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# Decline and local extinction of Fucales in the French Riviera: the harbinger of future extinctions?

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#### Abstract

The French Riviera is among the Mediterranean areas that have been subject to the most long-lasting anthropogenic influences with severe impact on the marine environment. Fucales are long-lived, habitat forming brown algae that constitute a good model for studying human impact on species diversity. We gathered all historical data (literature and herbarium vouchers), since the early 19<sup>th</sup> century, to reconstruct their past distribution. The present distribution was established on the basis of an extensive 7-year (2007-2013) survey of the 212-km shoreline (measured on a 1/2 500 map), by means of boating, snorkelling and scuba diving. A total of 15 taxa of *Cystoseira* and 3 taxa of *Sargassum* were reported. Upon comparison with historical data, 5 taxa were no longer observed (*C. elegans, C. foeniculacea f. latiramosa, C. squarrosa, C. spinosa* var. *spinosa* and *S. hornschuchii*) while *C. jabukae*, previously unrecorded, was observed. In addition to the 5, possibly extinct taxa locally, *C. amentacea, C. barbata f. barbata, C. brachycarpa, C. crinita, C. sauvageauana* and *S. vulgare* suffered a decline, while *C. foeniculacea f. tenuiramosa, C. spinosa* var. *compressa* and *S. acinarium* became nearly extinct. *Cystoseira barbata f. barbata, C. brachycarpa, C. crinita* and *C. spinosa* var. *compressa* that played significant functional roles in coastal communities in the past, can be considered as functionally extinct. A similar situation has already been reported, although on a smaller scale, in other Mediterranean localities. The following question, therefore, arises regarding the ecology of Fucales in the Mediterranean: are some species on the brink of extinction? Is their decline or possible extinction, as documented on the French Riviera, the harbinger of their extinction Mediterranean-wide?

Keywords: Cystoseira, Sargassum, threatened species, Mediterranean.

#### Introduction

All over the world, coastal ecosystems are highly impacted due to the cumulative impacts of increasing human pressure (e.g. destruction of habitats, pollution, non-indigenous species, overfishing, coastal aquaculture and global warming). Different forms of stress act over time and in unison, with a possible synergistic effect, on species, ecosystems and their ability to deliver ecosystem services (e.g. Worm et al., 2006; Halpern et al., 2008; Waycott et al., 2009). The Mediterranean Sea is a hotspot of marine species biodiversity that is under siege due to rapid demographic development, pollution, a high percentage of worldwide shipping and tourism and the highest rate of biological invasions (e.g. Bianchi & Morri, 2000; Galil, 2000; Boudouresque & Verlaque, 2002; Panayotidis et al., 2004; Lotze et al., 2006; Coll et al., 2010; Lejeusne et al., 2010; Zenetos et al., 2010; UNEP/ MAP, 2012; Bianchi et al., 2014).

Along temperate rocky coasts worldwide, large canopy-forming kelps (Laminariales, Phaeophyceae, Ochrophyta) and fucoids (Fucales, Phaeophyceae, Ochrophyta) represent the dominant species in pristine environments (Dayton, 1985; Steneck et al., 2002; Schiel & Foster, 2006); they provide shelter, food, habitat and nursery areas to a multitude of species, and important primary production involved in the maintenance of diversified trophic levels, and they also attenuate wave action in the case of the largest species (Steneck et al., 2002). These seaweeds can be controlled by top-down mechanisms, mainly in the case of the sublittoral species, while the subsurface species are controlled by a bottom-up mechanism (Hereu et al., 2008a; Cardona et al., 2013). The loss of kelps and fucoids is a worldwide phenomenon due, directly or indirectly, to human activities (Steneck et al., 2002; Diez et al., 2003; Helmuth et al., 2006; Worm & Lotze, 2006; Airoldi & Beck, 2007; Hawkins et al., 2008; Wernberg et al., 2010; Schiel, 2011; Lamela-Silvarey et al., 2012; Raybaud et al., 2013; Filbee-Dexter & Scheibling, 2014). Some taxa have been driven to regional extinction (Thibaut et al., 2005; Coleman et al., 2008; Phillips & Blackshaw, 2011) or are threatened by climate warming that might drive them toward areas where retreat is impossible (Wernberg et al., 2011). These impacts

are leading to shifts in habitat structure from a state with canopy forming species to alternative states, in the worst case to barren grounds composed of filamentous and encrusting species (Micheli *et al.*, 2005; Connell *et al.*, 2008; Perkol-Finkel & Airoldi, 2010; Sala *et al.*, 2012; Filbee-Dexter & Scheibling, 2014), with flow-on effects on adjacent communities (Bishop *et al.*, 2010).

In the Mediterranean Sea, species of the genus Cystoseira C. Agardh and Sargassum C. Agardh are habitatforming species dominating several assemblages, from the littoral fringe down to the lower sublittoral zone (Feldmann, 1937; Molinier, 1960; Pignatti, 1962; Verlaque, 1987; Ballesteros, 1988, 1990a,b; Giaccone et al., 1994). Their zonation depends on different environmental conditions (light, temperature, hydrodynamics and grazing) (Sauvageau, 1912; Ollivier, 1929; Vergés et al., 2009). Loss of Mediterranean fucoid algae has been reported all around the Mediterranean; caused by habitat destruction, eutrophication and overgrazing by herbivores and leading to a shift to lesser structural complexity, such as turf-forming, filamentous or other ephemeral seaweeds or urchin barren grounds where urchin density is a driver of habitat homogenization (Munda, 1974, 1982, 1993; Thibaut et al., 2005; Devescovi and Ivesa, 2007; Airoldi et al., 2008; Falace et al., 2010; Fraschetti et al., 2011; Orfanidis et al., 2011; Giakoumi et al., 2012; Sala et al., 2012; Tsiamis et al., 2013; Bianchi et al., 2014; Templado, 2014).

In order to analyse the long-term patterns of distribution of *Cystoseira* and *Sargassum* species along the French Riviera coast (north-western Mediterranean), we collected all available data (herbarium vouchers, published and grey literature) and we reconstructed their historical distribution. The aims of this study were i) to provide an up-to-date and exhaustive semi-quantitative map of the distribution of each taxon, ii) to compare this distribution with historical data, iii) to assess the status of the taxa: stable, in decline, functionally extinct or possibly locally extinct and iv) to analyse and identify the possible causes of the observed situation and its consequences at Mediterranean scale.

#### **Materials and Methods**

#### Study site

The French Riviera is located in the north-western Mediterranean and extends from Théoule-sur-Mer to the Italian border (Menton). The coast is rocky, interspersed with large sedimentary bays (Fig. 1). Densely urbanized and populated (more than one million permanent inhabitants), this coast is one of the most attractive coasts for tourism in the world, welcoming ~11 million tourists every year, with frequency peaking in August (600 000 visitors simultaneously present on August, 15<sup>th</sup> 2013) (Comité Régional du Tourisme Côte d'Azur, 2014).

#### Data collection

#### Historical data

There is a considerable amount of available historical data (published literature and herbarium collections) dealing with the occurrence of the genera *Cystoseira* and *Sargassum* along the French Riviera coastline. From the 19<sup>th</sup> to the early 21<sup>st</sup> century, numerous naturalists and



*Fig. 1*: The studied area; the French Riviera. We did not represent the shoreline between Antibes (Box Fig. 3) and Nice (Box Fig. 4) because it is only made of a large beach with the International Airport in the middle, any Fucales have never been observed in this area.

phycologists surveyed the French Mediterranean coasts. They received support from local natural history museums and they built up an efficient web of collectors providing large quantities of samples.

Vouchers held in herbaria are an exceptional source of data providing a basis for checking the identification of the specimens. We surveyed several thousand vouchers held in the following herbaria (names after Index Herbariorum). AV: The Muséum d'Histoire Naturelle d'Avignon; Herbarium Requien. HCOM: The herbaria held at Aix-Marseille University; Herbarium P. and H. Huvé, Herbarium Saint-Charles, Herbarium Thibaut, Herbarium M. Verlaque. **MPU**: The herbaria held at the University of Montpellier 2; Herbarium Flahault, Herbarium Général, Herbarium Raphélis. Musée Océanographique of Monaco (not indexed); Herbarium Aguesse, Herbarium Mouret, Herbarium Prince Albert I. NICE: The Muséum d'Histoire Naturelle de Nice; Herbarium Camous, Herbarium Algues Marines tome III, Herbarium Algues vertes 1890-1910. Nice-Sophia Antipolis University (not indexed); Herbarium Meinesz. PC: The Muséum National d'Histoire Naturelle (MNHN) in Paris; Carnet de récolte de Feldmann, Herbarium Bory de Saint-Vincent, Herbarium B. de Reviers, Herbarium J. Feldmann, Herbarium Général, Herbarium Lamouroux, Herbarium Leprieur in Herbarium Cosson, Herbarium Magne, Herbarium Montagne, Herbarium Sauvageau, Herbarium Thuret, VTA: The Botanical Garden of Villa Thuret in Antibes: a recently rediscovered collection of vouchers collected by Gustave Thuret and Edouard Bornet in the 19th century.

#### The '2007-2013' distribution

The field work was carried out during the period of maximum development of species (spring to autumn according to the taxon) from 2007 to 2013. When barely identifiable specimens were found, we returned to the site during the growth period in order to identify the species. We surveyed the whole shoreline with special attention to the sites sampled by previous phycologists. We used maps of the habitats, from the sea surface down to 50 m depth (Holon & Descamp, 2007, 2008), to locate the shallow and the deep reef habitats likely to harbour Fucales species; all these sites were investigated. Between the shallow reef habitats (usually less than 5 m depth and close to the shoreline) and the deep ones, most of the area is occupied by seagrass meadows and soft substrates unsuitable for Fucales species. Special attention was paid to Cystoseira amentacea, which thrives close to sea level, at less than 1 m depth, and can therefore be extensively mapped. Populations were drawn on black and white A3 format aerial photographs obtained from the IGN (French National Institute of Geographical and Forest Information: BD Ortho). The scale was 1:2 500. Three people were on board a small boat (length 5 m) moving at low speed (3 to 6 km h<sup>-1</sup>) a few meters from the shore. Cystoseira amentacea populations were recorded within 50-m stretches of shoreline, according to 6 classes, as defined by Ballesteros *et al.* (2007): C 0 =absence, C 1 = rare scattered individuals, C 2 = abundant scattered individuals, C 3 = abundant patches of dense stands, C 4 = almost continuous belt and C 5 = continuous belt of *C. amentacea.* For shallow water species, snorkelling was used to survey the reef habitats along the whole coast extensively, so that no surface area escaped observation. Finally, scuba diving was used in the deep areas down to 40 m depth; dives were focused on sites where Fucales were recorded in the past and on the hard bottom habitats suited to harbouring Fucales, together with the surrounding areas. It is worth noting that suitable deep habitats are only found in limited areas.

For species other than *C. amentacea*, sites hosting *Cystoseira* or *Sargassum* were geo-localised as points and their abundance was visually estimated: absent, isolated individuals, scattered population and dense population. Species were identified in the field if possible. Doubtful specimens were collected and identified at the laboratory, using appropriate bibliography (Sauvageau, 1912; Hamel, 1931-1939; Ercegović, 1952; Gómez-Garreta *et al.*, 2000; Cormaci *et al.*, 2012). Vouchers are deposited in the Thibaut Herbarium (HCOM) kept at the Mediterranean Institute of Oceanography of Aix-Marseille University.

The changes over time (past and present distribution) were analysed using a GIS (Geographical Information System) database (ArcGis10®) with Spatial Analyst tools. Each past or present location was geo-localised. All historical maps were digitalized to fit the same coastal line used for the present distribution (scale 1:2 500).

#### Results

The historical and '2007-2013' distributions of 15 and 3 taxa of Cystoseira spp. and Sargassum spp., respectively, are summarized in Tables S1-S17 and Figs. 2-5. Overall, 385 historical records have been listed since the beginning of the 19th century. Most of the historical records date back to the 19th and the beginning of the 20th century with extensive collections by several naturalists living or spending time on the Riviera, such as Stanislas Bonfils, Edouard Bornet, Auguste Camous, Charles Flahaut, Albert I of Monaco, Gaston-Maurice Ollivier, Alphonse Raphélis, Antoine Risso, Camille Sauvageau and Gustave Thuret. The later 20th century collections are scarcer but several studies were undertaken (Raphélis, 1907, 1924a,b,c; Ollivier, 1929, Gugliemi, 1969, Jaffrenou, et al., 1996; Verlaque & Bernard 1998; Meinesz et al., 2000) and specimens of Cystoseira and Sargassum were collected by phycologists such as Jean Feldmann, Francis Magne, Alexandre Meinesz and one of the authors (Marc Verlague).

#### Cystoseira amentacea (C. Agardh) Bory de Saint-Vincent

*Cystoseira amentacea* occurs throughout the Mediterranean Sea. Two varieties are sometimes considered, var. *amentacea* and var. *stricta* Montagne, but they are poorly



*Fig. 2:* Current distribution of *Cystoseira* and *Sargassum* species from the western limit of the French Riviera to Cannes. The colour indicates the presence and abundance of *C. amentacea*. No colour point or line means its absence. Other species, always present in very small patches, are located at the tip of the arrows. *C. compressa* subs. *compressa*, which is present everywhere on hard substrates, is not cited. Lines correspond to depth contours.



*Fig. 3*: Current distribution of *Cystoseira* and *Sargassum* species between Golfe-Juan and Antibes. The colour indicates the presence and abundance of *C. amentacea*. No colour point or line means its absence. Other species, always present in very small patches, are located at the tip of the arrows or beneath an asterisk. *C. compressa* subs. *compressa*, which is present everywhere on hard substrates, is not cited. Lines correspond to depth contours.



*Fig. 4:* Current distribution of *Cystoseira* and *Sargassum* species between Nice and Eze-sur-Mer. Colour indicates the presence and abundance of *C. amentacea*. No colour point or line means its absence. Other species, always present in very small patches, are located at the tip of the arrows or beneath an asterisk. *C. compressa* subs. *compressa*, which is present everywhere on hard substrates, is not cited. Lines correspond to depth contours.



*Fig. 5:* Current distribution of *Cystoseira* and *Sargassum* species between Cap d'Ail and the Italian border. Colour indicates the presence and abundance of *C. amentacea*. No colour point or line means its absence. Other species, always present in very small patches, are located at the tip of the arrows or beneath an asterisk. *C. compressa* subs. *compressa*, which is present everywhere on hard substrates, is not cited. Lines correspond to depth contours.

characterized and will not be distinguished here (Ribera *et al.*, 1992; Cormaci *et al.*, 2012; Guiry & Guiry, 2014). *Cystoseira amentacea* was mentioned in the literature and herbaria under several other names, such as *Cystoseira stricta* Sauvageau, *Cystoseira ericoides* (Linnaeus) C. Agardh and *Cystoseira ericoides* var. *amentacea* C. Agardh.

The species was collected for the first time along the French Riviera coastline in 1826 at Nice by Antoine Risso (*in* Bory de Saint-Vincent Herbarium). During the 19<sup>th</sup> century, the species was frequently collected at Cannes, Antibes, Nice, and Roquebrune-Cap-Martin (Raphélis, 1907, 1924a,b,c). Agardh (1842) reported the species precisely '*ad Nizzam ipse*' (in Nice). Montagne (1846) studied specimens collected by De Notaris '*ad Nicaeam*' (in Nice). In the 20<sup>th</sup> century, Ollivier (1929) drew the first map of the species, from Cap Martin to Cap Roux (Ezesur-Mer), described its distribution along the French Riviera coastline and highlighted that it was very abundant on exposed rocks and even in some bays. More recent authors noted that the species was still common (Gugliemi, 1969; Meinesz *et al.*, 2000; Susini, 2006) (Table S1).

In 2011, we mapped the entire populations of C. amentacea extensively (Figs. 2-5). Cystoseira amentacea was present along 44 km of shoreline. It was abundant on most of the suitable substrates and the populations are mainly constituted of continuous belts (Table 1). Populations were isolated from each other by large beaches and mostly located around the capes and islands. Regressions were localized around the entrance of ports and offshore from the cities (Antibes, Nice, Villefranche-sur-Mer, Saint-Jean-Cap-Ferrat), where *Mytilus galloprovincialis* and benthic assemblages of Corallina spp. dominated. In the vicinity of the Golfe-Juan fish farm, C. compressa subs. compressa was dominant over C. amentacea. In Monaco, a few C. amentacea patches subsisted at the foot of the old town (Le Rocher), the only natural coast remaining. On the man-made structures, Corallina spp. dominated.

#### Cystoseira barbata (Stackhouse) C. Agardh f. barbata

In the Mediterranean Sea, *Cystoseira barbata* f. *barbata* grows in the upper sub-littoral zone in sheltered places and shallow bays as well as in coastal lagoons. In the study area, some historical records were cited under the names: *Cystoseira hoppei* C. Agardh, *Cystoseira barbata* var. *hoppei* (C. Agardh) J. Agardh and *Cystoseira barbata* f. *hoppei* (C. Agardh) Woronichin.

The first record dates back to 1825, with specimens collected along the coast at Nice (*'côtes de Nice'*) (specimens held in the Sauvageau Herbarium). During the 19<sup>th</sup> and 20<sup>th</sup> century, the species was collected 49 times along the French Riviera. In the 19<sup>th</sup> century, *C. barbata* f. *barbata* was collected at Cannes (Raphélis Herbarium, Raphélis, 1924a), at Antibes (Saint-Charles Herbarium, Huvé Herbarium, Sauvageau Herbarium, Flahaut Herbarium, Le Prieur Herbarium, Villa Thuret Herbarium,

**Table 1.** Structure of the *Cystoseira amentacea* populations along the French Riviera coasts (% of hard substrate coastline). C 0: absence; C 1: Rare scattered plants; C 2: Abundant scattered plants; C 3: Abundant patches of dense stands; C 4: Almost continuous belts; C 5: Continuous belts.

C 0	C 1	C 2	C 3	C 4	C 5
57.51	0.91	2.12	5.67	6.54	27.24

Bornet & Flahault, 1883), at Nice (Sauvageau Herbarium, Montagne Herbarium, Algue VertesHerbarium), and at Menton (Bonfils *in* Raphélis 1924b).

At the beginning of the 20<sup>th</sup> century, vouchers and records remained numerous and the species was collected at Saint-Jean-Cap-Ferrat (J. Feldmann Herbarium, Carnet de récolte Feldmann, Ollivier 1929), Beaulieu-sur-Mer (Ollivier 1929), Roquebrune Cap-Martin (Bonfils in Raphélis 1924), and Menton (Raphélis Herbarium). The species was reported as common at Théoule (Raphélis Herbarium), Cannes (Raphélis Herbarium; Raphélis, 1924a), Golfe-Juan (Raphélis, 1924a), Antibes (Ollivier, 1929), Nice (Camous Herbarium) and between Saint-Jean-Cap-Ferrat and Eze-sur-Mer in 1912 (Camous, 1912). Ollivier (1929) described the species as very abundant in the shallow bays in the eastern and the western parts of Antibes but he noted that on the steep coast from Nice to Menton, the species was rare and located in Passable, Beaulieu-sur-Mer and Pointe Sainte-Hospice (Saint-Jean-Cap-Ferrat). Finally, Guglielmi (1969) reported the species as common at Villefranche-sur-Mer (rock pools on Pointe Colombier), Saint-Cap-Ferrat (Espalmador), and Beaulieu-sur-Mer (Baie de Fourmi). The species has become rare since the 1970s: only one citation (Debrat, 1974) and two specimens collected at Saint-Jean-Cap-Ferrat in the 1970s and Antibes in the 1980s (Meinesz Herbarium) (Table S2).

The '2007-2013' situation of *C. barbata* f. *barbata* is critical. The species was not found at most of its previously recorded localities. We observed it at only 3 sites: a sheltered shallow site of the western part of Cap d'Antibes and adjacent to Le Crouton, where individuals are scattered over several dozen square meters, mixed with *C. compressa* subsp. *compressa*, *C. crinita*, *C. jabukae* and *C.sauvageauana*. A few individuals have been observed behind a *Posidonia oceanica* (Linnaeus) Delile barrier reef, in the Anse de l'Espalmador at SaintJean-Cap-Ferrat, on very shallow rocks surrounded by hundreds of individuals of the sea urchins *Paracentrotus lividus* (Lamarck 1816) and *Arbacia lixula* (Linnaeus 1758). *Cystoseira barbata* f. *barbata* was observed during the entire study period at all sites.

#### Cystoseira brachycarpa J. Agardh

*Cystoseira brachycarpa* grows in littoral pools and sublittoral habitats, in moderately exposed and high light intensity sites. Some historical records were cited under the names: *Cystoseira balearica* Sauvageau, *Cystoseira*  *brachycarpa* var. *balearica* (Sauvageau) Giaccone and *Cystoseira caespitosa* Sauvageau.

Historical data concerning *C. brachycarpa* are scarce. The species has been recorded only 5 times: in 1899, as drift on a beach in Golfe-Juan (Raphélis Herbarium); frequent in Nice (Camous, 1912); collected in Antibes in 1928 (Raphélis *in* Général Herbarium); reported at Villefranche-sur-Mer by Hamel (1931-1939) by P. Dangeard; and two specimens collected at Antibes (Port Rousse Chaffa, now called Port La Salis) in 1979 (Verlaque Herbarium) (Table S3).

During the field study, the species was observed at 4 sites. At Cap d'Antibes, the species constituted a narrow belt below *C. amentacea* at l'Olivette and a dense monospecific assemblage in a rock pool of the Pointe de L'Ilette; at Cap Ferrat (Saint-Jean-Cap-Ferrat), a few sparse individuals, highly grazed, were growing at 10 m depth; some individuals were found slightly deeper than the *C. amentacea* belt at Eze-sur-Mer. *Cystoseira brachycarpa* was observed during the whole study period at all sites.

## *Cystoseira compressa* (Esper) Gerloff & Nizamuddin subsp. *compressa*

*Cystoseira compressa* subsp. *compressa* (hereafter *C. compressa*) grows in the upper sublittoral zone from the sea surface down to 15 m, at both sheltered and exposed sites, in pristine and moderately polluted areas. Some individuals have occasionally been observed at depths down to 40 m. Some historical records were cited under the names: *Cystoseira abrotanifolia* (Linnaeus) C. Agardh, *C. abrotanifolia* f. *fimbriata* Sauvageau, and *C. fimbriata* Bory de Saint-Vincent.

*Cystoseira compressa* was first collected in 1839 at Nice (C. Agardh *in* Requien Herbarium, Algues Vertes Herbarium). In the 19<sup>th</sup> century, the species was collected and reported at Cannes (Raphélis Herbarium; Raphélis, 1924a), Antibes (Saint-Charles, Général and Flahault Herbaria), Nice (Requien, Montagne and Lamouroux Herbaria; Raphélis, 1924c), Menton (Bonfils *in* Raphélis, 1924b).

In the 20<sup>th</sup> century, *C. compressa* was observed 'everywhere' between Eze-sur-Mer and Nice (Camous, 1912). Ollivier (1929) described the species as ubiquitous and abundant everywhere from the surface down to several meters depth. Gugliemi (1969) reported the species as very common, everywhere in sheltered and exposed locations. The species was also observed by Gilet (1954) and Huvé & Huvé (1963).

Voucher specimens were collected at Mandelieu-la-Napoule (Raphélis Herbarium), Cannes, where the species was noted as abundant in 1900 (Général Herbarium, Raphélis Herbarium), Golfe-Juan (Raphélis Herbarium), Juan-les-Pins (J. Feldmann Herbarium), Antibes (Villa Thuret Herbarium, Raphélis Herbarium, Verlaque Herbarium), Nice (Raphélis Herbarium, Camous Herbarium, Algues Marines tome III Herbarium), Villefranchesur-Mer (J. Feldmann Herbarium, Aguesse Herbarium, Magne Herbarium), Saint-Jean-Cap-Ferrat (J. Feldmann Herbarium, Meinesz Herbarium), Beaulieu-sur-Mer (Meinesz Herbarium), Monaco (Mouret Herbarium) and Menton (Général Herbarium) (Table S4).

During the field study, the species was not only very common still, but was by far the most common Fucales along the French Riviera coastline.

## *Cystoseira compressa* subsp. *pustulata* (Ercegović) Verlaque comb. nov.<sup>1</sup>

In the studied area, *C. compressa* subsp. *pustulata* grew in the shallow sublittoral zone. It was only sampled at Cannes in 1899 and 1912 (Général Herbarium) (Table S5) where it is still present.

We also found the species in the western part of Antibes and in shallow waters and two rock pools at Pointe Colombier at Saint-Jean-Cap-Ferrat. *Cystoseira compressa* subsp. *pustulata* was observed during the entire study period at all sites.

#### Cystoseira crinita Duby

*Cystoseira crinita* grows in the upper sublittoral zone, near the sea surface, in sheltered locations with high light intensity and warm temperatures in summer.

The first record of the species along the French Riviera dates back to 1826, with a specimen collected at Nice (Thuret Herbarium). In the 19<sup>th</sup> century, voucher specimens and records come from Golfe-Juan (Saint-Charles Herbarium), Antibes (Thuret Herbarium, Sauvageau Herbarium, Bornet & Flahault, 1883). Hamel (1931-1939) reported the species referring to a record of de Notaris in the 20<sup>th</sup> century), in Nice (Thuret Herbarium, Lamouroux Herbarium; Duby, 1830; Agardh, 1842) and in Villefranche-sur-Mer (Thuret Herbarium).

At the beginning of the 20<sup>th</sup> century, *C. crinita* was present at Antibes (Villa Thuret Herbarium, J. Feldmann Herbarium; Ollivier, 1929), Saint-Jean-Cap-Ferrat (Camous, 1912), Beaulieu-sur-Mer (Ollivier, 1929) and Cap-d'Ail (Ollivier, 1929). Ollivier (1929) mentioned the species as abundant between Juan-les-Pins and Le Crouton in the western part of Antibes and in the Bay of Beaulieu. In the 1960s, the species was collected at Saint-Jean-Cap-Ferrat (Meinesz Herbarium) (Table S6).

During the field study, *C. crinita* was observed at 7 sites. A few individuals were found near the Mouret Rouge port, at Cannes, a few square meters below the monastery of Saint-Honorat Island and a number of individuals were found at Sainte-Marguerite Island. In the western part of Antibes, over a few dozen square meters, *C. crinita* was mixed with *C. barbata* f. *barbata*, *C. compressa* subsp. *compressa* and subsp. *pustulata*, *C. jabukae* and *C. sau*-

<sup>1.</sup> See Nomenclatural note

*vageauana*. At Pointe de l'Ilette, the species occurred in a single rock pool. We also observed a few heavily grazed individuals in shallow waters at Rumpa Talon (Saint-Jean-Cap-Ferrat) and at Eze-sur-Mer. *Cystoseira crinita* was observed during the entire study period at all sites, but, it is no longer present at most of the historical localities. Where still present, populations have become fragmented and have dramatically declined to a few individuals.

#### Cystoseira elegans Sauvageau

*Cystoseira elegans* grows in the upper sublittoral zone, from the sea surface to a few meters depth, usually in moderately sheltered conditions. The species was only collected at Cannes in 1912 and 1926 (Raphélis *in* Général Herbarium) and at Antibes in 1961 (Huvé & Huvé, 1963) (Table S7).

We never found the species during our surveys. Considering its preference for a shallow habitat and that it is relatively easy to survey, its local extinction constitutes a likely hypothesis.

### *Cystoseira foeniculacea* (Linnaeus) Greville f. *tenuiramosa* (Ercegović) A. Gómez Garreta, M.C. Barceló, M.A. Ribera & J.R. Lluch

*Cystoseira foeniculacea* f. *tenuiramosa*is grows in sheltered places in the littoral zone to 1m depth (sometimes in rock pools). It is primarily an Atlantic species and the specimens that we observed in the herbaria all belong to the Mediterranean form *tenuiramosa*. Some historical records were cited under the names *Cystoseira discors* (Linnaeus) C. Agardh, *Cystoseira concatenata* C. Agardh and *Cystoseira schiffneri* Hamel.

*Cystoseira foeniculacea* f. *tenuiramosa* was first collected in 1825 by Thuret at Nice (Thuret Herbarium). In the 19<sup>th</sup> century, the species was collected at Cannes (Requien Herbarium, Raphélis, 1907), Antibes (Sauvageau Herbarium; Bornet & Flahault, 1883), Nice (Thuret Herbarium, Montagne Herbarium, Lamouroux Herbarium; Agardh, 1842), Villefranche-sur-Mer (Montagne Herbarium), Saint-Jean-Cap-Ferrat (Algues Vertes Herbarium) and Menton (Bonfils *in* Raphélis, 1924b).

In the first half of the 20<sup>th</sup> century, the taxon was collected at Cannes (Raphélis *in* Général Herbarium; Raphélis, 1907). The collector mentioned that the species was very abundant at Cannes (La réserve), between the two Islands of Lérins where it formed real forests (Raphélis, 1907). The taxon was also collected at Théoule-sur-Mer (Raphélis, 1907), Golfe-Juan (Raphélis, 1907), Antibes (J. Feldmann Herbarium; Ollivier, 1929), Villefranchesur-Mer (J. Feldmann Herbarium, J. Feldmann: carnet de récolte; Ollivier, 1929), Saint-Jean-Cap-Ferrat (J. Feldmann Herbarium; Ollivier, 1929), Roquebrune-Cap-Martin (Mouret Herbarium) and Menton (Raphélis in Général Herbarium). Ollivier (1929) observed that *C. foeniculacea* f. *tenuiramosa* was abundant in the rock pools of Pointe de L'Ilette (Antibes) and within the port of La Darse (Villefranche-sur-Mer). In the 1950s, the species was only collected once at Villefranche-sur-Mer (Magne Herbarium). In the 1970-1980s, *C. foeniculacea* f. *tenuiramosa* was collected at Golfe-Juan (Meinesz Herbarium), Antibes (Verlaque Herbarium) and Beaulieu-sur-Mer (Meinesz Herbarium) (Table S8).

During the field study, *C. foeniculacea* f. *tenuiramosa* was only observed at 2 sites: a single individual in shallow water at Sainte-Marguerite Island, in June 2007, and a dense population in a rock pool of a few square metres at Pointe de L'Ilette, Cap d'Antibes. This population was observed during the entire study period. The extensive exploration of the historical sites was unsuccessful in locating the taxon, with the exception of Pointe de L'Ilette; we can therefore consider that it is nearly extinct locally.

## *Cystoseira foeniculacea* f. *latiramosa* (Ercegović) A. Gómez Garreta, M.C. Barceló, M.A. Ribera & J.R. Lluch

A specimen dredged off Cap-Ferrat at 10-20 m depth and referred to as *C. discors* by Ollivier (1929) (Table S9), probably belonged to *C. foeniculacea* f. *latiramosa*, the deep form of the species.

We did not find this taxon during our surveys.

### Cystoseira jabukae Ercegović

*Cystoseira jabukae* has not been previously recorded along the French Riviera, and our two records are therefore the first. It has been regularly observed since 2007, growing in shallow waters (less than 1 m depth) in two moderately exposed areas: in the western part of Antibes, where a few individuals occurred together with *C. barbata* f. *barbata, C. compressa* (including subsp. *pustulata*), *C. crinita* and *C. sauvageauana*, and in rock pools at Pointe de L'Ilette with *C. crinita*.

#### Cystoseira sauvageauana Hamel

*Cystoseira sauvageauana* usually grows in sheltered places in the littoral and sublittoral zones, down to several metres depth. Some early records were cited as *Cystoseira selaginoides* Sauvageau.

The species was first collected in 1840 at Antibes (Saint-Charles Herbarium) and another specimen collected in the 19<sup>th</sup> century (not dated) was found at Antibes (Général Herbarium).

All the other records date back to the beginning of the 20<sup>th</sup> century when the species was collected at Cannes (Raphélis *in* Général Herbarium), Antibes (Ollivier, 1929), Villefranche-sur-Mer (Ollivier, 1929; J. Feldmann: carnet de récolte), Saint-Jean-Cap-Ferrat (Ollivier, 1929; J. Feldmann: carnet de récolte) and Beaulieu-sur-Mer (Ollivier, 1929). According to Ollivier (1929) the species could be found in rock pools and in all the rocky bays along the entire French Riviera; the species was also abundant on the *jetée septentrionale du Fort Carré* (Antibes), at the entrance of the Port of La Darse (Villefranche-sur-Mer), at l'Espalmador (Saint-Jean-Cap-Ferrat), between the rocks at Anse Lilong (Saint-Jean-Cap-Ferrat), in the north of Rumpa-Talon (Beaulieu-sur-Mer), while a few stunted individuals were growing in large rock pools dominated by *C. barbata* f. *barbata* at Pointe Sainte-Hospice (Saint-Jean-Cap-Ferrat). In 1999, the species was collected at Antibes (Verlaque Herbarium) (Table S10).

During the field study, *C. sauvageauana* was observed at 5 sites. Some specimens were found in the western part of Cap d'Antibes (regularly observed since 2007) in a mixed population with *C. barbata* f. *barbata*, *C. compressa* (including subsp. *pustulata*), *C. crinita* and *C. jabukae*, a few individuals of the species were also observed at Pointe de L'Ilette in rock pools (regularly observed since 2007), and some individuals in shallow waters (1 m depth), off the Marine Station of Ville-franche-sur-Mer (2007 and 2010) and at Anse de Lilong (Saint-Jean-Cap-Ferrat) (2013), and off Cap-Ferrat at 25 m depth (2010). The latter record constitutes the deepest observation ever made for this species.

#### Cystoseira squarrosa De Notaris

The species was originally described by De Notaris from material collected at Nice (Agardh, 1842) and has also been found growing near the sea surface at the entrance of the port of Nice in 1871 (Montagne Herbarium). Raphélis (1907) mentioned drift specimens on the beach of Cannes. Ollivier (1929) reported, with doubts, from De Notaris' observations in the 19<sup>th</sup> century, some individuals at the same Nice site (Table S11).

We did not find this species during our surveys, which nowadays lies within the port of Nice. The species can therefore be considered as locally extinct.

#### Cystoseira spinosa Sauvageau var. spinosa

Ollivier (1929) reported the two varieties of *C. spinosa*: var. *spinosa* and var. *compressa*. He described a *C. spinosa* 'facies' from the sea surface rock pools down to 30-50 m depth, at Pointe de Lilong (Saint-Jean-Cap-Ferrat), with var. *spinosa* in shallow habitats and var. *compressa* in the deep habitats (Table S12).

We did not find *Cystoseira spinosa* var. *spinosa* during our survey, including at the above-mentioned site.

### *Cystoseira spinosa* var. *compressa* Cormaci, Furnari, Giaccone, Scamaca & Serio

According to Cormaci, Furnari, Giaccone, Scamaca & Serio, *Cystoseira spinosa* var. *compressa* grows in the sublittoral zone down to 70 m depth. Some early records were quoted as *Cystoseira spinosa* Sauvageau (without mentioning the variety).

The first specimen of *Cystoseira spinosa* var. *compressa* collected at Antibes (Saint-Charles Herbarium) dates back to 1840. The taxon was collected in the 19<sup>th</sup> century

at Nice (Risso *in* Lamouroux Herbarium, De Notaris *in* Montagne Herbarium). In the first half of the 20<sup>th</sup> century, the taxon was collected off Saint-Honorat Island (Raphélis, 1930), round the Islands of Lérins at 70 m depth (Peyrissol *in* Général Herbarium), at Pointe de Lilong, Cap-Ferrat (Ollivier, 1929), on the western side of Cap Ferrat (J. Feldmann: carnet de récolte). Sauvageau collected the species at Cap-Ferrat at 40 m depth between 1930 and 1935 (Sauvageau, 1931, 1936). Finally, the taxon was collected in 1997 at Larvotto (Monaco), at 32 m depth (Verlaque Herbarium; Verlaque & Bernard, 1998) (Table S13).

During our field study, we observed a few isolated individuals at Cap Martin (30 m depth) in 2010.

#### Cystoseira zosteroides C. Agardh

*Cystoseira zosteroides* grows in the sublittoral zone down to 80 m depth. Some historical records were cited as *C. opuntioides* Bory de Saint-Vincent ex Montagne.

The species was first reported off the Port of Nice and in the Bay of Beaulieu-sur-Mer (Ollivier, 1929); this author noted that the species was less common than *C. spinosa*. Then, the species was only recorded in 1967 and 1968 at Cap Martin (Meinesz Herbarium) at 30 m depth (Gugliemi, 1969) (Table S14).

During the field study, we found a few specimens in Antibes, off La Garoupe (2008), at the entrance of the port of Nice (2007-2010), in the eastern part of the Bay of Villefranche-sur-Mer, off Le Lido-Passable, off Cap Ferrat (regularly observed since 2007), and off Cap Martin (2010), always between 30 and 40 m depth.

#### Sargassum acinarium (Linnaeus) Setchell

*Sargassum acinarium* usually grows in the sublittoral zone at several dozen meters depth. Some historical records were cited under the names: *S. linifolium* C. Agardh, and *S. vulgare* var. *linifolium* (C. Agardh) Zanardini.

The first record of the species dates back to 1821 at Cannes (Raphélis, 1907). In the 19<sup>th</sup> century, the species was collected at Cannes (Raphélis, 1907; Sarato *in* Raphélis, 1924c), Golfe-Juan (Raphélis, 1907), Antibes (Thuret Herbarium; Bornet & Flahault 1883), Nice (Algues Vertes Herbarium, Risso *in* Requien Herbarium; Algues Vertes Herbarium; Sarato *in* Raphélis, 1924c) and Menton (Bonfils *in* Raphélis 1924b). In the 20<sup>th</sup> century the species was collected as drift at Saint-Jean-Cap-Ferrat in 1910 and at Cannes in 1926 (Raphélis in Général Herbarium) (Table S15).

We found a single drift fertile specimen cast ashore on a beach of Larvotto (Monaco) in 2007.

#### Sargassum hornschuchii C. Agardh

*Sargassum hornschuchii* usually grows in the sublittoral zone at several dozen metres depth. The first specimen was collected in 1821 at Cannes (Raphélis, 1907). A few specimens were collected in the 19<sup>th</sup> century at Cannes (Raphélis in Général Herbarium; Raphélis, 1907), Antibes (Sauvageau Herbarium), and Villefranche-sur-Mer (Algues Vertes Herbarium). In the 20<sup>th</sup> century, *S. hornschuchii* was collected at Théoule-sur-Mer (Raphélis *in* Général Herbarium), Cannes (Raphélis *in* Général Herbarium), Antibes (J. Feldmann Herbarium), Villefranche-sur-mer (J. Feldmann *in* Hamel, 1931-1939) and Cap-Ferrat (J. Feldmann herbarium; J. Feldmann: carnet de récolte) (Table S16).

We did not find this species during our surveys.

#### Sargassum trichocarpum J. Agardh

Sargassum trichocarpum has been quoted by Raphélis (1907) as Sargassum boryanum Montagne. It was found in a fishing net, off Cannes. In the synonymy, Raphélis (1907) included S. salicifolium Bory, which is considered to be the very common S. vulgare. Raphélis' specimen was not located in his herbarium. Therefore, we consider this record as a probable misidentification, as doubt arises both from the proposed synonymy as well as the fact that this species has never previously been collected in France in natural habitats.

#### Sargassum vulgare C. Agardh

Sargassum vulgare grows in rock pools, on moderately wave-exposed rocks, and in the sublittoral zone down to ca. 40 m depth. Some historical records were cited under the names: Sargassum salicifolium auctorum (non Montagne) and S. megalophyllum Montagne.

The species was first mentioned as *S. salicifolium* Bory at Antibes (Agardh, 1842) and the first voucher specimen dates from 1849 as *S. vulgare* (Saint-Charles Herbarium). In the 19<sup>th</sup> century, the species was collected and observed at Cannes (Raphélis *in* Général Herbarium, Lenormand in Général Herbarium), Antibes (Saint-Charles Herbarium, Flahault Herbarium, Villa Thuret Herbarium; Agardh, 1842) and Nice (Hamel, 1931-1939, from De Notaris).

In the first half of the 20<sup>th</sup> century, observations of the species were made at Cannes (Raphélis & Séraillier in Général Herbarium; Raphélis, 1907, 1924a), Nice (Camous, 1912) and Saint-Jean-Cap-Ferrat (Raphélis in Général Herbarium). In the second half of the 20<sup>th</sup> century, the species was collected at Juan-les-Pins (Meinesz Herbarium), Nice (Meinesz Herbarium), Villefranche-sur-Mer (Magne Herbarium; Meinesz Herbarium; Hamel, 1931-1939 from J. Feldmann), Beaulieu-sur-Mer (De Reviers Herbarium; Meinesz Herbarium) and Monaco (Meinesz Herbarium). In 2000, one of us (T. Thibaut) observed a large population at Carnoles (Roquebrune-Cap-Martin) in a shallow bay, off a beach, growing on pebbles. Individuals were tall (around 50 cm height) and numerous, covering several dozen square metres. A year later, these populations had disappeared. Thereafter, a few small scarce individuals were sampled in a rock pool at Pointe Sainte-Hospice (Saint-Jean-Cap-Ferrat) (Herbarium T.

Thibaut), Pointe Bacon, Antibes, at 20 m depth (Herbarium Meinesz), Larvotto, Monaco at 31 m depth, and Cap Martin, at 30 m depth (Herbarium T. Thibaut) (Table S17).

During the field study, we regularly observed a few specimens of *S. vulgare* at Pointe Sainte Hospice (Saint-Jean-Cap-Ferrat), at Pointe de L'Ilette (Antibes), and on the dykes in Monaco.

#### Taxa excludenda

Cystoseira dubia Valiante was recorded in 1992 in Monaco at 43 m depth (Fredj et al., 1993). This determination, made by a non-specialist, is doubtful as this rare Mediterranean species is hitherto unknown in France and the record was only based on a video observation. Raphélis (1907) mentioned several species of the genera Cystoseira and Sargassum that constitute obvious misidentifications: Cystoseira corniculata (Turner) Zanardini, C. baccata (S.G. Gmelin) P.C. Silva (as C. fibrosa (Hudson) C. Agardh), an Atlantic species, C. squamosa Kützing, a possible misspelling for C. squarrosa and Sargassum natans (Linnaeus) Gaillon (as S. bacciferum (Turner) C. Agardh), an Atlantic species (Guiry & Guiry 2014). Camille Sauvageau, who examined the Raphélis herbarium, left a manuscript letter kept with it, casting doubt on most of Raphélis' determinations.

#### Discussion

#### The loss of species

The Mediterranean treatment of the genera *Cys*toseira and *Sargassum* differs according to the authors (Ribera *et al.*, 1992; Gómez Garreta *et al.*, 2000; Coll *et al.*, 2010; Draisma *et al.*, 2010; Cormaci *et al.*, 2012; Rožić *et al.*, 2012; Guiry & Guiry, 2014). The taxonomy of these genera is complex and progress will depend on molecular studies unravelling the relationships between the species, varieties and forms.

On the French Riviera, 15 and 3 taxa of Cystoseira and Sargassum were reported, respectively (if the taxa excludenda are not taken into consideration). If we compare the historical data with the '2007-2013' distribution, the decline in the number of species is real although far from conspicuous: 5 species were no longer observed (C. elegans, C. foeniculacea f. latiramosa, C. squarrosa, C. spinosavar. spinosa and S. hornschuchii) while C. jabukae, previously unrecorded, was observed. In addition to these taxa, probably extinct at the scale of the French Riviera, 9 other taxa suffered a decline (C. amentacea, C. barbata f. barbata, C. brachycarpa, C. crinita, C. sauvageauana and S. vulgare) or became nearly extinct (C. foeniculacea f. tenuiramosa, C. spinosa var. compressa and S. acinarium) (Table 2). In the past, four of them (C. barbata f. barbata, C. brachycarpa, C. crinita, C. spinosa var. *compressa*) played a significant functional role in the Mediterranean sublittoral reef ecosystem with large pho-

Taxon	Before 1950	After 1950	Current	Comment
Cystoseira amentacea	Very common	Very common	Very common	Slight decline
C. baccata	Record (mis-id.)	?	Absent	Excludendum
C. barbata f. barbata	Common	Less common	Very rare	Dramatic decline
C. brachycarpa	Common	?	Rare	Decline
C. compressa subs. compressa	Very common	Very common	Very common	Stable
C. compressa subs. pustulata	Rare?	?	Rare	Stable?
C. corniculata	Record (mis-id.)	?	Absent	Excludendum
C. crinita	Common	Rare	Very rare	Dramatic decline
C. dubia	?	Record (mis-id.)	Absent	Excludendum
C. elegans	Very rare	Very rare	Absent	Locally extinct
C. fibrosa	Record (mis-id.)	?	Absent	Excludendum
C. foeniculacea f.latiramosa	Very rare	?	Absent?	Stable?
C. foeniculacea f. tenuiramosa	Common	Rare	Very rare	Locally near Extinct
C. jabukae	?	?	Very rare	Stable?
C. sauvageauana	Common	Rare	Relatively rare	Decline
C. squarrosa	Very rare	?	Absent	Locally extinct
C. spinosa var. spinosa	Common?	?	Absent	Locally extinct
C. spinosa var. compressa	Common	Very rare	Very rare	Dramatic decline
C. zosteroides	Rare	Rare	Rare	Stable
Sargassum acinarium	Common	?	Very rare	Dramatic decline
S. hornschuchii	Rare	?	Absent	Locally extinct?
S. natans	Record (mis-id.)	?	Absent	Excludendum
S. trichocarpum	Record (mis-id.)?	?	Absent	Excludendum
S. vulgare	Common	Common?	Rare	Decline
Number of taxa (not excludenda)	17	10	13	

Table 2. Status of the Cystoseira and Sargassum taxa along the French Riviera coasts over time. Mis-id: probable misidentification.

tophilous seaweeds (Molinier, 1960; Ballesteros I Sagarra, 1992; Sala *et al.*, 2012); on this basis, we can claim that they are functionally extinct, i.e. the reduced population no longer plays a significant role in ecosystem functioning (Sala & Knowlton, 2006). The Mediterranean Fucales belong to perennial species that structure the habitats. Their tolerance to disturbances (Ecological plasticity) varies according to the species (Orfanidis *et al.*, 2011). Certain species such as *C. barbata, C. compressa* or *S. vulgare* have higher ecological plasticity than others. However, along the French Riviera, only one taxon, namely *C. compressa* subsp. *compressa*, which was very common in the past, is still very common and can therefore undoubtedly be considered as stable over the last two centuries.

The question is, how reliable is the overview of the situation of *Cystoseira* and *Sargassum* species along the French Riviera coastline presented here? The baseline, consisting of a large number of collectors who published their data or left extensive herbariums, is probably biased, at least as regards deep water species, i.e. *C. foeniculacea* f. *tenuiramosa, C. spinosa* var. *compressa* and *Sargassum* spp. Most of these collectors did not dive (whether snorkelling or scuba diving). Indications of abundance, often based on a few access points to the sea, or on casual records in

fishing nets or grapnels, must be considered with caution (see Coleman & Brawley, 2005, for a thorough discussion on problems with herbarium specimens). With regard to the shallow water species, historical data are probably more reliable. As regards species that were so common and thus easy to collect, despite the poor means available, for which our thorough and comprehensive exploration, lasting six years and using the whole range of modern methods and tools, all year round, resulted in a very limited number of sightings, it is unrealistic to claim that the decline could be due to sampling bias. In addition, in other areas (such as eastern Provence and Corsica), using the very same protocol, we had no difficulty in reporting the conspicuous abundance of species, such as *C. brachycarpa, C. crinita* and *C. barbata* (results not shown).

#### Possible causes of decline

Why such a near-total loss? The possible causes of the decline of Fucales along the French Riviera are multiple and cumulative, but some have yet to be clearly identified.

The most severe probable cause of decline is habitat destruction; in the French Riviera and Monaco, 19% and 88% of the shallow waters between 0 and 10 m depth ,

respectively, have been irremediably destroyed by road enlargement, ports, dykes, jetties, embankments, artificial beaches, urbanization and airport construction (Meinesz et al., 2013). The most severely impacted species are shallow water species such as C. barbata f. barbata and C. crinita, the populations of which have been destroyed, especially because of port constructions or enlargements at Cannes, Golfe-Juan, Antibes, Nice, Saint-Jean-Cap-Ferrat, Beaulieu-sur-Mer and Roquebrune-Cap-Martin. The population of C. squarrosa, located at the entrance of the port of Nice, has been destroyed by port enlargement. *Cystoseira amentacea* is the least severely impacted by habitat destruction because of its dwelling under exposed conditions. However, in some areas, C. amentacea has experienced major losses in relation to habitat destruction: widening of the road in the 1950's on the Italian border; widening of the road to Eze-sur-Mer around 1975 and construction of the port in 1969 at Beaulieu-sur-Mer; port, embankments and artificial beaches in Monaco from 1963 to 2002; enlargement of the port and construction of an embankment in Le Lido in 1972, Saint-Jean-Cap-Ferrat (Meinesz et al., 2013) (Table 3). These losses represent c.a. 6.5 km of shoreline compared to 44 km of living populations mapped during this study. Other populations of C. amentacea have probably been lost through coastal urban development and port enlargements at Mandelieula-Napoule, Cannes, Antibes and Nice.

In contrast with habitat destruction, pollution appears to be a less important cause of decline with regard to C. amentacea, in contrast to observations from other Mediterranean areas (e.g. Arnoux & Bellan-Santini, 1972). It is only in the immediate vicinity of port facilities and fish farms (sources of pollution) that C. amentacea has been replaced by Corallina spp. or C. compressa subsp. compressa. Ollivier (1929) noticed that the species was not impacted by sea surface outfall of untreated sewage located at Cap-Ferrat. Since the 1990s, the sewage of the French Riviera cannot impact C. amentacea because of the location of outlets between 20 and 100 m depth and the setting up of sewage treatment plants (Agence de l'Eau Rhône Méditerranée & Corse, 2014). Trace metal contamination could have also impacted the survival of C. barbata f. barbata and the growth of C. crinita, as reported by Sales et al. (2011).

It is now well known that overgrazing by the sea urchins *Paracentrotus lividus* and *Arbacia lixula* is a cause of decline of the sublittoral species of *Cystoseira* and *Sargassum* (e.g. Cormaci & Furnari 1999; Thibaut *et al.*, 2005; Serio et *al.*, 2006. *Paracentrotus lividus* is known to feed preferentially on these erect macrophytes, while *A. lixula* feeds on plantlets and prevents new settlement (Verlaque & Nédélec 1983; Verlaque 1984; Knoepfler-Péguy *et al.*, 1987; Frantzis *et al.*, 1988; Hereu *et al.*, 2008a). The major causes of the spread of sea urchins are the reduction of populations of sea urchin predators (mainly Labridae and Sparidae) due to overfishing (e.g. Sala *et al.*, 1998; Hereu

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Reference	Concerned area	Difference (%)		
Ollivier, 1929	Eze-sur-Mer to Cap Martin	-24.8		
Guglielmi, 1969	Beaulieu-sur-Mer to Saint-Jean-Cap- Ferrat	-29.9		
Meinesz et al. 2000	Coastline of Nice	-3.8		

2006; Hereu et al., 2005, 2008a) and regulation of sea urchin harvesting. On the French Riviera, the harvesting of *P. lividus* is regulated by period (banned for  $\sim 6$  months) and quantity (up to 120 individuals/ person<sup>-1</sup> d<sup>-1</sup>) (DIRM Méditerranée, 2014). Arbacia lixula is not collected because of a low organoleptic value. Depletion of Cystoseira and *Sargassum* by the teleost *Sarpa salpa* (Linnaeus 1758) has also been documented (Thibaut et al., 2005; Vergés et al., 2014). On the French Riviera, this species is rarely fished because of low interest by consumers. On the French Riviera, loss due to the alien herbivorous fishes Siganus luridus (Rüppel 1829) and S. rivulatus (Forsskål & Niebuhr 1775), as observed in the eastern Mediterranean Sea (Sala et al., 2011; Bianchi et al., 2014), is currently unlikely, even if a school of dozens of individuals of Siganus sp. has been observed once in the Bay of Villefranche-sur-Mer in 2012 (Heike Molenaar, pers. comm.).

Competition with two invasive macroalgae, *Cauler-pa taxifolia* (Vahl) C. Agardh and *C. cylindracea* Sonder, which are extensively present along the French Riviera coastline, over a wide depth range and with high cover rate, can also contribute to outcompeting *Cystoseira* spp. (Verlaque & Fritayre, 1994a,b; Boudouresque *et al.*, 1995; Boudouresque, 1997; Ferrer *et al.*, 1997; Rollino *et al.*, 2001; Piazzi & Ceccherelli, 2006).

Collection by scientists and students in rock pools at Pointe de Colombier at Saint-Jean-Cap-Ferrat may also be blamed. There, one of the main sites of the French Riviera for *C. barbata* f. *barbata* and *C. sauvageauana* was steadily pillaged to total depletion by various phycologists during a course in phycology at the University of Nice. The same occurred in the rocks pools at Collioure (French Catalonia) where several species of *Cystoseira* have been extirpated by 5 decades of extensive collecting (Thibaut *et al.*, 2005).

Concerning the deep water species, the maps of benthic assemblages (Meinesz *et al.*, 1994, 2000; Belsher & Houlgatte, 2000, Francour *et al.*, 2003, Holon & Descamp, 2007, 2008; Leblond, 2010) and our survey did not show any large populations such as those reported in the National Park of Port-Cros (Hereu *et al.*, 2008b) and the MPA (Marine Protected Area) of Scandola (Ballesteros *et al.*, 2009). This could be due to fishing activities, as specimens are easily ripped by fishing nets and the increase in turbidity can affect the deep population (Thibaut *et al.* 2005; Hereu *et al.*, 2014). The extreme rarefaction of *C. spinosa* var. *compressa* versus *C. zosteroides* could be due to lower photosynthetic efficiency, which makes the former taxon sensitive to an increase in turbidity (Sant Funk, 2003).

#### Consequences

The loss of habitat structuring species is worrying. We are witnessing a typical regime shift with a replacement of macroalgal forests by less structured algal assemblages dominated by Halopteris scoparia, Padina spp., Dasycladus vermicularis, Cladostephus spongiosus, Laurencia spp. Dictyotales and Corallinales or by barren grounds dominated by encrusting species, filamentous algae and sea urchins. It is clear that vestigial isolated populations of Fucales have lost most of their functional role. Only few small and dispersed shallow water populations remain along the coasts of the French Riviera, i.e. 3 sites with C. barbataf. barbata, 4 with C. brachycarpa, 7 with C. crinita, 2 with C. foeniculacea f. tenuiramosa, 2 with C. jabukae and 4 with C. sauvageauana, along more than 212 km of coastline. We can consider that these habitat forming species (engineer species) are functionally extinct. In addition, the decline of Cystoseira species results in a decrease of benthic assemblage diversity (i.e. homogenization of seascapes).

For example, *Cystoseira brachycarpa*, which still grows in dense subtidal forests down to 15 m depth in undisturbed areas such as Corsica (Ballesteros *et al.*, 2002; Thibaut *et al.*, 2008; Sales & Ballesteros 2010; Cheminée, 2012), is known to be a nursery for some teleost species (Cheminée *et al.*, 2013); obviously, it no longer plays this role along the French Riviera.

#### Comparison with other Mediterranean areas

It is not the first time that similar local extinction of Fucales populations has been reported in the Mediterranean; C. foeniculacea (as C. ercegovicii), C. sauvageauana and C. spinosa in Mar Piccolo, Southern Italy (Cecere et al., 1991); C. dubia (as C. fucoides Ercegović), C. foeniculacea (as C. ercegovicii), and all the species of Sargassum in the Northern Adriatic (Munda, 1993); C. crinita, C. foeniculacea, C. humilis, C. spinosa, S. acinarium and S. hornschuchii at Tremiti Islands, Sicily (Cormaci & Furnari, 1999); C. brachycarpa, C. sauvageauana, C. spinosa, C. zosteroides, S. acinarium and S. trichocarpum at Linosa Island, off Tunisia (Serio et al., 2006); C. corniculata, C. foeniculacea f. tenuiramosa, C. spinosa, S. acinarium and S. hornschuchii along the Adriatic Italian coastline (Cecere et al., 2001; Falace et al., 2006); half of the species historically present in the Gulf of Naples were no longer collected (Buia et al., 2013); C. crinitophylla in the Gulf of Saronikos, Greece (Tsiamis et al., 2013); C. brachycarpa, C. corniculata, C. crinita, foeniculacea and S. vulgare at Kos Island, Greece (Bianchi et al., 2014). Finally, in French Catalonia, Thibaut

*et al.* (2005) reported the local extinction of 11 taxa out of 15 initially reported; only 2 species, *C. compressa* subsp. *compressa* and *C. mediterranea* (the vicariant species of *C. amentacea* in this region) were still abundant, the other species formed small and isolated populations without the functional role of habitat forming species.

It is surprising to note the total absence along the French Riviera of *C. funkii*, a deep-water species common in Provence and Corsica (Hereu *et al.*, 2008b). We did not dive deeper than 50 m, so we cannot exclude the possibility that some populations have been missed on isolated rocks and detritic bottoms. Information on the situation of deep water species is lacking and calls for further study.

#### **Conservation questions**

Despite the dramatic decline or local extinction of most *Cystoseira* and *Sargassum* species along most of the French Riviera coastline, we discovered a kind of small 'oasis' that harbours, along only 3 km of coast (from the port of Crouton to Pointe de L'illette; on the western side of Cap d'Antibes), 10 taxa, i.e. most of the surviving taxa in the study area. Unfortunately, this site does not belong to the EU Natura 2000 site of Cap d'Antibes (n° FR9301573). We suggest the inclusion of this area within the Natura 2000 site.

Most of the species of the genus *Cystoseira* are under protection within the framework of international conventions (Berne Convention, Barcelona Convention). Obviously, these conventions are far from sufficient in effectively protecting these species, not only on the French Riviera, but also at Mediterranean scale.

The causes of decline of Mediterranean Sargassaceae are multiple and act not only in a cumulative but also in a synergic way. Dynamics, vulnerability to disturbances and regime shift are well known for certain Cystoseira species (e.g. C. amentacea, C. brachycarpa, C. crinita and C. zosteroides) (e.g. Hereu et al., 2008a; Sales & Ballesteros, 2010; Sala et al., 2011, 2012; Sales et al., 2011; Maggi et al., 2012; Mangialajo et al., 2012; Cardona et al., 2013). For the other species, more long-term field surveys and experimental and physiological studies are required. To stimulate the natural restoration of lost populations, the setting up of MPAs is necessary but is probably not sufficient. The conservation of habitats, the improvement of sewage treatment systems and the limitation of sea urchin populations are also required. As far as *Sargassum* species are concerned, the presence of aerocysts allows the drifting of fertile fragments and their remote dispersal; thus, the recovery of lost populations from distant areas is possible. The best example is that of the rapid invasion of European coasts by the introduced species Sargassum muticum (Yendo) Fensholt (Critchley et al., 1990). In the case of Cystoseira species, similar recoveries can be expected for the taxa bearing aerocysts (i.e. C. barbata, C. compressa subsp.

compressa, C. foeniculacea). Some natural recoveries of Cystoseira species from nearby populations were reported in the Rovinj region (Croatia) (Hanel, 2002; Iveša et al., 2014). Such a phenomenon has never been reported in France. Whatever the species of Cystoseira, a natural recovery seems unlikely on the French Riviera because of the loss of suitable habitats, the small number of vestigial populations and the low dispersal range of Cystoseira zygotes (Susini, 2006). Transplantation has been suggested as a tool to improve the restoration of extinct populations. Techniques are available (Falace et al., 2006; Susini et al., 2007; Perkol-Finkel & Airoldi, 2010; Sales et al., 2011, Gianni et al., 2014). Attempts have been made on the French Riviera to restore small populations of C. barbata f. barbata, C. crinita, C. foeniculacea and S. vulgare at sites (Saint-Jean-Cap-Ferrat) known to have hosted Fucales in the past. However, the transplants never survived, due to waves, human presence and grazing pressure, even when the sea urchin P. lividus was removed prior to the experiment (Robvieux, 2013). These attempts, therefore, clearly question the usefulness of the restoration strategy in small areas subjected to multiple pressures. Restoring populations and their ecological functions makes sense only over a large area and within the framework of an integrated management policy.

#### Conclusion

Such a comprehensive exploration of costal habitats, over 7 years (2007-2013) along a significant stretch of coastline (~212 km, measured on a 1/2 500 map), has never before been undertaken in the Mediterranean Sea. In addition, the production of a check-list of all historical records, since the early 19<sup>th</sup> century, from both shallow and deep water habitats, made it possible to localize and thoroughly explore historical habitats. As a result, the non-observation of a species, or its scarcity, enables us to conclude with reasonable certainty, at least for shallow water species, on its extinction or near-extinction, respectively, along the French Riviera.

The worrying situation for the *Cystoseira* and *Sargassum* species on the French Riviera is far from being a local case, linked for example to exceptionally intensive human impact. Similar studies, although concerning less extensive areas, in other parts of the Mediterranean, ranging from west (Catalonia) to east (Greece) and from north (French Riviera) to south (Linosa, off Tunisia), all lead to the same conclusions. These species could, therefore, really be on the brink of extinction. Will their actual extinction be the next step? The local recoveries reported from the Adriatic Sea show that the decline can be stopped if we take immediate action to reduce disturbances (eutrophication, sea urchin populations).

Another question arises: is it the tip of an iceberg of local and functional species extinction? Fucales constitute good material for such a study: they are long-lived, large-sized, easy to observe year-round and relatively stable at sites where they are established. In contrast, most other Mediterranean macroalgae are more or less seasonal, often present a complex life-cycle with several phases that may be microscopic or encrusting (and therefore difficult to observe) and experience multi-annual phases of abundance and rarity. Phycologists do not worry when they fail to observe them for years, even decades. Could these less visible species actually be threatened in the same way, as being in fact the hidden part of the iceberg?

#### Nomenclatural note

In 1952, Ercegović described Cystoseira abrotanifolia subsp. pustulata Ercegović from the Adriatic Sea. Giaccone and Bruni (1972-1973) reduced this taxon to a heterotypic synonym of C. myriophylloides Sauvageau (= C. humilis Schousboe ex Kützing), a species described from Atlantic France (Sauvageau, 1912). Verlaque (1988) rejected this synonymy and reported the Ercegovic entity as 'Cystoseira compressa (Esper) Gerloff & Nizamuddin var. pustulata Ercegović' from Corsica. On the basis of a study of genuine Atlantic specimens of C. humilis from the Canary Islands, Spain and Morocco, we can confirm the distinction between the two taxa. In Cystoseira humilis, the axes are always cylindrical, the branches are never distichously inserted (thallus with pyramidal outline) and the cryptostomata are inconspicuous (branches smooth), whereas in Cystoseira compressa subsp. pustulata, the axes are frequently compressed at the basis, the branches are more or less distichously inserted in one plane and the cryptostomata are large and prominent (whence the name 'pustulata'). As we frequently observed, the taxon 'pustulata' in mixed populations with C. compressa subsp. compressa, cannot be considered as an ecotype. Given that the currently accepted name for C. abrotanifolia C. Agardh is C. compressa (Esper) Gerloff & Nizamuddin, we propose the ranking of subspecies and we validate, hereafter, the transfer of this entity from C. abrotanifolia to C. compressa.

## *Cystoseira compressa* subsp. *pustulata* (Ercegović) Verlaque comb. nov.

**Basionym**: *Cystoseira abrotanifolia* subsp. *pustulata* Ercegović (1952). *Fauna i Flora Jadrana. Jadranske cistozire. Njihova morfologija, ekologija i razvitak / Fauna et Flora Adriatica. Sur les* Cystoseira *adriatiques. Leur morphologie, écologie et évolution.* Vol. 2: 113, plates XXX, XXIVe,g. Syntype localities: Split, Lovište and Pelješcu, Croatia.

**Comment**: *Cystoseira epiphytica* Schiffner ex Gerloff & Nizamuddin (1976: 165-167, pls 1-3) was hitherto treated as a later heterotypic synonym of *C. humilis* (Guiry and Guiry, 2014). However, when Gerloff and Nizamuddin (1976) validated '*Cystoseira epiphytica* Schiffner' (nomen in sched.) from the Adriatic Sea, they specified: "*C. epiphytica resembles* C. compressa (*Esper*)

Gerloff and Nizam. in possessing flat, primary axes (if and when present)...", and "C. epiphytica appears to be nearer to C. abrotanifolia subsp. pustulata of Ercegović (1952) which has the similar arrangement of cryptostomata". In our opinion, the only difference between C. epiphytica and C. compressa subsp. pustulata is its epiphytic development on other species of Cystoseira, and we consider the two taxa as putative synonyms..

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