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The high heritage value of the Mediterranean sandy beaches, with a particular focus on the *Posidonia oceanica "banquettes"*: a review

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Abstract. Sandy beaches, together with the foredune and the dune, form a morphological, functional and ecological complex, the beach-dune complex. This complex provides ecosystem services which have by far the highest value in the coastal areas, both marine and terrestrial habitats considered; it requires an overall management approach. Sandy beaches are often wrongly perceived by the public at large and by stakeholders as 'ecological deserts', the value of which is mainly economic. In fact, beaches harbour an extraordinary range of biological diversity, with dozens of species, plant and animal, which are specific to them. This biological diversity is sometimes not very visible, due to the small size of the individuals, the fact that they live hidden in the sand and their rarity on beaches artificialized by inappropriate management. Mediterranean beaches are unique worldwide by virtue of the permanent, or not, presence of accumulations of dead leaves of the endemic seagrass *Posidonia oceanica*. These accumulations, up to 2.5 m in thickness, are called *banquettes*. They play a prominent role in protecting beaches from erosion. In addition, they contribute to the construction of the dune. Eventually, sooner or later, dead leaves from the *banquette* will return to the sea, where they constitute a major source of organic matter and nutrients, for the benefit of coastal ecosystems and artisanal fisheries. The Mediterranean coastal regions welcome much of the world's tourism. This tourism is to a large extent seaside beach-based tourism. In the 1980s, after a century of *Posidonia*-compatible seaside tourism, tourism operators and mayors of coastal cities began to 'sell' *Posidonia*-free beaches and accustom tourists to unnatural, groomed, 'clean' beaches. Clean beaches were now free of human-made detritus, which is a positive factor, but also of naturally beach-cast *P. oceanica* dead leaves, seaweed, driftwood and even shells. It is not clear whether the concept of *Posidonia*-free beaches actually corresponds to tourists' requirements, or to the tour-operators' and mayors' own perceptions. Experiments involving maintaining in place the *Posidonia banquettes*, with information boards explaining the ecological and management issues, seem to indicate the latter. In any case, removing *banquettes*, driftwood, etc., results in a dramatic impoverishment of the beach biota: until recently, beaches were anything but deserts, but that is what they are becoming now! In addition, the *Posidonia*-free beach doctrine has resulted in catastrophic economic losses. Beaches, the cornerstone of seaside tourism, now unprotected, are washed away by storms and costly sand replenishment accelerates their erosion in a kind of vicious circle. This represents a paradigm example of mismanagement and of its costly consequences. It is probably time to promote the spread of 'ecological beaches', i.e. *Posidonia*-compatible beaches, in order to save the seaside tourism industry, the financial resources of local authorities and, of course, Mediterranean biodiversity. Well-managed beaches are a typical example of what is now referred to as a socio-ecosystem: an ecosystem of which man is a part. This of course means that they must be managed in a sustainable way, retaining their natural characteristics, or most of them, their long-term durability, and finally their value as a symbol of the Mediterranean identity, a vital asset for 21st century tourism.

Keywords: banquettes of drift seagrass leaves, beaches, crustaceans, dunes, ecosystem services, heritage value, insects, Mediterranean Sea, *Posidonia oceanica*.

***Résumé.* La grande valeur patrimoniale des plages de sable de Méditerranée, avec une attention spéciale pour les banquettes de *Posidonia oceanica* : une revue.** Les plages, associées à l'avant-dune et à la dune d'arrière-plage, constituent un écosystème, c'est-à-dire un ensemble géomorphologique, écologique et fonctionnel qui ne peut pas être dissocié, que ce soit du point de vue de l'écologie, des services écosystémiques et de la gestion des usages. Les services écosystémiques (les bénéfices que la nature fournit à l'Homme) que produit l'écosystème plage-dune sont exceptionnellement élevés : plus de 100 000 $/ha/an, soit 4 fois plus que les herbiers marins et presque 30 fois plus que les forêts terrestres. Le public et les gestionnaires considèrent parfois les plages comme un désert biologique, avec quelques 'mauvaises herbes' près de la dune. C'est pourtant tout le contraire. Les plages hébergent une incroyable diversité biologique, avec des dizaines d'espèces (crustacés, insectes, araignées, plantes, etc.) qui leur sont spécifiques et des milliers d'individus par mètre carré. Cette richesse est certes peu visible, en raison de la petite taille des individus, de leur mode de vie caché dans le sable (surtout le jour) et de leur rareté sur les plages déstructurées par un mode de gestion inapproprié. Toutefois, cette diversité biologique joue un rôle important dans le fonctionnement de l'écosystème, en relation avec les autres écosystèmes littoraux, par exemple par l'intermédiaire des oiseaux. Beaucoup de ces espèces sont devenues tellement rares qu'elles sont aujourd'hui considérées comme menacées.

Une des originalités, à l'échelle mondiale, des plages méditerranéennes est la présence, permanente ou non, de feuilles mortes de la magnoliophyte (plante à fleurs) endémique *Posidonia oceanica*. On nomme 'banquettes' (en français comme en anglais ; un terme issu du vocabulaire des pêcheurs provençaux) ces accumulations de feuilles mortes, qui peuvent atteindre, dans des cas exceptionnels, 2.5 m d'épaisseur. Les banquettes jouent un rôle écologique et économique important. Elles protègent directement les plages contre l'érosion et le départ du sable. Elles alimentent la dune en feuilles mortes et en sels nutritifs et contribuent à son édification et, indirectement, à la stabilité de la plage. Les feuilles mortes de la banquette ont vocation à retourner en grande partie, au gré des tempêtes, au milieu marin, où elles constituent une ressource alimentaire majeure, directe pour les écosystèmes littoraux et indirecte pour la ressource halieutique dont dépend la pêche artisanale.

La Méditerranée constitue la première destination touristique mondiale. Le tourisme y est basé sur le patrimoine culturel, gastronomique, paysager, mais aussi, parfois surtout, sur les plages et les activités balnéaires. Il représente une part importante du PNB des pays riverains. Dans les années 1980s, après un siècle de tourisme posidonies-compatible et des millénaires de plages dévolues aux banquettes de posidonies, les opérateurs du tourisme et certains maires de communes littorales ont 'vendu' le concept de plages artificiellement 'propres', c'est-à-dire libres de posidonies, et ont accoutumé les touristes à les revendiquer. Le 'nettoyage' des plages, qui fait souvent appel à des engins lourds, constitue la première étape d'un dramatique 'cercle vicieux'. Les plages, désormais non-protégées, sont emportées lors des tempêtes ; il s'ensuit de coûteuses opérations de ré-ensablement ; ce sable, emporté à son tour, ensevelit et détruit les herbiers adjacents de *P. oceanica* ; or ces herbiers protègent également les plages contre l'érosion ; leur régression accélère donc le recul des plages.

Au total, il s'agit d'un cas d'école pour la définition d'un 'cercle vicieux' très coûteux pour l'environnement comme pour les finances des communes littorales.
Les usagers, les touristes en particulier, demandent-ils réellement des plages sans banquettes, ou cette demande constitue-t-elle une construction due aux opérateurs du tourisme ? Il semble bien que la réponse soit : un artéfact construit, en particulier, par les opérateurs du tourisme. En effet, partout où les banquettes sont maintenues en place, y compris en été, dans le cadre du concept de 'plages écologiques', c'est-à-dire d'un nettoyage préservant les feuilles de posidonies et les bois flottés naturels, et où les usagers sont informés des enjeux (par des panneaux, des brochures, la presse, les agents du parc, etc.), l'acceptation est bonne et la fréquentation ne diminue pas. Les plages sont tout sauf des déserts : ce sont au contraire des habitats d'une grande richesse biologique et d'une grande valeur patrimoniale. C'est une gestion inadaptée qui les transforme en déserts, déserts par ailleurs coûteux pour l'économie (tourisme et pêche en particulier). Les plages de Méditerranée constituent l'exemple-paradigme des conséquences économiques et écologiques négatives d'une gestion naïve, contre-productive et à très court terme. Les 'plages écologiques', posidonies-compatibles, constituent au contraire un symbole fort de l'identité méditerranéenne et un atout pour le tourisme durable, en plus de la préservation de la biodiversité, et bien au-delà des espaces protégés qui ont vu naître le concept.
Les plages bien gérées constituent un exemple typique de ce que l'on désigne aujourd'hui sous le nom de socio-écosystème : un écosystème dont l'homme fait partie. Cela implique bien sûr qu'elles soient gérées de façon durable, en conservant leurs caractéristiques naturelles, ou la plupart d'entre elles, et non comme des systèmes artificiels, des sortes d'anthroposystèmes.

Mots-clés : banquettes de feuilles mortes, crustacés, dunes, insectes, Méditerranée, plages, *Posidonia oceanica*, services écosystémiques, valeur patrimoniale.

Introduction

Sandy beaches are strongly dependent upon the seawater dynamics (waves, storms), coastal currents, sand transport, continental sources of sediment (*via* the rivers) and, last but not least, the production of biogenic sediment (e.g. shell debris) by sublittoral coastal ecosystems. Sandy beaches, together with the foredune and the dune, form a morphological, functional and ecological complex, the beach-dune complex (hereafter the beach ecosystem) (McLachlan *et al.,* 1981; Vellinga, 1982; Brown and McLachlan, 2002; Chelazzi *et al.,* 2005; Schlacher *et al.*, 2008; Defeo *et al.,* 2009; Schlacher *et al.*, 2014).

Seaweed and seagrass wrack can be found on beaches throughout the world (Kirkman and Kendrick, 1997; Short, 1999; Mossbauer *et al.,* 2012). They constitute a feeding resource for the beach ecosystem fauna. Driftwood, originating from coastal forests such as mangroves after wind storms, and from river watershed riparian forests after river spates, are also a ubiquitous feature of beaches (Walls, 1997). Driftwood constitutes worldwide a habitat for many animal species: amphipods, isopods, crabs (crustaceans), beetles (insects), spiders, burrowing bivalves (molluscs), etc. (Walls, 1997). Beaches, together with the foredune and the dune, harbour a variety of plant communities with their specific fauna, e.g. molluscs, crustaceans, insects, seabirds, terrestrial birds; mammals also frequent beaches for feeding or resting, and participate in the functioning of the beach ecosystem *lato sensu*; finally, in temperate and tropical areas, sea turtles utilize beaches as a nesting place (e.g. Hedgpeth, 1957; McLachlan *et al.,* 1981; Bigot *et al.,* 1983; Groombridge, 1990; Argano *et al.,* 1992; Paskoff, 1993; Laurent *et al.,* 1994; Schlacher *et al.,* 2008). The beach ecosystem interacts (energy flows) with adjacent terrestrial environments *via* the sand dune, and with the sea *via* the surf zone (McLachlan *et al.,* 1981).

Mediterranean sandy beaches experience major alterations in their morphology (e.g. progradation, erosion), grain size features and cast-ashore organic debris (e.g. macroalgae, driftwood and seagrass dead leaves) during intense storms, over a year span and between years (Simeone *et al.,* 2014, 2016; De Falco *et al.,* 2017).

Sandy beaches are often perceived by the public at large and by stakeholders as 'ecological deserts', the value of which is mainly economic. This is hardly surprising, given that the 21 Mediterranean countries receive ~450 million tourists annually (one third of the world's tourists), of which ~175 million are concentrated near the shores, and that tourism represents a large part of their Gross National Product (Benoit and Comeau, 2005, extrapolated data; Gauci *et al.,* 2005; Lanquar, 2011; Serantoni, 2015). The main driver of this tourism is still the SSS triptych (Sea, Sun and Sand), although other drivers, such as culture, architectural heritage and gastronomy also contribute to the success of Mediterranean tourism (Boyer, 2012).

Tourists are assumed to require beaches with 'clean', white sand. The public is assumed to believe that formerly, in a Golden Age, beaches were clean, 'groomed', free of terrestrial 'weeds', of cast-ashore *Posidonia oceanica* (Linnaeus) Delile and other seagrass dead leaves, and of driftwood. The public is assumed to appreciate driftwood whenever its size makes it suitable for collection as a souvenir or to be brought home as firewood. Many stakeholders regard *P. oceanica* leaves and driftwood as waste matter, like processed wood, soft-drink cans, tar-balls and plastic. Is this a view widely held by the public or only shared by a minority? Is this perception natural or artificially constructed by tour operators, stakeholders and mayors of coastal municipalities?

The aim of the present article is not to address these sociological issues. It is simply **(i)** to present the sandy beaches in general (including the foredune and dune) from an ecosystem standpoint, **(ii)** to highlight the heritage value of Mediterranean beaches, their flora, and their rich hidden fauna, with a focus on protected areas (e.g. national parks, nature reserves and the French *Conservatoire de l'Espace Littoral et des Rivages Lacustres*), **(iii)** to focus on one of their most striking features, the *banquettes* of drift *P. oceanica* dead leaves, a term derived from the language of Provence fishers, **(iv)** to highlight the outstanding ecosystem services these *banquettes* provide, **(v)** and to discuss the social acceptability of natural, ungroomed, Mediterranean beaches.

The source of the *banquettes*: the *Posidonia oceanica* meadows

Posidonia oceanica is a seagrass endemic to the Mediterranean Sea. It constitutes extensive meadows in the infralittoral zone, from sea level down to 30-40 m depth (Molinier and Picard, 1952; Pérès and Picard, 1964; Boudouresque and Meinesz, 1982; Boudouresque *et al.,* 2012). The *P. oceanica* meadows are common throughout most of the Mediterranean Sea, from west (Alboran Sea) to east (Egypt, Turkey) and from south (Libya, Tunisia) to north (Catalonia, Provence, Croatia) (Boudouresque *et al.,* 2012; Pergent *et al.,* 2012). The estimates of the total surface area of *P. oceanica* meadows range between ~19 500 and 37 500 km^2 (Pergent *et al.,* 1995; Telesca *et al.,* 2015).

Posidonia oceanica seagrass meadows have a high heritage value and provide ecological goods and ecosystem services (Boudouresque *et al.,* 2012; Personnic *et al.,* 2014; Boudouresque, 2015; Boudouresque *et al.,* 2016). **(i)** They harbour ~25 % of the known Mediterranean Sea epsilon species diversity, while covering ~1.5 % of its surface area (Pasqualini *et al.,* 1998; Boudouresque *et al.,* 2012; for the biodiversity concept, see Boudouresque, 2014). **(ii)** They harbour dozens of species characteristic of the ecosystem, i.e. never found outside *P. oceanica* meadows (Pérès and Picard, 1964; Boudouresque, 1984). **(iii)** The primary production is exceptionally high and sustains complex food webs (Romero, 2004; Bakran-Petricioli and Schultz, 2010; Personnic *et al.,* 2014; Boudouresque *et al.*, 2015). **(iv)** The structure constituted by live and dead parts of rhizomes and roots, together with the sediment which fills the interstices, is called '*matte*' (Molinier and Picard, 1952; Boudouresque and Meinesz, 1982; Boudouresque and Jeudy de Grissac, 1983; Boudouresque *et al.,* 2012, 2016). On average, 29-36 % of the primary production of *P. oceanica* is stocked within the matte and part of this stock can persist over the geological timescale, resulting in a carbon sink. This carbon sink partly mitigates the CO^2 emissions produced by Mediterranean countries since the beginning of the Industrial Revolution (Pergent *et al.,* 1994; Matteo *et al.,* 1997; Pergent *et al.,* 2012, 2014; Boudouresque *et al.,* 2016). **(v)** *Posidonia oceanica* meadows constitute spawning and nursery areas for fish and crustaceans of economic value (Francour and Le Direach, 1995; Jimenez *et al.,* 1996). **(vi)** *Posidonia oceanica* meadows reduce swell and wave strength, resulting in enhanced sand deposition, beach progradation and hence protection of beaches from erosion (Gacia and Duarte, 2001; Infantes *et al.,* 2012; Manca *et al.,* 2012). **(vii)** *Posidonia oceanica* meadows can be the main 'factories' for the production of carbonate sediment (composed of rhodobiont - red algae -, molluscan and bryozoan debris) to be transported towards the beaches and dunes; at San Giovanni (western Sardinia), 28 % of the biogenic sediment produced by *P. oceanica* meadows is exported towards the beach-dune system (De Falco *et al.,* 2017). The role of the *P. oceanica* factory for sediment production is all the more essential in that the inputs from the rivers have often declined as a consequence of dams, resulting in a sediment shortage on the continental shelf (Syvitski *et al.,* 2005; Mazarrasa *et al.,* 2015; López *et al.,* 2016; Sadaoui *et al.,* 2016). Other services, specific to the beach *banquettes* (cast ashore dead leaves and rhizomes), which is the subject of the present article, will be addressed hereafter.

Interestingly, coral reefs in tropical regions play a similar role to seagrass meadows. In La Réunion Island (southern Indian Ocean), there is beach withdrawal opposite degraded reefs, while there is beach progradation opposite healthy reefs (Mioche *et al.,* 2002).

Posidonia oceanica meadows are sensitive to human impact, mainly coastal development, trawling, fish farms, eutrophication and anchoring (Montefalcone *et al.,* 2006, 2008; Boudouresque *et al.,* 2009, 2012; Giakoumi *et al.,* 2015; Burgos Juan, 2016). For this reason, and taking into consideration the heritage value of the ecosystem and the ecosystem services it provides, the species and/or the habitat are protected in France and Spain and are included in the appendices of international conventions: European Union Habitat Directive, Bern Convention and Barcelona Convention (Pergent, 1991; Habitat Directive, 1992; Boudouresque *et al.,* 2012; Boudouresque, 2013)

Structure and formation of the *banquettes*

Only a small part of the living leaves of *P. oceanica* is consumed by herbivores (Pergent *et al.,* 1994; Cebrián *et al.,* 1997; Boudouresque *et al.,* 2006; Vizzini, 2009; Boudouresque *et al.,* 2012). The lifespan of the leaves ranges between 4 and 13 months (Ott, 1980; Thélin and Boudouresque, 1983). After shedding, dead leaves constitute a litter within the meadow, together with rhizomes broken off by water movements, during storms, or through the impact of human activities, such as anchoring and trawling (Personnic *et al.,* 2014). A large part of this litter (hereafter 'necromass'), representing between 10 and 55 % of the primary production of the meadow, is exported out of the meadow (Ott and Maurer, 1977; Pergent *et al.,* 1994; Boudouresque *et al.,* 2006, 2012, 2016). This corresponds to Odum's (1968) concept of 'outwelling' of carbon from coastal primary producers, namely seagrass ecosystems, towards adjacent ecosystems (e.g. Bach *et al.,* 1986; Ochieng and Erftemeijer, 1999). Necromass export from *P. oceanica* beds has a threefold destination: **(i)** Towards infralittoral rocky-reef and sandy habitats (Verlaque, 1987; Dimech *et al.,* 2006; Cardona *et al.,* 2007; Vizzini, 2009; Cresson *et al.,* 2012; Thibaut *et al.,* 2017). **(ii)** Towards the deep water in circalittoral and bathyal zones (Boudouresque *et al.,* 1990; Fourt and Goujard, 2012). Both within the *P. oceanica* meadow and in other subtidal habitats (infralittoral, circalittoral and bathyal), the necromass is channelled to higher trophic levels, in food-webs, mainly through SOM (Sedimentary Organic Matter), SOM-consumers, and to a lesser extent through detritus-feeders (Vizzini *et al.,* 2002; Lepoint *et al.,* 2006; Vizzini, 2009). **(iii)** And towards beaches, where the necromass constitutes *banquettes* (Boudouresque and Meinesz, 1982; Farghaly and Denizot, 1984; Vitale and Chessa, 1998; Mateo *et al.,* 2003; Simeone and De Falco, 2012; Manca *et al.,* 2013).

Posidonia oceanica leaves and sediment are the main components of *banquettes*; leaves are dominant in the foreshore part of the *banquette* (**Fig. 1A, B**), while sand is dominant in the backshore. Aegagropilae are sea-balls made of *P. oceanica* leaf fibres, the main component of which is lignin, entangled by sea motion in shallow sand areas (Boudouresque and Meinesz, 1982; Khiari *et al.,* 2000; Verhille *et al.,* 2017); they are a common constituent of the *banquettes* (**Fig. 1C**). Broken rhizomes can also become part of the *banquette*, especially on very exposed beaches (**Fig. 1D**); it is unclear whether or not broken rhizomes might also characterize beaches facing human-degraded meadows (Pergent-Martini *et al.,* 2006; Simeone and De Falco, 2012). In Sardinia, the mean sand content is 93 kg/m^3 (De Falco *et al.,* 2008). During storms with strong waves, blocks of *matte* can be uprooted and washed up on beaches (**Fig. 2**) (Boudouresque *et al.,* 2016). The thickness of the *banquettes*, in sites where they are not removed as part of beach management, ranges between a few centimetres and 2.5 m; their thickness, volume and cross-shore length are greater on exposed beaches than on sheltered beaches (**Figs. 3 and 4**; Molinier and Picard, 1952; Boudouresque and Meinesz, 1982; Bellan-Santini and Picard, 1984; Farghaly and Denizot, 1984; Mateo *et al.,* 2003; Simeone and De Falco, 2012, 2013; Boudouresque *et al.,* 2016; but see De Falco *et al*., 2008; Vacchi *et al.,* 2017). Temporary lagoons can occur within the *banquette*s (**Fig. 5**) and storms can isolate temporary offshore outliers during the process of *banquette* withdrawal (**Fig. 6**). Exceptionally, under very exposed conditions, *banquette*s can rest on littoral rocks and not, as is usually the case, on sand (**Fig. 7**).

Figure 1. Constituents of the *Posidonia oceanica banquettes*. **A** (top left). *Posidonia oceanica* dead leaves. **B** (top right). Broken *P. oceanica* dead leaves. **C** (bottom left). Broken rhizomes of *P. oceanica*. **D** (bottom right). Aegagropilae (sea balls) made of *P. oceanica* fibres; near the centre, a cast-ashore *Codium bursa* (Chlorobionta, kingdom Archaeplastida). A-C: Ostriconi beach, L'Agriate, Corsica, April 2017. D: Macinaghju (Macinaggio), Capicorsu (Cap Corse), northern Corsica, April 2017. Photos © Charles F. Boudouresque.

The volume of the *banquettes*, per beach length occupied, can reach 12.5 m^3/m (Simeone and De Falco, 2012). Overall, along the 48 km of suitable coastline in the Maltese Islands, the maximum volume of *banquette* has been estimated to be 42 000 m^3 (Deidun *et al.,* 2011).

Figure 2. A (left). A block of *Posidonia oceanica matte*, ~20 cm wide, washed up after a strong storm on a beach. U Barcaghju (Barcaggio), Capicorsu, northern Corsica, February 2013. **B** (right). The leaves (on the right), still in place, indicate that the block of matte belonged to a living meadow when it was uprooted during a storm. Ostriconi beach, L'Agriate, Corsica. Photos © Charles F. Boudouresque.

Figure 3. A relatively thin *banquette* of *Posidonia oceanica* leaves, Cala di Paragnu, west of Bunifaziu (Bonifacio), southern Corsica, December 2016. Leaves are never removed for beach management purposes (see **Fig. 24**). Photo © Charles F. Boudouresque.

Figure 4. A thick *banquette* of *Posidonia oceanica* leaves on Ostriconi beach, northern Corsica, April 2015. Leaves are never removed for beach management purposes. The figures (the French phycologist Michèle Perret-Boudouresque and her dog Diego) give an idea of the scale. Photo © Charles F. Boudouresque.

Figure 5. A temporary lagoon, within a *Posidonia oceanica banquette*. Northern side of L'Ostriconi beach, L'Agriate, Corsica. April 2017. Photo © Charles F. Boudouresque.

Figure 6. An outlier of *Posidonia banquette*. Macinaghju beach, Capicorsu, northern Corsica. Photo © Charles F. Boudouresque.

Figure 7. *Banquettes* of *Posidonia oceanica* unusually located on a rocky substrate (rather than on sand). Between Macinaghju and Finachjarola Islands, Capicorsu, northern Corsica, April 2017. Photo © Charles F. Boudouresque.

Posidonia oceanica sheds leaves year-round, but mostly in summer and autumn (Pergent *et al.,* 1983). Deposition of dead leaves on the beaches predictably occurs in autumn and winter, when litter is available and when wind speed and waves cause the litter to be cast ashore (Vacchi *et al.,* 2017). Over a year span, one or several cycles of accretion and erosion of the *banquette* can occur; peaks occur in autumn and early spring, while the beach can be free of litter in summer (Chessa *et al.,* 2000; Cancemi and Buron, 2008; Gómez-Pujol *et al.,* 2013; Simeone *et al.,* 2013). On moderately exposed beaches, the *banquette* can be present year-round; accretion is then continuous over years or decades, resulting in the stratification of the *banquette*, with strata of ancient and compacted litter at the base and more recent litter above; the basal compacted strata can be as hard as wood (**Figs. 8** and **9**). Alternating layers of *P. oceanica* leaves and sand can also be observed (De Falco *et al.,* 2003, 2008).

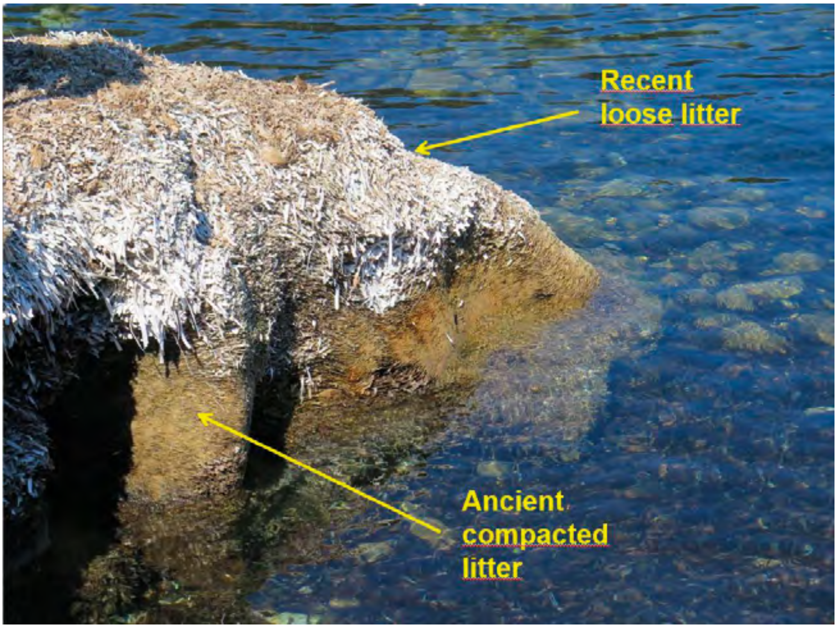

Figure 8. A permanent *banquette* (present year-round) showing the stratification of compacted, hard layers of ancient litter, capped with recent, loose litter (dead *Posidonia oceanica* leaves are still recognizable). Les Chevaliers beach, Giens Peninsula, Port-Cros National Park, eastern Provence, July 2016. Photo © Charles F. Boudouresque.

Figure 9. A permanent *banquette* (present year-round) showing the stratification of compacted layers of ancient litter, capped with recent, loose litter (dead *Posidonia oceanica* leaves are still recognizable). Zarzis beach, southern Tunisia, December 2015. Photo © Charles F. Boudouresque.

Beaches and *banquettes* do not constitute a final and permanent receptacle for *P. oceanica* litter (necromass: dead leaves and broken rhizomes). The litter continuously moves, in phase with alternating storms and periods of calm, between the beach (**Fig. 10**, box 7) and the adjacent subtidal bottoms (**Fig. 10**, boxes 6, 9 and 11) (Cancemi and Buron, 2008; Simeone *et al.,* 2013; Vacchi *et al.,* 2017). For a large part of the litter stored within the *banquettes*, coastal marine habitats constitute the final destination (**Fig. 10**, boxes 1-3, 9-11), where they are a prominent source of nutrient and organic carbon (see hereafter the section 'ecosystem services') (Boudouresque *et al.,* 2016). The percentages of the mass of litter consumed by the detritus-feeders on site (beaches), carried inland by wind or persistent *in situ*, were thought to be negligible (Matteo *et al.,* 2003; Guala *et al.,* 2006). However, consumption by beach detritus-feeders could in fact prove to be significant (Pergent-Martini *et al.,* 2006), as well as the mass of litter carried inland by wind, such as along the western tombolo of Giens Peninsula (eastern Provence, France) (Frédéric Médail, pers. comm.).

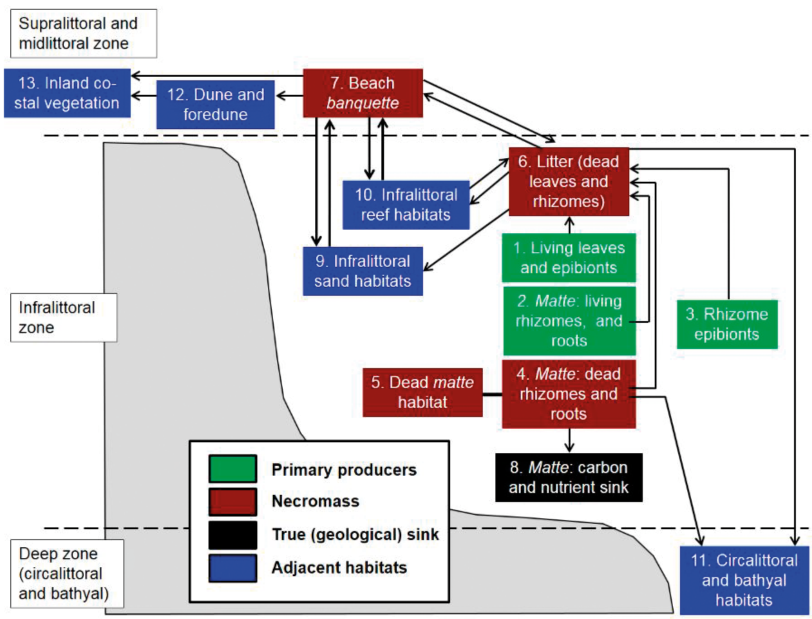

Figure 10. The fate of the *Posidonia oceanica* necromass. Some possible fluxes are not represented, in order to make the diagram clearer. The line between dead *matte* habitat and *matte* (boxes 4 and 5) means a change over time, not a flux. Boxes are numbered 1 through 3 (primary producers), 4 through 7 (necromass), 8 (sink) and 9 through 13 (adjacent habitats). From Boudouresque *et al.* (2016), modified.

The Mediterranean sandy beaches: a unique ecosystem

The Mediterranean beach ecosystem **(i)** harbours six 'habitats of community interest', under the European Habitat Directive, with their characteristic flora and fauna (Veyret, 1950-1951; Ponel, 1983; Habitat Directive, 1992; Loisel, 1994; Kovoor and Muñoz-Cuevas, 2000; Wiedemann and Pickart, 2004; Médail *et al.,* 2013; Serantoni, 2015). Among the outstanding plant species (Magnoliophyta, kingdom Archaeplastida), *Ammophila arenaria* (Linnaeus) Link, *Cakile maritima* Scopoli, *Echinophora spinosa* Linnaeus, *Eryngium maritimum* Linnaeus, *Euphorbia paralias* Linnaeus, *E. peplis* Linnaeus and *Pancratium maritimum* Linnaeus, can be cited (Loisel, 1994). **(ii)** Infralittoral and circalittoral drift macroalgae, such as *Codium fragile* (Suringar) Hariot, *C. bursa* C. Agardh (kingdom Archaeplastidia), *Cystoseira* spp. and *Sargassum* spp. (kingdom stramenopiles) (Thibaut *et al.,* 2016) are a feeding resource for beach detritus-feeders (**Fig. 1D**). **(iii)** Driftwood (**Fig. 11**) constitutes a habitat for a number of beetles (coleopterans) such as *Styphloderes exsculptus* (Boheman, 1843), *Mesites pallidipennis* Boheman 1838 and *Brachemys brevipennis* (Laporte de Castelnau, 1838) (**Fig. 12**) (Ponel, 1984; Médail *et al.,* 2013). As for the *P. oceanica banquettes*, there is a back-and-forth displacement of driftwood between the beach and the sea, in phase with storms and periods of calm sea; over time, driftwood is fragmented to a kind of wood litter; three years after the 2011 flood event in eastern Provence, 70 % of the driftwood at L'Oustaou dé Diou Cove (Porquerolles Island; **Fig. 11**) had disappeared by natural means (Serantoni, 2015). **(iv)** The Mediterranean beach ecosystem is unique in the thickness (up to 2.5 m) and the relative permanence of the *P. oceanica* litter, called *banquette,* despite conspicuous seasonal variation of the amount of litter. In the southern Mediterranean, dead leaves of *Cymodocea nodosa* (Ucria) Ascherson, another seagrass, can also occur within the *banquettes* (Deidun *et al.,* 2007). This litter constitutes a habitat for metazoans: a number of coleopterans, including many staphylinids (rove-beetles) (Franck and Ahn, 2011), such as *Cafius xantholoma* (Gravenhorst, 1806), *Remus sericeus* (Holme, 1837), *Aleochara albopila* (Mulsant & Rey, 1852), dipterans, a dozen species of Acari as *Indotritia krakatauensis* (Sellnick, 1923) and *Hermannia minuta* Woas, 1980, spiders such as *Chaerea maritimus* Simon, 1884 (Bosmans *et al.,* 2016; Lissner and Chatzaki, 2016 ; **box 1**; **Figs. 13, 14**), Myriapoda, such as the centipede species *Geophilus fucorum* Brölemann, 1909 and *Tuoba poseidonis* (Verhoeff, 1901) (Iorio and Noël, 2017), at least ten species of crustaceans such as *Armadilloniscus candidus* Budde-Lund, 1885, *Buchnerillo litoralis* (Verhoeff, 1942), *Chaetophiloscia elongata* (Dollfus, 1884), *Halophiloscia couchi* (Kinahan, 1858), *Talitrus saltator* (Montagu, 1808), *Spaelaeoniscus vallettai* Caruso, 1975, *Trichoniscus fragilis* Racovitza, 1908 and *Tylos europaeus* Arcangeli, 1938, annelids such as *Ophelia bicornis* Savigny, 1819 and gastropods such as *Truncatella subcylindrica* (Linnaeus, 1767) (Veyret, 1950-1951; Ponel, 1984; Travé, 1984; Noël, 2003; Colombini *et al.,* 2009; Deidun *et al.,* 2009; Audisio and Vigna Taglianti, 2010 ; Médail *et al.,* 2013). **(v)** Regardless of the presence of a layer of *P. oceanica* dead leaves, the sand is colonized down to at least 30 cm below the beach surface by a rich metazoan fauna of e.g. spiders, crustaceans (Isopoda, Amphipoda), insects (Coleoptera, Diptera, Hemiptera, Hymenoptera, Orthoptera), annelids and molluscs (Bigot *et al.,* 1983; Chelazzi *et al.,* 2005; Gauci *et al.,* 2005, Deidun *et al.,* 2009) (**boxes 2** and **3**; **Figs. 14** and **15**).

Figure 11. Driftwood cast ashore in L'Oustaou dé Diou Cove of Porquerolles Island (Port-Cros National Park, eastern Provence, France). This accumulation resulted from the heavy rainfall which occurred in Provence in November 2011, followed by severe floods, the worst in the region since 1827. It should be noted that driftwood accumulated on shingle beaches or on rocky substrata is less favourable to the development of a saproxylophagous invertebrate community, because such wood is rapidly dried out by the sun, in contrast to partly rotten wood fragments deposited on sandy beaches and half buried in wet sand. Photo © Charles F. Boudouresque, June 2012.

Figure 12. Beetles (coleopterans) associated with driftwood on Mediterranean beaches. Left: *Styphloderes exsculptus*. Middle: *Mesites pallidipennis*. Right: *Brachemys brevipennis*. Bar scale = 1 mm. From Médail *et al.* (2013). Photos © Philippe Ponel.

A poorly-known and relatively rare cricket, *Pseudomogoplistes squamiger* (Fischer, 1853), thrives on the beaches, between a few tens of centimetres and a dozen meters from the water edge. It is hidden during daytime under pebbles or clumps of *P. oceanica* drift leaves and could be a detritus-feeder, consuming e.g. *P. oceanica* debris (Berville *et al.,* 2012; Dusoulier, 2017).

Up to ~68 000 individuals of metazoans per cubic metre have been recorded on uncleaned (i.e. where the *P. oceanica banquette*, if present, has not been removed) Maltese beaches (Deidun *et al.,* 2007, 2009), which highlights the fact that beaches are anything but a desert.

Box 1 (by Philippe Ponel)
Rediscovery of a forgotten Mediterranean spider associated with drift seagrass leaves, *Chaerea maritimus*

In the course of surveys aiming at identifying the coleopterans associated with the *P. oceanica banquettes* near the small beach of L'Aygade (Giens Peninsula, Hyères, eastern Provence), on 14 December 2013, one of the authors (PP) was able to collect several specimens of a small spider, the study of which revealed that it did not belong to any known species in France (**Figs. 13, 14**). The external morphology of the animal and the structure of the genitals of both sexes corresponded well to a representative of the family Dictynidae. The investigations then concentrated on the non-

French species of Dictynidae associated with the Mediterranean littoral environments. Among these few species, *Chaerea maritimus*, described in 1884 by Eugene Simon (one of the greatest arachnologists of his time), attracted our attention. It was discovered in Nemours (today Ghazaouet, Tlemcen Province, Algeria), '*where it thrived on the beach under the tufts of plants; we found it under the same conditions at the Mar Menor near Cartagena*'. The short description, in Latin and without any illustration, did not enable us to conclude with certainty regarding the identity of the specimens of Giens as *Chaerea maritimus*. The examination of the type specimens preserved in the collections of the Muséum National d'Histoire Naturelle, Paris, led the Belgian arachnologists Robert Bosmans and Pierre Oger to conclude that it was indeed this species, which no one seems to have revised since its description. By an astonishing coincidence, Lissner and Chatzaki (2016) described at the same time *Altella emilieae* Lissner from the coasts of Greece (Crete, Telendos). The photos that accompanied the description left no doubt that *Altella emilieae* was a junior synonym of *Chaerea maritimus* (Bosmans *et al.,* 2016). This species is probably widely distributed in the Mediterranean basin. Some lessons can be drawn from this rediscovery: **(i)** the rich fauna of *P. oceanica banquettes* is still poorly known; **(ii)** a species only observed three times in 130 years could be widely distributed all around the Mediterranean, associated with *P. oceanica banquettes*; **(iii)** A tiny and inconspicuous spider could be as representative of the Mediterranean Sea species diversity as the iconic *Posidonia oceanica.*

Left. Figure 13. The *Posidonia oceanica banquette* of L'Aygade (Giens Peninsula, Hyères, eastern Provence) where the spider *Chaerea maritimus* was rediscovered by Philippe Ponel (here sampling the drift *P. oceanica* leaves). Photo © Valérie Andrieux-Ponel. **Right. Figure 14.** *Chaerea maritimus*. Scale bar: 1 mm. Photo © Pierre Oger, courtesy of the author.

Box 2 (by Philippe Ponel)
More about sand coleopterans

Several small species of psammophilous Coleoptera spend their whole life cycle deeply buried in the substratum and are rarely observed roaming on the sand surface (in contrast to large diurnal darkling beetles such as *Pimelia bipunctata* Fabricius, 1781). This small cryptic community probably feeds upon rotten plant debris (saprophagous species) or small invertebrates (predatory species). Among saprophagous beetles, a small synusia comprises, for example, *Brindalus porcicollis* (Illiger, 1803), *Trachyscelis aphodioides* Latreille, 1809,
Ammobius rufus Lucas, 1849, belonging to 2 remote families (Aphodiidae for the former, Tenebrionidae for the two latter), but with a very similar ecology and adaptations (**Fig. 15**). All of them present a modified body characterised by long hairs playing probably a role of protection against abrasion by sand grains, modified posterior legs which bear some resemblance to a blunderbuss (i.e., with an enlarged apex) enabling the insect to push the sand grains behind it when it "swims" buried in the sand, and modified anterior legs, flattened and more or less oar-shaped. *Brindalus porcicollis* and *Ammobius rufus* have fused elytra and are apterous or micropterous. An attempt to determine the food regime for these 3 species was made by Ponel (1986) by dissecting the digestive tract, a difficult task due to the small size of these creatures (about 2 mm long). Analyses of several Coleoptera collected at Flèche de la Gracieuse (Bouches-du-Rhône, i.e. western Provence) revealed that all the studied specimens contained a vast quantity of conidia, suggesting that fungi probably growing on mouldy plant debris seem to form the basis of the food regime of *Brindalus porcicollis*, *Trachyscelis aphodioides* and *Ammobius rufus*. However, such investigations were not repeated, either later or elsewhere, and thus require confirmation. These 3 species are widespread in the Mediterranean basin.
At Presqu'île de Giens near Hyères (Var, i.e. eastern Provence), on the beach of La Capte on the eastern tombolo of Giens, Ponel (1983) showed that *Brindalus porcicollis* is present in 100 % of the samples, and *Trachyscelis aphodioides* and *Ammobius rufus* are present in 92 % of the samples. Thus they are qualified as '*espèces constantes*', according to the classification of Bigot and Bodot (1972, 1973), along with 3 other Coleoptera species. *Xenonychus tridens* (Jacquelin du Val, 1852) **(Fig. 15**) is a small Histeridae, a predatory species that probably feeds upon small arthropods, but its precise regime is unknown (small Diptera larvae, etc.). Again, this is an extraordinary example of a beetle perfectly adapted to underground life in sand (very hairy body, modified legs, etc.) (Ponel, 1986), and occurring on Mediterranean shores, but also in sand dunes in the heart of the Sahara Desert (Vienna, 1980). At Giens it is much less abundant than the 3 previous species.

Figure 15. Left to right: *Trachyscelis aphodioides*, *Ammobius rufus*, *Brindalus porcicollis* and *Xenonychus tridens*. Bar scale = 1 mm. Photos © Philippe Ponel.

Box 3 (by Philippe Ponel)
More about banquette coleopterans

The community of Coleoptera associated with *Posidonia oceanica banquettes* is very rich in species (**Fig. 16**). This community is relatively poorly known due to the small size and the difficulty of identification of many species. Finding these small insects in the thick accumulations of dead leaves of *P. oceanica* is like looking for a needle in a haystack, and it is appropriate to use an entomological sieve (Winkler apparatus) to separate the smaller beetles from the larger vegetal fragments. Investigations on the shores of the Giens Peninsula, Les Embiez Island (eastern Provence, France) and Saint-Honorat Island (French Riviera), reveal that almost 20 beetle species are regularly found in this habitat, and most of them are exclusively associated with it.

By far the dominant family is the Staphylinidae, with at least 11 species, all of them being predatory and feeding upon very small arthropods:

Omalium riparium impar Mulsant & Rey 1861
Cafius xantholoma (Gravenhorst, 1806)
Remus filum (Kiesenwetter 1849)
Remus sericeus Holme 1837
Heterothops binotatus (Gravenhorst 1802)
Halobrecta cf. *algae* Hardy 1851
Myrmecopora boehmi Bernhauer 1910
Myrmecopora laesa (Erichson 1839)
Myrmecopora sulcata (Kiesenwetter 1850)
Heterota plumbea (Waterhouse 1858)
Pseudopasilia testacea (Brisout 1863)

Figure 16. Top left: *Actinopteryx fucicola*.
Top centre: *Cercyon arenarius*.
Top right: *Halacritus punctum*.
Bottom left: *Omarium riparium impar*.
Bottom centre: *Remus sericeus*.
Bottom right: *Pseudopasilia testacea*.
Bar scale = 0.5 mm for *Actinopteryx fucicola* and *Halacritus punctum*, 1 mm for the other species. Photos © Philippe Ponel.

From a taxonomic point of view, this is a very difficult group, and even if some genera were recently revised (Assing, 1997) or clarified (Tronquet, 2003), some others need more research in the Mediterranean basin (e.g., *Halobrecta*, see Tronquet 2014). In this context, the case of *Arena tabida* (Kiesenwetter, 1850) and *Pseudopasilia testacea* (Brisout 1863) (both associated with sea wrack: *Fucus*, *Posidonia*) is interesting; Tronquet (2003) has demonstrated that these two different taxa, belonging even to two different genera, were confused until now, due to similar habitats and habitus. But only *Pseudopasilia testacea* occurs on Mediterranean shores. Apart from the Staphylinidae, the other strictly predatory beetle in this community is the tiny Histeridae *Halacritus punctum* (Aubé 1843). The Ptiliidae are represented by two extremely small species, *Actinopteryx* *fucicola* (Allibert 1844) and *Ptenidium punctatum* (Gyllenhal 1827). Both adults and larvae of Ptiliidae feed on fungal hyphae and spores. *Holoparamecus bertouti* Aubé 1861 (Endomychidae) is also found in *banquettes*, but also on rotten animal debris, e.g. inside dead urchins and crustaceans. Its food regime is not well known. The Hydrophilidae *Cercyon arenarius* Rey 1885 is a regular inhabitant of the *banquettes* and could be predatory (Hansen, 1987).

Strikingly, this beetle community does not contain any species able to feed exclusively upon dead leaves of *P. oceanica*, since almost all are predatory, or mycophagous/microphagous. Colombini *et al*. (2009) suggest that the crustacean *Talitrus* does not feed on *Posidonia* either, the *banquettes* playing merely a role of refuge and habitat; however, personal observations show that accumulations of *P. oceanica* leaves are quickly decomposed and disaggregated, thus the actors of this process need still to be identified. An interesting observation was made by Binaghi (1951), and may be easily repeated by any casual observer: the beetles in particular are not evenly distributed within the *banquette*; by far the maximum abundance is restricted to the basal layers of the *P. oceanica* leaves, where the dead leaves are in contact with the substratum: rock, pebbles, gravels or sand. Compact layers of leaves are almost devoid of beetles. Binaghi (1951) suggests that the interstices in the mineral substratum are favourable to these insects since they enable the beetles to move easily and allow the penetration of oxygen.

As far as the functioning of the beach ecosystem *lato sensu* is concerned, dead *P. oceanica* leaves are a prominent source of organic carbon for the whole ecosystem. Litter bags, set up in winter on the *banquette* of L'Alga beach (near Calvi, Corsica), lost ~55 % of their initial dead leaf mass within four weeks; although several causes may be involved, consumption by detritus-feeders is probably the main reason for this loss (Pergent-Martini *et al.,* 2006). In addition, dead *P. oceanica* leaves are a significant source of nitrogen for the foredune plants (Cardona and García, 2008).

Accumulation of beach-cast seagrass material along the shore, e.g. *Zostera marina* Linnaeus*, Z. noltei* Hornemann and *Thalassodendron ciliatum* (Forsskål) Den Hartog, has also been observed along open sea coasts of temperate and tropical areas, respectively. In brackish lagoons, *Z. marina, Z. noltei* and *Ruppia cirrhosa* (Petagna) Grande dead leaves can also form cast-ashore accumulations. However, the only accumulation similar to the *P. oceanica banquettes*, with regard to both its thickness and its permanence, is produced by southern Australian *Posidonia* species (Kirkman and Kuo, 1990).

Ecosystem services of sandy beaches and dunes, with a particular focus on the *banquettes*

Ecosystems offer benefits to current and future generations. The concept of ecosystem services is defined as the flow of benefits from nature to people (Brenner *et al.,* 2010). Sandy beaches and dunes provide worldwide a wide range of ecosystem services and values that cannot be supplied by any other ecosystem: recreation and tourism, sport and entertainment venues, education and research, human health and well-being, storm protection, nesting and foraging sites for birds and turtles, etc. (Schlacher *et al.,* 2008). In addition, they harbour a unique biodiversity. Because these values depend on the specific cultural, economic and environmental context, it is not worth attempting to prioritise them (Schlacher *et al.,* 2008; Defeo *et al.,* 2009).

An assessment of the non-market value of the ecosystem services provided by the habitats of the Spanish Catalonia coastal zone (**Table I**; Brenner *et al.,* 2010) highlights the value of the beach and dune complex: e.g. 4 and 27 times higher than that of seagrass beds and temperate forests, respectively. Overall, the beach and dune ecosystem is the habitat with by far the highest ecosystem services value, taking into account both marine and terrestrial domains.

Table I. Non-market value of ecosystem services provided by each land and marine type of habitat along the Catalan coast (US $ in 2004). From Brenner *et al.* (2010), modified and simplified.

Domain	**Habitat**	**Total ecosystem services value (US$/ha/year)**
Coastal and marine	Shelf (0-50 m depth; all habitats)	3 210
	Seagrass bed (including Posidonia oceanica meadows)	24 228
	Beach and dune	104 146
	Saltwater wetland (e.g. brackish lagoons)	15 147
Terrestrial	Temperate forest	3 789
	Grassland	230
	Cropland	2 140
	Freshwater wetland	28 585
	Open freshwater	1 890
	Riparian buffer	8 539
	Urban greenspace	6 111
	Urban/barren/burned/mining	0

Banquettes protect beaches from erosion by winter storms, by modifying the beach profile and reducing sediment movement (Boudouresque and Jeudy de Grissac, 1983; Boudouresque *et al.,* 2012, 2016).

Figure 17. *Posidonia oceanica* dead leaves, blown by the wind from the *banquette* to the foredune, help to trap the sand and significantly contribute to the accretion of the foredune. Ostriconi beach, northern Corsica, April 2015. Photo © Charles F. Boudouresque.

The *P. oceanica* leaves blown inland by the wind to the foredune can trap the sand and significantly increase the potential seaward accretion of the foredune (**Fig. 10**, box 12; **Fig. 17**) (Bovina, 2009). In addition, the beach-cast leaves are a significant source of nitrogen and therefore contribute to the fertilization of the foredune vegetation, where most of the leaves blown by the wind are trapped; they have a positive effect on further colonization by nitrophilous plants such as *Cakile maritima* and, as a result, contribute to the growth of the foredune (Cardona and García, 2008; Simeone *et al.,* 2013). Some dead leaves can be blown further inland (to the backshore), where they are trapped by the littoral vegetation (**Fig. 10**, box 13; **Fig. 18**).

Figure 18. *Posidonia oceanica* dead leaves, blown by the wind from the *banquette* to the inland (backshore) vegetation. Near Bunifaziu, southern Corsica, October 2012. Photo © courtesy Gérard Pergent.

Other beach litter deposits and other species of seagrass, outside the Mediterranean Sea, play a similar role (Hemminga and Nieuwenhuize, 1990; Nordstrom *et al.,* 2011). In the Red Sea, for example, *Thalassodendron ciliatum* leaves cast up on the beach can be carried several kilometres inland by winds and accumulate in the desert (Lipkin, 1988).

For the *P. oceanica* litter, the *banquettes* are just a provisional receptacle. The fate of most of the litter accumulated within *banquettes* is to return, sooner or later, to coastal marine habitats. There, they constitute a prominent source of nutrient and organic carbon for all ecosystems: infralittoral reef habitats (Verlaque, 1987; Thibaut *et al.,* 2017), coralligenous (Boudouresque *et al.,* 1990; Ruitton *et al.,* 2014), sea caves (Airoldi and Cinelli, 1996), soft bottoms (Cardona *et al.,* 2007), etc.

Threats to the biodiversity of sandy beaches

Sandy beaches are under threat worldwide, being squeezed between rising sea levels from the marine side (Brown and McLachlan, 2002; Adloff *et al.,* 2015; Dieng *et al.,* 2017) and expanding human populations and development on the landward side (Brown and McLachlan, 2002; Martínez *et al.,* 2004; Schlacher *et al.,* 2008; Defeo *et al.,* 2009; Schlacher *et al.*, 2014). Human-related disturbances vary from beach to beach; however, structures or activities that impede natural sand transport or alter the sand budget often lead to severe beach erosion, often irreversible (Brown and McLachlan, 2002). Many beaches also suffer damage from pollution, off-road vehicles, mining, trampling, bait collection, tourism and beach cleaning (Brown and McLachlan, 2002; Martínez *et al.,* 2004). On Southern California groomed beaches, unvegetated sand zones were four times wider, native plant abundance 15 times lower and native plant richness >3 times lower (Dugan and Hubbard, 2010).

It is not predicted that the projected 21st century temperature changes will have a significant direct impact on the world's beaches by 2025; however, the expected rise in sea level, if coupled with an increase in the frequency and intensity of storms, as predicted for some regions, is likely to lead to increasing erosion of the beaches and consequently a loss of natural habitats (Brown and McLachlan, 2002).

The flora of Mediterranean beaches and dunes, together with their metazoan fauna, are increasingly threatened by seaside tourism: trampling, removal of driftwood, removal of the *P. oceanica banquette* and, more generally, cleaning ('grooming') of the beaches (Lavagne, 1972; Ponel, 1983; Loisel, 1994; Kovoor and Muñoz-Cuevas, 2000; Comor *et al.,* 2008; Médail *et al.,* 2013).

On the sandy beaches of the island of Port-Cros, although located in the core area of the Port-Cros National Park, less frequented and managed in a less 'aggressive' way than those of the neighbouring mainland, half of the species of plants (Magnoliophyta) which were recorded by Jahandiez (1929), Molinier (1937) and/or Lavagne (1972) are no longer present (Medail *et al.,* 2013): *Aeluropus littoralis* (Guan) Parl., *Eryngium maritimum, Euphorbia paralias, Matthiola sinuata* (Linnaeus) R. Brown, *Silene nicaeensis* Allioni and *Spergularia media* (Linnaeus) C. Presl ex Griseb.

The harvestman arachnid *Nelima doriae* (Canestrini, 1871) is locally near extinct at Port-Cros and Porquerolles Archipelagos (Kovoor and Muñoz-Cuevas, 2000; Médail *et al.,* 2013). The beetles (coleopterans) associated with driftwood, such as *Styphloderes exsculptus, Mesites pallidipennis* and *Brachemys brevipennis,* are also on the decline and/or locally extinct (**Fig. 12**) (Médail *et al.,* 2013). The fate of some other species such as *Calicnemis latreillii* Laporte de Castelnau, 1832 and *Isidus moreli* Mulsant & Rey, 1874 is even worse, since they have not been observed between Camargue and the Franco-Italian border for decades and are almost certainly extinct in this area (Ponel *et al.*, 2017, this issue). Two centipede species (Myriapoda), *Geophilus fucorum* and *Tuoba poseidonis*, dwelling in the *P. oceanica banquettes*, are considered as threatened in France; Port-Cros beaches are today their only French locality (Iorio and Noël, 2017). In Malta, the gastropod

Truncatella subcylintrica is absent from cleaned beaches, while the isopods *Spelaeoniscus vallettai* and *Chaetophiloscia elongata* and the annelid *Ophelia bicornis* are much less abundant on cleaned beaches (Deidun *et al.,* 2009); overall, the alpha species diversity of metazoans of cleaned beaches represents 19-21 % of that of uncleaned beaches, and the number of individuals 4-28 % (Deidun *et al.,* 2009). In contrast, in Provence, Comor *et al.* (2008) observed the pullulation of the beetle *Trachyscelis aphodioides* in disturbed beach dunes, significantly correlated with the Beach Disturbance Index (BDI).

In order to better assess the ecological consequences of these threats, this Beach Disturbance Index (BDI) has been proposed by Comor *et al.* (2008). It takes into account four parameters: urbanization, tourism intensity (beach use), dune trampling and beach cleaning (i.e. removal of macroalgal, seagrass and driftwood deposits). Each parameter (X) is quantified on an ordinal scale ranging from 0 (no impact) to 5 (maximum impact). The DBI is computed as follows: the values of the four parameters are reduced to the [0-1] interval using Gover's method [$X' = (X-X_{min})/(X_{max}-X_{min})$] (Legendre and Legendre, 1998). The BDI for each site is the average of the X' values (Comor *et al.*, 2008). As far as the beaches of the Mediterranean shores of France are concerned, the BDI ranges from 0 to 0.30 for Camargue beaches, 0.65 to 0.80 for Hyères beaches (L'Almanarre, Hyères Plage and Les Salins d'Hyères), and 0.75 to 1 for Pampelonne and Cogolin beaches, the most disturbed beaches (Comor *et al.*, 2008).

The difficult management of the sandy beaches, including the *Posidonia oceanica banquettes*

In the Mediterranean countries, *Posidonia oceanica banquettes* are often regarded as waste matter. Public authorities, and even some scientists working in fields other than biology and ecology (e.g. technology and bioresources), consider that they cause problems. For example, Zaafouri *et al.* (2016) surprisingly wrote that *P. oceanica banquettes* '*cause serious problems of marine pollution* (sic) *in the Mediterranean*', suggesting that they therefore offer '*an abundant, renewable and low cost feedstock for biorefinery purposes*'.

In Italy, waste matter from beaches is considered as solid urban waste. Beaches are cleaned by local agencies, municipalities and private companies that do not distinguish between true waste matter and *P. oceanica banquettes* (Chessa *et al.,* 2000; De Falco *et al.,* 2008). In addition, *P. oceanica banquettes* are believed to detract from beach value, mainly on aesthetic grounds (Guala *et al.,* 2006). In many administrative districts, *banquettes* are therefore removed in large quantities from beaches, supposedly for the benefit of tourists (De Falco *et al.,* 2008;

Boudouresque *et al.,* 2016). The same thing occurs in Malta Islands (Deidun *et al.,* 2007, 2009) and in the Balearic Islands (Roig *et al.,* 2009). Removal operations are carried out with heavy machines such as bulldozers and excavators, more rarely by beach-cleaning machines or by hand (**Fig. 19**) (De Falco *et al.,* 2008; Roig *et al.,* 2009). In Sardinia, the total amount removed for the year 2004 was estimated at ~106 000 m³. As *banquettes* trap large amounts of sediment, the amount of sand taken away from beaches by *banquette* removal amounts, in Sardinia, to as much as ~6 000 to 10 000 t/year (Guala *et al.,* 2006; De Falco *et al.,* 2008; Simeone and De Falco, 2013).

Figure 19. Heavy machines used to clean the beaches and to remove the *Posidonia oceanica banquette*, in Marseilles (Provence, France). The caption (bottom left) says: '*In Marseilles, the beaches are combed every morning in summer*'. From MPMag, Le magazine de Marseille Provence Métropole, July 2013.

In France, removing *P. oceanica banquettes* is theoretically banned, as the species *P. oceanica* has been strictly protected since July 1988 (*Arrêté du 19 juillet 1988 relatif à la liste des espèces végétales protégées*); strict protection means that the species, dead or alive, as complete individuals or as fragments of individuals, cannot be collected, transported, purchased or sold (Pergent, 1991; Boudouresque *et al.,* 1994, 2012; Boudouresque, 2013; Boudouresque and Bianchi, 2013). However, local agencies of the French Ministry of the Environment (DREAL: *Direction Régionale de l'Environnement, de l'Aménagement et du Logement*) systematically grant exemptions from the law to local authorities (municipalities).

The removal of the *banquettes* has a manifold geomorphological, ecological and economic negative impact:

Figure 20. Behind the beach of Pardigon (La Croix-Valmer, eastern Provence, France), a container filled with *Posidonia oceanica* leaves (and mostly sand) collected on the beach, ready to be transported to the landfill, June 2015. Photo © Charles F. Boudouresque.

(1) It deprives beaches of huge amounts of sand, either directly or indirectly, as 'collateral damage' of *banquette* removal (**Fig. 20**). In Sardinia, the direct impact has been assessed at 60 to 90 kg of lost sand per cubic metre of removed *banquette* (De Falco *et al.,* 2008; Simeone and De Falco, 2013); in Balearic Islands, the sand content of removed banquettes has been estimated at 23 % of their mass (Roig *et al.,* 2009). The impact is also indirect, the sand being washed into the sea, because beaches are no longer protected through the coating of the beach and the cushioning of wave impact by the *banquettes,* particularly during winter storms (Boudouresque and Meinesz, 1982; Roig i Munar and Martín Prieto, 2005; Pergent *et al.,* 2012; Simeone and De Falco, 2012, 2013; Boudouresque *et al.,* 2016). As a result, erosion mostly concerns beaches where removal operations are carried out, especially when removal is performed with a heavy machine (De Falco *et al.,* 2008; Roig *et al.,* 2009). In the Balearic Islands, it has been estimated that each metre of coating of the beach by dead *P. oceanica* leaves (along a transect perpendicular to the sea) results in a 2 m progradation of the beach (Roig *et al.,* 2009).

(2) As already stated above, the fate of most of the beach-cast litter is, sooner or later, to return to the sea. *Banquettes* represent a huge amount of organic carbon and of nutrients (Guala *et al.,* 2006; Simeone and De Falco, 2013). Considering *banquettes* as waste matter, and disposing of them in terrestrial garbage dumps, constitutes a huge and unacceptable waste that deprives the coastal marine ecosystems of an irreplaceable resource, and finally reduces the production of exploitable fish and other seafood (Guala *et al.,* 2006).

(3) In addition to this reduction of the fish stock and the resulting shortfalls for artisanal fishers, *banquette* removal constitutes the first step in a vicious circle (**Fig. 21**). The second step is the loss of sediment and beach erosion (Roig *et al.,* 2009). To attempt to compensate for this regression, many coastal public authorities launch costly beach replenishment operations (**Fig. 21**, box 3). Beach replenishment increases water turbidity, when the sediment used contains fine sediment, and causes the silting of the adjacent *P. oceanica* meadow, when the sediment is swept offshore by storms and currents (**Fig. 21**, box 4). If the height of the annual deposit is greater than the growth capability of orthotropic (i.e. vertical) *P. oceanica* rhizomes (a few centimetres per year), the tips of the plant are buried and the *P. oceanica* meadow dies (**Fig. 21**, box 5) (Boudouresque and Jeudy de Grissac, 1983; Manzanera *et al.,* 1998; Alcoverro *et al.,* 2012; Boudouresque *et al.,* 2012; Gera *et al.,* 2014; Boudouresque *et al.,* 2016). The origin of the sand used for beach replenishment also constitutes a controversial issue (Roig *et al.,* 2009; Boudouresque *et al.,* 2012); sand is often extracted in areas close to the regressing beach, further contributing to its erosion, or close to other beaches, resulting in a kind of 'game of musical chairs', the restoration of one beach entailing the erosion of the next (Roig *et al.,* 2009). In addition, the extraction of sand close to a *P. oceanica* meadow (less than ~300-500 m) results in a sand deficit within the meadow and the baring of the rhizomes, which become vulnerable to being broken off during storms. Degraded or collapsed *P. oceanica* meadows are less capable of reducing swell and current strength, which further accelerates the beach erosion process (**Fig. 21**, box 6) (Jeudy de Grissac and Boudouresque, 1985; Duarte, 2004; Infantes *et al.,* 2009; Stratigaki *et al.,* 2011; Infantes *et al.,* 2012; Manca *et al.,* 2012). Public authorities therefore intensify the beach replenishment process, which triggers a second phase in the vicious circle (**Fig. 21**).

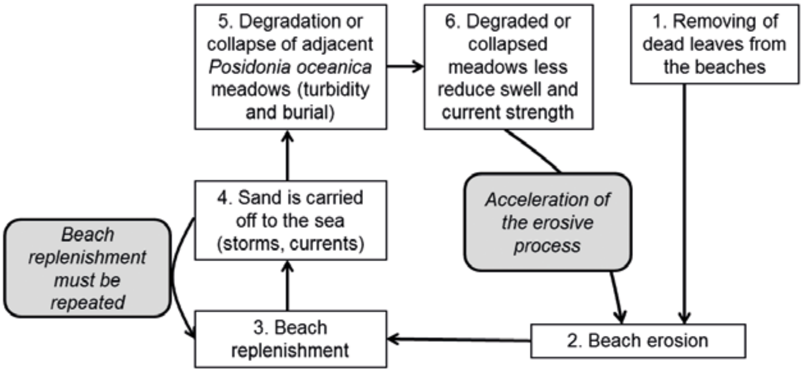

Figure 21. Consequences of the removal of *Posidonia oceanica banquettes* of dead leaves from beaches: a vicious circle. From Boudouresque *et al.,* 2016.

Surveys were carried out with the administrative departments of the French littoral coastal municipalities (‘*communes*’), in order to determine their management strategy with regard to the *banquettes* (Thibaut *et al*., 2015, 2016). The results are to be considered with great caution, as many *communes* have not replied, or have submitted very imprecise answers. In most cases, dead leaves are sent to the garbage dump or permanently stored on land far from the beaches. In a small number of cases, they are moved and provisionally stored at the end of the beach, in late spring, to be replaced on the beach in early fall, or dumped into the sea. The storage on the beach is theoretically temporary, with the leaves due to be replaced in the fall; however, the *communes* often forget to put them back in place (**Fig. 22**). In the Balearic Islands, local authorities also forget (even when it is planned) to put back in place the removed *banquettes*, at the end of the tourism season (Roig *et al.,* 2009). Dumping at sea could be a less harmful solution, since it allows a return of the organic carbon and nitrogen from the leaves to the coastal ecosystem. The so-called *millefeuille* technique is practiced by some *communes*; it consists in interposing layers of leaves and layers of sand. Its effectiveness in protecting beaches against erosion is still poorly known. Some of the above-mentioned techniques may be less damaging than others in terms of beach erosion (e.g. provisional storing at the end of the beach) or depriving the coastal marine ecosystems of a carbon and nutrient irreplaceable resource (e.g. dumping at sea). But all of them are harmful for the beach ecosystem.

Figure 22. Tamarone beach, Macinaghju, Capicorsu, northern Corsica, April 2017. **1.** A restaurant allowed to be set up on the beach, permanently or not, by French authorities, in spite of the ban under the '*Loi Littoral*'. Beach restaurants like this are popularly referred to as '*paillotes*' (literally: huts). **2.** The *Posidonia oceanica banquette* built during the previous autumn and winter. **Arrow:** A heavy machine used to remove the *banquettes* from the beach and to move them back, in spring. **3.** A kind of false dune built by the managers, behind the beach, with the *P. oceanica* dead leaves of the *banquette*. It is unlikely that this false dune is compatible with the true sand dune, its fauna and its flora. **4.** Plants beginning to grow on the false dune made of *P. oceanica* leaves; this shows that, contrary to what is often announced, the displacement of the *banquettes* is not temporary (seasonal) but definitive. Tamarone beach belongs to the *Conservatoire du Littoral*, a French national agency with a mission to safeguard, in partnership with local authorities (here a municipality), coastal natural areas of biological and landscape value. Photo © Charles F. Boudouresque.

The removal of the *banquettes* is accompanied by that of the driftwood, with consequences for the fauna associated with them. Surprisingly, in the Lavezzu Island nature reserve, from 1990 to 2013, volunteers from Nice collected the garbage together with the driftwood, the latter being treated as waste matter and burned on the beaches (Meinesz, 2013). This last practice has fortunately been abandoned.

Towards good management practices

In the Mediterranean, some mayors try to influence the tastes of the public, in order to 'sell' sandy *Posidonia*-free beaches resembling Polynesian beaches. Only the coconut palms are missing; perhaps they will end up trying to plant coconut palms to complete the image. It is of interest to note that, in inter-tropical zones, such tourist-brochure beaches can also constitute artefacts. In La Réunion Island, for example, the coral debris on the beaches was removed to satisfy the tastes of the tourists as the tour-operators have formed them. The result, again, was a loss of thickness of the beaches: 1.5 cm/year between 1979 and 1988 (Roland Troadec, pers. comm.; Gabrié, 1985; Tocquet and Porcher, 1987; Crestey, 1991; Masson, 1991).

As far as the Mediterranean beaches are concerned, they have harboured *banquettes* of dead *Posidonia* leaves for millions of years. These *banquettes* constitute a strong feature of the Mediterranean beaches. Since antiquity, the peoples bordering the Mediterranean have coexisted with the *banquettes*. In the 20th century, and until very recently, tourists also had no difficulty in coping with the *banquettes* (**Fig 23**). It is surprising that some mayors have not yet understood that the *banquettes* are not a handicap for tourism, but rather an emblem of Mediterranean identity and therefore a potentially attractive feature. In fact, the dead leaf *banquettes* could represent a key asset for sustainable tourism in the 21st century, both as a protection for the beaches and as a strong sign of Mediterranean identity.

Figure 23. The Plage d'Argent beach (Porquerolles Island, Provence) during the interwar period. Early tourists and inhabitants seem to have no difficulty coping with *Posidonia oceanica banquettes*. Could the fashion for *Posidonia*-free beaches be an artificial construction of modern tour operators? A photo dating back to the 1930s, provided by Michèle Dard and Charlotte Le Ber.

Fortunately, an increasing number of coastal districts (e.g. Hyères in Provence) and of public organizations (e.g. the French *Conservatoire de l'Espace Littoral et des Rivages Lacustres*, the *Parc national de Port-Cros* in Provence and the *Réserve Naturelle des Bouches de Bonifacio* in Corsica) have stopped removing the *banquettes*, to a greater or lesser extent (Serantoni, 2015; Boudouresque *et al.,* 2016; Thibaut *et al.,* 2016b). The same goes for Saint-Honorat, a small island off the French Riviera, home to a community of monks since the 5th century CE (**Fig. 24**). As the beach, the foredune, the dune and the backshore constitute transitory receptacles for the dead *P. oceanica* leaves, which frequently move from one to the other, a global management approach is required, rather than dealing specifically with each of these habitats. At Porquerolles and Port-Cros Archipelagos (*Parc national de Port-Cros*), the dead *P. oceanica* leaves are left in place, except in particular cases, and in these cases they are removed manually. Human-generated waste matter (e.g. plastic, processed wood such as planks, metal cans) is removed manually. Natural driftwood (i.e. non-processed wood) is left in place, with some exceptions, e.g. when this represents a problem or a danger to the public; this depends upon the diameter and the length of the driftwood (Serantoni, 2015). At Porquerolles, the collected driftwood is used to build natural-looking barriers along the paths (Vouillon, 2016). Partial removal, i.e. the dumping of removed beach seagrass debris (and the associated sand) at particular sites on the beach, allowing their return to the sea, is also practised, e.g. in Alghero (Sardinia, Italy) (Manca *et al.,* 2013).

Figure 24. A beach of Saint-Honorat Island, off the French Riviera, which has been home to a community of monks since the 5th century CE. The *Posidonia oceanica banquette* and driftwood are never removed. The beach harbours a rich fauna of coleopterans (ten species). Photo © Philippe Ponel.

Informing the public, especially children, about why the management measure consisting in not to removing *banquettes* and driftwood has been adopted, is done verbally by park rangers, through the local press, by leaflets and by information boards (**Figs. 25, 26**) (Boudouresque, 2010; Gasquy *et al.,* 2014; Serantoni, 2015). Generally speaking, the public's reaction to this management strategy is favourable and the number of visitors to these 'ecological beaches', when they have been properly informed, has not declined (Boudouresque, 2010; Zakhama-Sraieb *et al.,* 2011; Boudouresque *et al.,* 2012, 2016). In addition, bathers and tourists can easily observe that dead *P. oceanica* leaves are harmless, constitute a rather comfortable resting place and do not smell unpleasant, rather just a 'tidal scent' (Boudouresque, 2010). Ecosystem-based management may prove to be the most effective coastal defence in the face of modern tourism, economic issues and global change (Temmerman *et al.,* 2014).

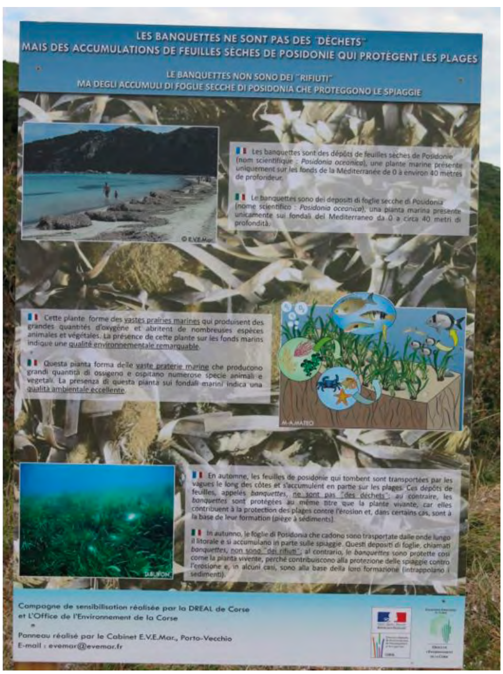

Figure 25. An information board, in French and Italian, on the beach of Cala di Paragnu, west of Bunifaziu, southern Corsica. The title (top of the board) reads: 'Banquettes *do not constitute waste matter, but drift dry leaves of* Posidonia *which protect the beaches*'. The text explains the reasons why the *banquettes* are not removed: the presence of *P. oceanica* is an indicator of good ecological quality, and the *banquette* contributes to protecting the beach from erosion, and even, in some cases, contributes to its construction. The information board was produced by the DREAL of Corsica (local agency of the French Ministry of the Environment) and by the *Office de l'Environnement de la Corse – Uffiziu di l'Ambiente di a Corsica* (the Corsican environment agency). Photo © Charles F. Boudouresque, December 2016.

Figure 26. An information board, in French and English, on a beach at Porquerolles Island (Port-Cros National Park, eastern Provence, France). It illustrates the concept of 'ecological beach'.

Conclusions

Beaches, together with the adjacent terrestrial habitats (foredune and dune), are anything but a biological desert. They harbour a rich flora and fauna, the latter mainly hidden within the sand, with species which are generally specific to this habitat. In addition, they constitute a feeding place for non-permanent dwellers, such as birds. Many of the species that thrive on beaches are rare and have become threatened. The common presence of *banquettes* made of dead leaves of the *Posidonia oceanica* seagrass, constitutes a unique feature of Mediterranean beaches. These *banquettes* protect beaches from erosion, contribute to dune construction and feed, through the release of nutrients, the dune and the backshore vegetation.

The Mediterranean coastal regions welcome much of the world's tourism activity. This tourism is for a large part beach-based, seaside tourism. In the 1980s, after a century of *Posidonia*-compatible seaside tourism, tourist operators and mayors of coastal cities began to 'sell' *Posidonia*-free beaches and to accustom tourists to unnatural groomed, 'clean' beaches. Clean beaches were now free of human-made detritus, which is understandable, but also of naturally cast-ashore *P. oceanica* dead leaves, seaweed, driftwood and even shells.

It is not clear whether the concept of a *Posidonia*-free beach actually corresponds to the tourists' requirements, or to the stakeholders' and mayors' own perception. Experiments aiming at maintaining the

Posidonia banquettes in place*,* with information boards explaining the issues, seem to indicate the latter. In any case, removing *banquettes*, driftwood, etc., results in a dramatic impoverishment of the beach biota: until recently, beaches were anything but deserts, but that is what they are now becoming! In addition, the *Posidonia*-free beach doctrine has resulted in catastrophic economic losses. Beaches, the cornerstone of the seaside tourism industry, now unprotected, are washed away by storms and costly sand replenishment accelerates their erosion in a kind of vicious circle. It is probably time to promote the spread of 'ecological beaches', i.e. *Posidonia*-compatible beaches, in order to save the seaside tourism industry and, incidentally, municipal financial resources and the Mediterranean biodiversity.

Well-managed beaches are a typical example of what is now referred to as a socio-ecosystem: an ecosystem of which man is a part. This of course means that they are managed in a sustainable way, retaining their natural characteristics, or most of them, and their long-term durability. Such sustainable beaches can be qualified as 'ecological beaches'. Ecological beaches are the exact opposite of artificial beaches, 'anthroposystems' made by municipal authorities devoid of vision of the future. Tourism is changing, tourists are becoming better informed and are often more aware than is generally thought. Their tastes are perhaps very different from what the tour-operators and some mayors seem to believe. In 5 or 10 years, municipalities that have made the wrong choice of 'concrete beaches' versus ecological beaches may regret their choice. But it will be too late. The so-called 'ecological engineering' may not be able to rebuild what has been destroyed forever (Temmerman *et al.,* 2014). Lost tourists may not return.

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