity. It is not only the lack of connectivity that can impact the functionality of the lagoon parts of the saltmarsh, but also inadequate salinity and DO (dissolved oxygen). Salinity is the main driver of fish assemblage composition (Malo-

Michèle 1979, Alliot *et al.* 1983, Bodinier *et al.* 2010), associated with oxygen (Person-Le Ruyet 1986) and habitat characteristics (Astruch *et al.* 2020, Massinelli *et al.* 2021). Salinity is also the main driver of plankton communities. The plankton community can react very fast after shifts in water condition. Sites well connected with the open sea show a low abundance of both phyto- and zooplankton and larger individuals and greater stability (*i.e.*, older populations). In less well-connected and stable areas, abundance is higher, particularly for phytoplankton, mainly represented by small individuals corresponding to a young population. As shown by Quintana *et al.* (1998), flooding episodes induce a dilution of the zooplankton and increased resources due to phytoplankton bloom. The saltmarshes of Hyères host a very high a species diversity of birds (the cumulative number, over several decades, is about 300 species), including waterfowl wintering species and shorebird species, most of them being of high heritage value (Audevard 2017, 2019). This is one of the main successes of the first management plan implemented in early 2000s.

The management policy has enabled the inclusion of the saltmarshes of Hyères within the Natura 2000 network ('Rade d'Hyères' FR9301613) as well as the Camargue and coastal lagoons of the Gulf of Lion. The monitoring of bird populations shows connectivity between the saltmarshes of Hyères, the Camargue and Gulf of Lion lagoons, all considered as nesting and wintering areas and privileged sites for migrations (Audevard 2019). Within the saltmarshes of Hyères, one habitat is considered a priority habitat of European interest, in the sense of the EU Habitat Directive: 1150-2 – Mediterranean lagoon. In addition, about thirty species of plant are of heritage value, with national or local protection status, highlighting the maintenance of a remarkable species diversity, despite the considerable transformations to which man has previously subjected these saltmarshes (Noble & Michaud 2016).

DISCUSSION AND CONCLUSION

The present work enables us to better understand the overall functioning of the SME (saltmarsh ecosystem – saltmarsh, including wetland and coastal lagoon) such as the saltmarshes of Hyeres and their management through an ecosystem-based approach (EBA). The next step should be to implement an Ecosystem-based Quality Index (EBQI) for the SME. The index should be tested with data provided from a wide range of Mediterranean SMEs: (i) size (surface area, mean and maximum depth), (ii) water conditions (salinity, temperature), (ii) connectivity to the open sea, (iii) eutrophication, (iv) gradient of human pressure other than eutrophication (fishing activities, non-indigenous species abundance and diversity, habitat destruction or withdrawal). This approach would provide the basis for an effective tool for assessment of the conservation status of Mediterranean SMEs. Obviously, assessment of the health status of coastal lagoon and wetland ecosystems is complex and several indices and methods already exist (Lepareur *et al.* 2013); most of these existing indices take into account only part of the ecosystem (plankton community, endofauna, macrophytes, etc.) and were developed to assess the quality of the water body within the framework of the Water Framework Directive. Further studies are needed to define a typology of saltmarshes following an EBA, *i.e.*, wetlands and coastal lagoons, in an Euro-Mediterranean context (Dyer 1998, Ibañez *et al.* 2002, Almeida 2016), according to: (i) the size of the system (including the watershed basin), (ii) the ratio between wetland and lagoon surface areas, (iii) the effectiveness of the connectivity with the open sea. The conceptual model should be adapted for each category by adjusting the weight of each box without changing its overall structure (*e.g.*, box 2 'submerged Magnoliophyta' will get a higher weighting for a category including large Mediterranean lagoons, *e.g.*, Thau lagoon, southern France). It is a challenging perspective for better monitoring and management of such habitats of interest.

Despite the lack of innovative indices and typology, the ecosystem-based approach enables us to highlight ways to improve the functioning of saltmarshes considering consequences of the management at the ecosystem scale. Relative to the initial objectives of the first management plan for the saltmarshes of Hyères established in 2004, centered on waterfowl and saltmarsh landscape conservation, the results have met the expectations of the managers. Since 2019, the new management plan will not exclude these previous aims but will also consider the improvement of the whole ecosystem functioning (based on water circulation and connection with the open sea) together with better access to the sites for the public and the conservation of heritage landscape. This is a direct consequence of the application of the ecosystem-based approach. Our analysis underlines the need to improve (i) the water circulation in selected ponds where high salinity and low connectivity prevents their use by teleost fish, of which the juveniles could thrive there; inappropriate management of water circulation can lead to the trapping of juvenile fish that cannot escape to join the open sea adult population (Bruslé & Carbony 1992); (ii) the water quality along the belt channel is impacted by contaminated freshwater inputs from adjacent urbanized areas. In addition, the erosion of the shore and frequent submersion events have alerted the management team to the risk of the future 'marinization' of the area, in relation with the current increased rate of sea level rise (Blanfuné *et al.* 2016, Dieng *et al.* 2017). Major transformations are therefore expected and are of long-term concern in the future management plan. The former role of fishery, before the wetland/coastal lagoon system was converted into salt evaporation ponds, is known in the area (Chauvet 1986, Réveillon 2018). Historical data regarding the use of the Salin des Pesquiers lagoon as an active fishery proves that the functioning of the site was completely different from that of today. The functioning of the Salin des Pesquiers lagoon was close to that of a Mediterranean lagoon, including permanent connectivity with the open sea, sometime on both sides of the tombolo (Réveillon 2018). Taking into account global change, sea level rise and the increase in submersion events, a 'marinization' of the saltmarshes of Hyères is to be expected. Taking this 'marinization' into account constitutes an important challenge for the new management plan.

The upcoming decisions to be taken by managers will take into account all the following priorities: (i) Waterfowl conservation is of major importance not only at local scale but at regional scale (Audevard 2017); managers will therefore continue to favor the nesting of birds; but they will consider water circulation, flooding risk in surrounding urbanized areas and the future submersion of the north-western ponds of the Salin des Pesquiers (*e.g.*, with the destruction of a nesting site of the Kentish plover *Charadrius alexandrinus* Linnaeus, 1758). (ii) The awareness of the need to improve the water circulation, and the connectivity to the open sea, is a key factor for appropriate day-by-day management. (iii) It appears appropriate to use water management to conserve both the technical integrity of the site (belt channel, canals, ponds, locks, etc.) and the ecological functioning (*i.e.*, maintaining water level for bird nests, water circulation to allow fish to move in and out of the sites). (iv) Within Vieux Salins, a nozzle has been dug to improve water circulation without disturbing vehicle access for mosquito control. (v) A sluice gate will be installed between the poorly connected North Lagoon (Etang Nord, Salin des Pesquiers) to the inlet channel, creating a floodgate-like device for trapping the fish and allowing them to reach the open sea from the North Lagoon. (vi) Managers aim to improve access for the public, enhancing the awareness-raising role of the saltmarshes for the local population and tourists. (vii) The establishment of a small-scale salt production operation is planned in the Salin des Pesquiers; the aim is to make the public aware of the heritage value of the saltmarshes landscape as exploited salinas. (viii) The dredging of the belt channel will improve water circulation and quality and reduce eutrophication, nitrophilous macrophytes and *Ficopomatus enigmaticus* spread. (ix) A '*bourdigue*', *i.e.*, traditional Mediterranean fixed fishing gear trapping fish in shallow lagoons and channel systems, should be installed in the entrance channel of the Salin des Pesquiers; this device should not be used to catch fish from the saltmarsh but could serve as a tool to raise public awareness regarding a previous use of the site before industrial salt production (Réveillon 2018). This new management plan can obviously be described as 'interventionist'. Some authors favor a more passive recovery of the saltmarshes to improve ecosystem services (Almeida *et al.* 2017, De Wit *et al.* 2019, De Wit 2020). However, the configuration of the sites, particularly the Salin des Pesquiers, does not allow such passive restoration. Most of the ponds and channels are down to the mean sea level. A passive approach from the management team in this context would soon lead to the flooding of the whole site and the general transformation of the old evaporation ponds into a coastal lagoon. The choice of the managers is to control the water circulation and the infrastructure of the sites to accompany the inevitable changes and to preserve the SME as far as possible.

The Ecosystem-based Approach applied to SME management presented here must be considered as a logical development from current management activities within the scope of current guidelines (*e.g.*, Marine Strategy Framework Directive for European Union). Worldwide, the species-centered approach applied during the 20th and early 21st centuries has allowed the conservation of heritage, threatened and rare taxa (Boudouresque *et al.* 2020b) and the maintaining of extensive surface areas of well-functioning SMEs (De Wit *et al.* 2019, De Wit 2020). The present approach also takes into account those high-value taxa, but associated with the 'ordinary biodiversity' for enhanced consideration of the functioning of the ecosystem. Of course, the EBA does not rule out the specific protection and management of some threatened and rare taxa according to the management goals. The consideration of human activities within the SME is more consistent with management objectives taking into account both conservation of fauna and flora and the preservation of sustainable economic and social activities such as (i) pastoral activities (Duncan & D'Herbes 1982), agriculture (*e.g.*, ricefield: Tourenq *et al.* 2001, Lloret *et al.* 2005), (ii) fishing and hunting (although some authors consider hunting activities as disruptive, highlighting the need for hunting reserves) (Mathevet & Tamisier 2002, Tamisier *et al.*, 2003), (iii) salt production (De Wit *et al.* 2019), and (iv) public access. This approach matches the socio-ecosystem concept, where the Human is considered as part of the system and contributes to its functioning, the impact being considered as not solely negative (Turner *et al.* 2008, Boudouresque *et al.* 2020b). Ecosystem services provided by SME (Himes-Cornell *et al.* 2018) are taken into account to highlight the benefits allowed by a well-functioning ecosystem. Issues regarding global change and its impact on ecosystem functioning are of concern worldwide and especially for the SME (Lloret *et al.* 2008, De Wit 2011, Green *et al.* 2017). The EBA takes into account these issues to understand the impact of warming, the rise of the sea level, submersion and the arrival of non-indigenous species in both terrestrial and aquatic compartments of the ecosystem. Within the Mediterranean, current monitoring of community shifts in marine ecosystems has evidenced a decline in the previously so-called 'high-value taxa', threaten by warming and the spread of invasive species (Francour *et al.* 1994, Lejeusne *et al*. 2010). A species-centered approach, based on an unachievable reference state of the ecosystem (*e.g*., before the industrial revolution), cannot fit with appropriate management within the context of global change. On the other hand, the EBA can assess and monitor the functioning of the SME taking into account the expected changes. The rise in sea level (RSL) will contribute to an increase in marine conditions in the SME, aquatic compartments will shift to assemblages more connected with the open sea with, in some particular cases, a positive impact for teleost fish species of fishery interest, of which the juveniles settle in brackish water (*e.g*., *Sparus aurata*, *Dicentrarchus labrax*). The RSL will also increase erosion of the seashore and submersion, resulting in the withdrawal of halophytic vegetation and the destruction of the nesting and breeding habitat essential for waterfowl. More than ever, the management of the SME, and particularly the saltmarshes of Hyères, calls for a comprehensive approach to anticipate and accompany the inevitable changes.

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