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11 Invasive Seaweeds: Impacts and Management Actions

11.1 Introduction

In the world, many alien species are seaweeds. Alien species have been reported for all the three taxonomical divisions, with Rhodophyta more than twice as much as both Ochrophyta and Chlorophyta (Williams & Smith, 2007), even though they are the least studied. The highest number of alien seaweeds has been reported in the Mediterranean, mainly coming from the Northwest Pacific and Indo-Pacific regions (Klein *et al.*, 2005; Williams & Smith, 2007).

Most alien seaweeds were accidentally introduced (Hewitt *et al.*, 2007), with only a small percentage introduced intentionally, mainly for aquaculture purposes in past times when knowledge of risks deriving from the introduction of alien species was low (Pickering *et al.*, 2007). Some species seem more likely to become invasive due to distinctive features (e.g. capacity for successful spread), but it is not always a sure thing that, once introduced, they will successfully establish in the new area or become harmful (Boudouresque & Verlaque, 2002b). For this reason, one seaweed species cannot be defined as invasive in an absolute sense (Inderjit *et al.*, 2006) and when invasive it can show different behaviours; that is, it may have diverse impacts in different areas and on different scales (Schaffelke *et al.*, 2006, Williams & Smith, 2007, Thomsen *et al.*, 2009a).

Since biological invasions by seaweeds can cause irreversible damage to the biodiversity, structure, and functioning of receiving ecosystems, once an introduced species is detected, the assessment of its real distribution and of its impact at each trophic level should be of primary importance in ecological studies (Bulleri *et al.*, 2012). The planning of either its possible eradication or its management should follow (Aguilar-Rosas *et al.*, 2013). However, the finding of an invasive species is often tardy compared with its arrival in a given environment, such that it can be difficult to disentangle its impact from other impacts due to pollution, climate change, or habitat destruction (Junqueira, 2013).

According to available literature, about 280 species of introduced seaweeds are currently present in the world's seas (Williams & Smith, 2007). The majority did not show any visibly high invasiveness until now (Johnson, 2007); after all, only few were deeply studied concerning their invasion patterns and impacts (Lyons & Scheibling, 2009), even though their capacity for invasion, even a long period after their introduction, was already known (Smith *et al.*, 2004).

The aim of this paper is to take stock of the situation regarding the distribution and impact of three of the most spread invasive seaweeds around the world, one for each taxonomic division: the chlorophycean *Codium fragile* (Suringar) Hariot ssp. *fragile*, the rhodophycean *Gracilaria vermiculophylla* (Ohmi) Papenfuss, and the phaeophycean *Undaria pinnatifida* (Harvey) Suringar.

Information about the most common vectors of introduction of alien seaweed species, management actions, as well as the present laws regulating the transfer of imported organisms and possible precautionary measures were also analysed.

11.2 Most Widespread Invasive Seaweeds

11.2.1 *Codium fragile* ssp. *fragile* (Chlorophyta, Bryopsidales) (Figure 11.1)

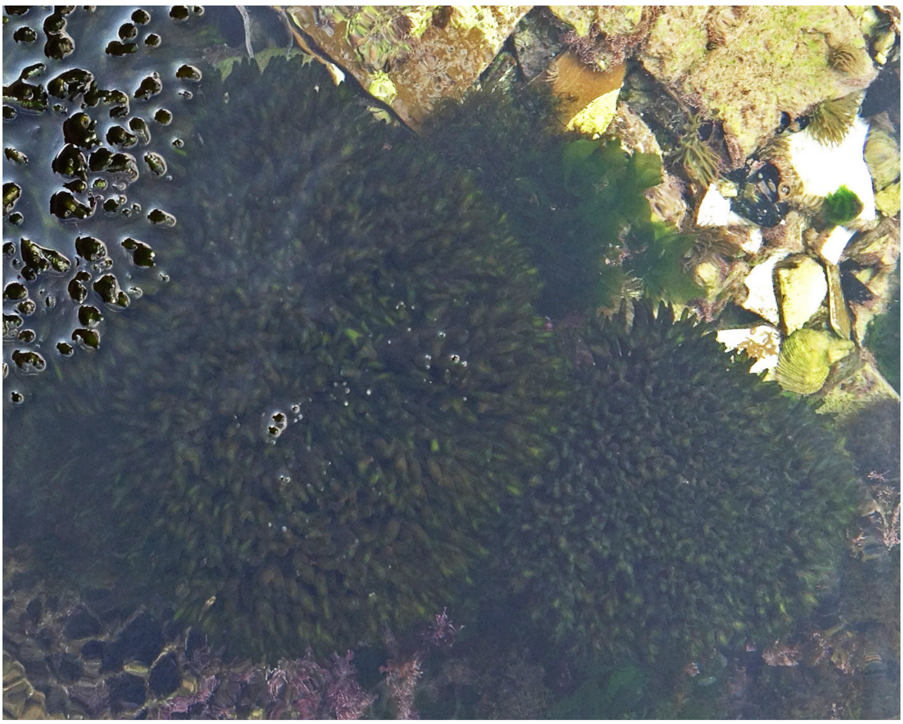

Fig. 11.1: Thallus of *Codium fragile* ssp. *fragile* in the Mar Piccolo of Taranto. 1 cm = 6 mm.

Codium fragile ssp. *fragile* (hereafter *C. fragile*) is a worldwide introduced species (Provan *et al.*, 2005) (Figure 11.2). It ranks first among the top five hazardous invasive seaweeds, due to dispersal and establishment ability as well as ecological and economic impact (Nyberg & Wallentinus, 2005; Provan *et al.*, 2005). Its possible impacts vary from the reduction of biodiversity in the invaded communities to fouling of fishing gear and damage to shellfish aquaculture activities (Bridgwood, 2010) (Table 11.1). One of the nicknames of *C. fragile* is “oyster thief”, because it commonly fouls shellfish and can sweep them away, causing considerable economic losses (Trowbridge, 1999). In Chile, the invasion of *C. fragile* caused substantial economic damage to seaweed farms, since alien thalli remained entangled with cultivated plants of *Gracilaria chilensis* Bird, McLachlan et Oliveira causing them to sink before harvesting. The burden of work and time imposed by having to remove the invader even bankrupted a farm (Neill *et al.*, 2006). In Nova Scotia, a marked competition with local seaweed species, mainly kelp, was observed: the presence of well-structured kelp communities did not allow *C. fragile* settlement, while dense populations of *C. fragile* prevented kelp settlement (Scheibling & Gagnon, 2006). In a lagoon in Eastern Canada, a negative impact of *C. fragile* on the eelgrass *Zostera marina* Linnaeus was observed in manipulative experiments: higher *C. fragile* biomass values matched lower density of eelgrass shoots and lower values of leaf length. However, the observations performed in the field did not support the entirety of the experimental results (Drouin *et al.*, 2012).

Tab. 11.1: Impact (positive or negative) of the alien seaweeds *Codium fragile*, *Gracilaria vermiculophylla* and *Undaria pinnatifida* on biodiversity, structure and function of ecosystems or economic. O = observed; E = experimental; S = supposed.

Species	Impact	Locality	Reference
Codium fragile			
O	negative, economic: ”oyster thief” fouling and sweeping of reared shellfish	Australia	Trowbridge, 1999
O	negative, biodiversity: replacement of native canopy species	Atlantic Ocean, Gulf of Maine, USA	Harris & Tyrrel, 2001
E	negative, biodiversity and functioning: death of fed sea-urchins	Atlantic Ocean, Nova Scotia, Canada	Scheibling & Anthony, 2001
O	negative, structure: reduction of kelp abundances	Atlantic Ocean, Canada	Chapman *et al.*, 2002
O, E	negative, biodiversity: replacement of native kelps	Atlantic Ocean, Gulf of Maine, USA	Levin *et al.*, 2002
O, E	negative, biodiversity and structure: “eelgrass thief” removing shoots and rhizomes of Z. marina	Atlantic Ocean, Prince Edward Island and Nova Scotia, Canada	Garbary *et al.*, 2004

continued **Tab. 11.1:** Impact (positive or negative) of the alien seaweeds *Codium fragile*, *Gracilaria vermiculophylla* and *Undaria pinnatifida* on biodiversity, structure and function of ecosystems or economic. O = observed; E = experimental; S = supposed.

Species	Impact	Locality	Reference
O, E	positive, biodiversity and functioning: favouring of mussel recruitment	Mediterranean Sea, Adriatic Sea, Italy	Bulleri *et al.*, 2006
O	negative, economic: decrease of cultivated Gracilaria chilensis yeld	Pacific Ocean, Chile	Neill *et al.*, 2006
E	negative, biodiversity and structure: prevention of kelp colonization	Atlantic Ocean, Nova Scotia, Canada	Scheibling & Gagnon, 2006
E	negative, biodiversity and structure: decrease of eelgrass shoot density	Atlantic Ocean, Canada	Drouin *et al.*, 2012
Gracilaria vermiculophylla			
O	positive, biodiversity: increase of filamentous seaweeds	Atlantic Ocean, Virginia, USA	Thomsen *et al.*, 2006
O	positive, biodiversity: increase of animal abundances	Kattegat, Sweden	Nyberg *et al.*, 2009
O	positive, biodiversity: increase of animal abundances	Atlantic Ocean, Virginia, USA	Nyberg *et al.*, 2009
E	negative, biodiversity and function: survival of Z. marina	Baltic Sea, Isle of Fyn, Denmark	Martínez-Lüscher & Holmer, 2010
E	positive, biodiversity: increase of associated fauna	Baltic Sea, Denmark	Thomsen, 2010
S	positive, economic: production of good quality food grade agar	Atlantic Ocean, Portugal	Villanueva *et al.*, 2010
E	positive, function and economic: bioremediation	Atlantic Ocean, Portugal	Abreu *et al.*, 2011
E	positive, biodiversity and structure: enhancement of epifaunal densities	Atlantic Ocean, Georgia and South Carolina, USA	Byers *et al.*, 2012
E	positive, structure and function: fostering survival of native blue crab	Atlantic Ocean, Chesapeake Bay, USA	Johnston & Lipcius, 2012
E	negative, biodiversity and structure: grazer avoidance against native species	Baltic Sea, Denmark	Nejrup *et al.*, 2012
E	negative, biodiversity and structure: reduction of native Fucus growth	Baltic Sea, Kiel Fjord, Germany	Hamman *et al.*, 2013a
E	positive, biodiversity: increase of invertebrates abundance	Odense Fjord, Denmark	Thomsen *et al.*, 2013

continued **Tab. 11.1:** Impact (positive or negative) of the alien seaweeds *Codium fragile*, *Gracilaria vermiculophylla* and *Undaria pinnatifida* on biodiversity, structure and function of ecosystems or economic. O = observed; E = experimental; S = supposed.

Species	Impact	Locality	Reference
O	positive, structure: increase of egg capsule deposition of invertebrates	Atlantic Ocean, Rhode Island, USA	Guidone *et al.*, 2014
E	positive, structure and function: reduction of predation on invertebrates	Atlantic Ocean, Georgia, USA	Wright *et al.*, 2014
Undaria pinnatifida			
O	negative, biodiversity and structure: decrease of native species total cover	Mediterranean Sea, Venice, Italy	Curiel *et al.*, 2001
O	positive, biodiversity: increase of refuges for cryptic fauna	Mediterranean Sea, Mar Piccolo of Taranto, Italy	Cecere *et al.*, 2003
E	negative, biodiversity: decrease of native seaweed species richness	Atlantic Ocean, Nuevo Gulf, Argentina	Casas *et al.*, 2004
E, S	positive, function and economic: bioremediation	Atlantic Ocean, Patagonia, Argentina	Torres *et al.*, 2004
E	neutral, biodiversity and structure: no variation in associated flora and fauna	Atlantic Ocean, Cracker Bay, Argentina	Raffo *et al.*, 2009
O	negative, biodiversity and structure: reduction of rocky-reef fishes	Atlantic Ocean, Nuevo Gulf, Argentina	Irigoyen *et al.*, 2011a
O	negative, economic: obstruction of the entrance of fish holes	Atlantic Ocean, Nuevo Gulf, Argentina	Irigoyen *et al.*, 2011a
E	positive, biodiversity and structure: increase of invertebrate species richness	Atlantic Ocean, Nuevo Gulf, Argentina	Irigoyen *et al.*, 2011b
O	negative, economic: obstacle for local navigation	Mediterranean Sea, Venice, Italy	Sfriso & Facca, 2013

By contrast, the interaction between *C. fragile* and *Mytilus galloprovincialis* Lamarck on artificial structures dipped in the Adriatic Sea showed a benign effect. The presence of both germlings and canopy of the macroalga favoured the settlement of the mussel recruits, while on the bare surfaces the number of these recruits was much lower. Contrarily, the presence of a well-developed mussel bed reduced the abundance of *C. fragile* (Bulleri *et al.*, 2006).

Fig. 11.2: Worldwide distribution of *Codium fragile* ssp. *fragile*. Green star indicates the type locality; green circles indicate native distribution; red circles indicate alien distribution.

In the Mar Piccolo of Taranto (southern Italy, Mediterranean Sea), a small number of thalli of *C. fragile* were found for the first time in July 2002 and successively in 2003, in a zone characterised by the presence of several seafood shops. No other thalli were found until 2009, when a new finding was registered in the same zone, possibly due to a new introduction event. Since then, only a few thalli have appeared on pebbles in the same zone each summer with no negative impact (Petrocelli *et al.*, 2013).

Several features could justify the high invasiveness of *C. fragile* around the world:

1. High tolerance to chemical-physical variability (Thomsen & McGlathery, 2007);
2. Sexual, vegetative, and parthenogenetical reproduction (Bridgwood, 2010);
3. Opportunistic behaviour. In its native region, where the dominant species were removed, *C. fragile* predominated as a canopy-forming species; where the canopy species were well developed, it was an understory species (Chavanich *et al.*, 2006);
4. High dispersal potential. Notwithstanding the absence of specialised structures for floating, *C. fragile* thalli have a notable capacity for buoyancy due to the accumulation of gas bubbles deriving from the photosynthetic process within the thallus, particularly at the tip level (Gagnon *et al.*, 2011). Laboratory experiments showed that *C. fragile* (as *C. fragile* ssp. *tomentosoides*) can live up to 90 days of emersion in a dry environment, entangled on anchors or fishing nets during vessel travel, recovering its photosynthetic capacity after re-submersion (Schaffelke & Deane, 2005). Moreover, besides easily spreading through man-mediated activities, *C. fragile* can also spread naturally through drifting vegetative thallus fragments, buds, and

detached fertile thalli. Due to the capacity for reattachment of these structures, the species can colonize new areas at great distances from the initial introduction site. The presence of turf algae enhances their settlement (Watanabe *et al.*, 2009);

5. Unpalatability for most grazers. The production of dimethylsulfoniopropionate and its derivatives, experimentally determined in *C. fragile* (as var. *tomentosoides*) from Nova Scotia, favours the alien's success by reducing its palatability for sea urchins (Lyons *et al.*, 2007). A partial natural control by the snail *Littorina littorea* (Linnaeus, 1758) on *C. fragile* populations was observed. The snail actively grazed on the alien seaweed, but only on new plantlets and residual basal parts, damaging thalli growth; adult healthy thalli did not suffer this grazing (Scheibling *et al.*, 2008).

A genetic molecular analysis was performed on the plastid genome of *C. fragile* (as ssp. *tomentosoides*) collected in the native range in Japan as well as the Mediterranean, Northern Europe, North Atlantic, and South Pacific. It showed that the spread of this invasive species was due to two different introduction events, one into the Mediterranean and the other to the rest of the world. Therefore, only two alien haplotypes are present worldwide (Provan *et al.*, 2005).

Presumably, *C. fragile* was mainly introduced around the world through the importation of shellfish, but also through fouling of ships and boat hulls as a possible vector (GISD, 2014).

Eradication of *C. fragile* was not effective in Australia, either by chemical methods or by manual removal (Trowbridge, 1999). No other attempt has been performed anywhere in the world, since the morphological and physiological features of the species would surely have made them unsuccessful (GISD, 2014).

11.2.2 *Gracilaria vermiculophylla* (Rhodophyta, Gracilariales) (Figure 11.3)

Fig. 11.3: Thallus of *Gracilaria vermiculophylla* in the Venice Lagoon (courtesy of A. Sfriso). 1 mm = 3 mm.

Gracilaria vermiculophylla is native to East Asia, and in less than two lustra invaded the coasts of other continents such as Europe, North America and, recently, North Africa (Figure 11.4). It became one of the main invasive seaweeds, especially in estuarine and lagoon environments, where it commonly lives unattached, partially embedded in the mud, and less frequently as attached (Kim *et al.*, 2010; Abreu *et al.*, 2011; Sfriso *et al.*, 2012; Hammann *et al.*, 2013b). In two years, *G. vermiculophylla* spread for about 150 km along the Swedish coasts, with a larger expansion range than other invasive seaweeds, such as *U. pinnatifida* and *Sargassum muticum* (Yendo) Fensholt, neither of which reached 50 km per year (Nyberg *et al.*, 2009).

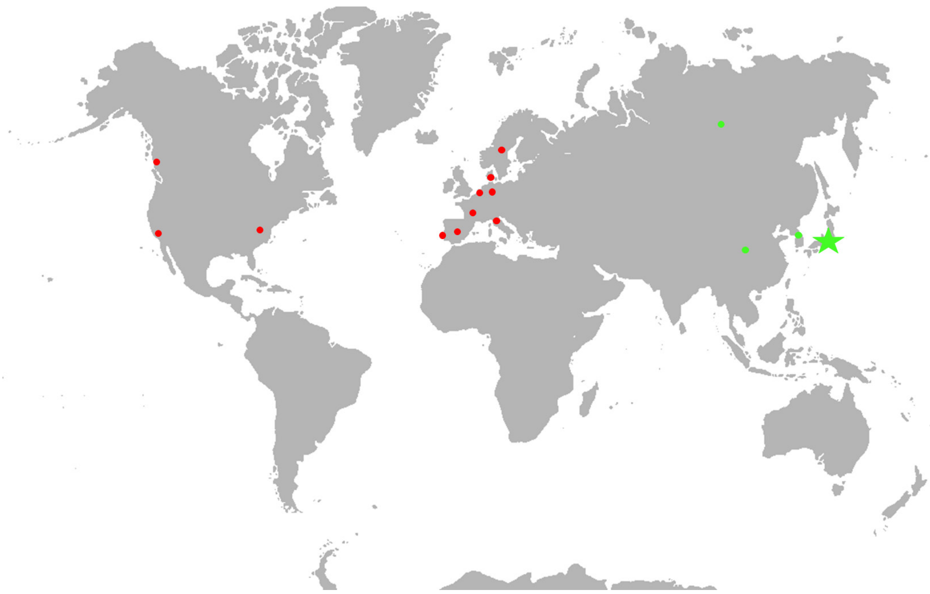

Fig. 11.4: Worldwide distribution of *Gracilaria vermiculophylla*. Green star indicates the type locality; green circles indicate native distribution; red circles indicate alien distribution.

A recent review summarized the main impacts recorded after *G. vermiculophylla* invasions around the world (Hu & Juan, 2014) (Table 11.1). In the Baltic Sea, considerable unattached biomasses of *G. vermiculophylla* drifted on soft bottoms, so high interference with both the settlement of plantlets and the growth of adults of native *Fucus vesiculosus* Linnaeus occurred. Moreover, *Gracilaria vermiculophylla* threatened *F. vesiculosus*'s survival, giving hospitality to grazers greedy for this species (Hammann *et al.*, 2013a). In Danish coastal communities, both field observations and lab experiments showed that the prevalence of *G. vermiculophylla* was promoted by the lack of grazing by local herbivores, which preferred the short-lived Ulvales. *G. vermiculophylla* may produce secondary metabolites that deter grazer activity (Nejrup *et al.*, 2012). Mesocosm experiments showed that the presence of considerable biomasses of *G. vermiculophylla* reduced net photosynthesis of *Z. marina* leaves (Martínez-Lüscher & Holmer, 2010). Considering that successive lab experiments showed a high sensitivity of *Z. marina* growth to high temperature (Hoffle *et al.,* 2011), it was hypothesised that, in a future warmer world, the combined effect of higher temperatures and *G. vermiculophylla* presence could cause eelgrass disappearance (Hoffle *et al.,* 2011).

However, some cases of positive impacts of this alien on biodiversity were also recorded. Field experiments demonstrated a positive influence of *G. vermiculophylla* on the faunal assemblages in a *Z. marina* meadow in Denmark, probably through the increase of refuges from predators, of food for herbivores, and of attachment space for epibionts (Thomsen, 2010). In Swedish waters, a high diversity of associated fauna and flora was observed on both attached and unattached biomass of *G. vermiculophylla* (Nyberg *et al.*, 2009). In the Adriatic Sea, association with molluscs, tunicates, and worms was reported (Sfriso *et al.*, 2012). The presence of *G. vermiculophylla* in a lagoon in Virginia (USA) proved to be beneficial for overall local biodiversity. In particular, the biomass of epiphytic filamentous algal species positively correlated with that of this alien seaweed, which served as a hard substratum for the attachment in a place characterised by soft bottoms (Thomsen *et al.*, 2006). Moreover, the invasive *G. vermiculophylla* in Ria de Aveiro (Portugal) was found to produce a good quality of food grade agar (Villanueva *et al.*, 2010). Therefore, in the case of the eradication of threating biomasses, a useful by-product could be obtained.

Gracilaria vermiculophylla adapts well to estuarine and lagoon conditions due to (Nyberg & Wallentinus, 2009; Abreu *et al.*, 2011):

1. Tolerance to high variation in salinity and temperature. Experiments carried out in Denmark, with variously combined values of light and temperature, showed that *G. vermiculophylla* responds with great plasticity to these variations, reaching high growth rates. This could explain its recent spread in the Scandinavian waters (Nejrup *et al.*, 2013);
2. Capacity to grow well on muddy and sandy bottoms;
3. Capability of surviving long periods of darkness;
4. Ability to vegetatively propagate through thallus fragmentation;
5. Resistance to grazing and desiccation.

The low palatability of the alien plants of *G. vermiculophylla* for *Littorina littorea* could explain the success of this species in Germany (Hammann *et al.*, 2013b).

Japanese oysters have been considered the main vector for the introduction of *G. vermiculophylla* into Western Atlantic waters; but, the vicinity of harbours to several zones of first observation suggests that shipping from Japan, Korea and Russia may also have acted as a source (Kim *et al.*, 2010). Indeed, from the results of molecular analysis, it is clear that multiple introductions from different geographical areas have occurred (Gulbransen *et al.*, 2012). For Swedish waters, a likely vector of introduction could have been the dredges used for the excavation of the Gothenburg harbour chartered from the Netherlands (Rueness, 2005). In the lagoons of the North Adriatic Sea (Italy), *G. vermiculophylla* was most probably introduced through the importation of the Manila clam *Venerupis philippinarum* (Adams & Reeve, 1850). Afterwards, high nutrient concentrations and moderate salinity were the environmental factors that most likely favoured its establishment and spread (Sfriso *et al.*, 2012). *Gracilaria vermiculophylla* was also observed in the unattached form in some salt marshes in Virginia (USA), where seaweeds are typically absent. Its most likely origin was from nearby lagoons, where it lives in tight association with the tubeworm *Diopatra cuprea* (Bosc, 1802) (Thomsen *et al.*, 2009b). No information about any attempt of *G. vermiculophylla* eradication is available to date.

11.2.3 *Undaria pinnatifida* (Ochrophyta, Laminariales) (Figure 11.5)

Fig. 11.5: Thallus of *Undaria pinnatifida* from the Mar Piccolo of Taranto. 1 cm = 1.7 cm.

Undaria pinnatifida is native to Japan. It has been introduced along the coasts of all the continents except for Africa and Antarctica (Figure 11.6), generally found in sheltered zones (Aguilar-Rosas *et al.*, 2004). In Europe, it is considered the third most invasive seaweed (ICES, 2007; Báez *et al.*, 2010).

When introduced, the behaviour of *U. pinnatifida* can differ, generally depending on the environmental conditions of the recipient system (Table 11.1). Where the species retains its typical seasonal cycle, it can be controlled by native species regrowth during summer, when alien sporophytes die (Zabin *et al.*, 2009).

In contrast, where *U. pinnatifida* endures year round, it can most likely outcompete native species, so invasion can have negative consequences at a biodiversity level, causing a reduction of local species, and also at an economic level if it invades communities of commercial species (Casas *et al.*, 2004). Therefore, when possible, eradication is advisable. Indeed, in Nuevo Gulf (Argentina), the rocky coast has been almost completely and continuously colonised by this alien since 1992. Its experimental removal triggered a large increase (+175%) in the number of native seaweeds (Casas *et al.*, 2004).

Fig. 11.6: Worldwide distribution of *Undaria pinnatifida*. Green star indicates the type locality; green circles indicate native distribution; red circles indicate alien distribution.

In New Zealand, the results of a risk assessment model showed that *U. pinnatifida* has the potential for high negative impact in High Value Areas (Campbell & Hewitt, 2013). In Tasmania, manipulation experiments in the field demonstrated that any already-present disturbance of the natural ecosystems favours the establishment of *U. pinnatifida* populations, and continuous disturbance seems necessary for its persistence (Valentine & Johnson, 2003; 2005). In the Venice Lagoon, *U. pinnatifida* is one of the two major invasive seaweeds, together with *S. muticum*. It is present from autumn to spring, in different sites, with very high biomass and cover values on different hard substrata (Sfriso & Facca, 2013), and competes with the native species for the substratum, causing the reduction of their cover index rather than of their number (Curiel *et al.*, 1998). Conversely, it does not compete with other alien seaweeds, which are preferentially floating and distributed on mobile bottoms. Due to its large dimensions, *U. pinnatifida* can represent an obstacle for local navigation along the canals, but its biomass is negligible in comparison with that of all the seaweeds present in the Lagoon. It does not cause any anoxic crises since, after detachment, it either is carried away to the sea or is run aground (Sfriso & Facca, 2013). In the Mar Piccolo of Taranto, *U. pinnatifida* was observed for the first time in April 1998. After an initial increase in population density (Cecere *et al.*, 2003), it completely disappeared within ten years, most likely due to the inability of microscopic gametophytes to overcome the high summer temperatures reached by the basin seawater (Cecere & Petrocelli, 2009). However, the small size of the founder population should not be undervalued (Báez *et al.*, 2010). No negative impact was registered in that period.

Besides its ecological negative effects on coastal systems, *U. pinnatifida* can also interfere with some recreational human activities, such as diving and angling. In Argentina, detached and drifting old thalli were observed clinging to the rocky reefs, obstructing the entrance of fish holes (Irigoyen *et al.*, 2011a).

However, this species could have also a positive impact. For example, it houses many epibionts, since its morphology seems to enhance the availability of refuges for cryptic benthic fauna, as occurred in the Mar Piccolo of Taranto (Cecere *et al.*, 2003). Moreover, *U. pinnatifida* is a food resource for some animals and can enhance consumer populations (Irigoyen *et al.*, 2011b).

Undaria pinnatifida can be considered an opportunistic species, which succeeds in invading spaces due to the following characteristics (Valentine & Johnson, 2003; ICES, 2007):
1. Easy settling on artificial substrates, including in disturbed zones;
2. Tolerance to wide variations in both temperature and salinity;
3. Fast growing, including in extreme conditions of turbidity and pollution;
4. Survival of gametophytes out of seawater for up to one month;
5. Year-round reproduction in some localities, and production of a huge quantity of zoospores transported by the currents.

Except for Brittany, where it was intentionally introduced for cultivation purposes, *U. pinnatifida* was accidentally introduced around the world either by fouling boats and ship hulls or by oyster transportation (ICES, 2007). In both Atlantic and Mediterranean France, the introduction of this species was probably due to the massive importation of the oyster *Crassostrea gigas* (Thunberg, 1793) from Japan (Boudouresque *et al.*, 1985). In the Venice Lagoon (Italy), the first report of *U. pinnatifida* was from Chioggia, where the importation of edible molluscs from northern Europe and the Mediterranean Sea is common (Curiel & Marzocchi, 2010). In the Mar Piccolo of Taranto (Ionian Sea, southern Italy), the introduction was most likely due to the importation of Japanese oysters (*C. gigas*) from France. To keep imported molluscs hydrated, they were transported covered with seaweed blades, which were presumably later thrown into the seawater and attached to the surrounding docks (Cecere *et al.*, 2000). Boats are the most probable vector for the introduction of *U. pinnatifida* into British waters, since some plants were observed attached to the hulls of recreational vessels moored at marinas in several ports (Fletcher & Farrell, 1999; Farrell & Fletcher, 2006). In Todos Santos Island (Mexico), this alien seaweed was probably introduced via commercial and touristic sailing, but also by recreational boats (Aguilar-Rosas *et al.*, 2004). Several possible vectors could have favoured *U. pinnatifida* introduction in central Patagonia, e.g. ballast waters, fouling of cargo ships or fishing boats from Japan or Korea (Casas *et al.*, 2004).

For prevention and control of *U. pinnatifida* introduction, boats and ship hulls should be continuously checked and cleaned out of water, taking care that when present, fertile specimens have to be disposed of and not re-immersed. Cargo ship ballast water must be treated with high temperatures before being discharged to avoid the release of any *U. pinnatifida* gametophytes, since they can survive at temperatures near to 30°C for long periods. All the structures in marinas and ports where *U. pinnatifida* thalli are found have to be carefully scraped. Moreover, a continuous monitoring of not-yet-colonised zones, especially in close proximity to already colonised areas, is necessary to avoid new settlements. The cultivation of *U. pinnatifida* in areas where it is not present must also be avoided, as well as its maintenance in aquaria where flow-through systems are used (ICES, 2007).

In New Zealand, mussel farming was considered the first vector for the spread of *U. pinnatifida*, by way of seeded ropes and mussel seeds. Therefore, careful cleaning was suggested, through a first washing followed by a second treatment by means of an environmentally friendly system such as high pressure, air-drying, freshwater, hot water (Forrest & Blakemore, 2006).

Eradication of this kelp is only possible at an early stage and in narrow colonised areas (Aguilar-Rosas *et al.*, 2004). Up to now, few attempts have been carried out. The only documented effective eradication was in the Chatham Islands (New Zealand), where *U. pinnatifida* was completely removed from a sunken ship at a depth of 20 m, through a heat treatment method (Wotton *et al.*, 2004). In the Venice Lagoon, eradication was unsuccessful when performed both during and after the reproductive period (Curiel *et al.*, 2001). In British waters, a manual eradication was initially attempted, but was unsuccessful since many of the removed thalli were already fertile (Fletcher & Farrell, 1999). In a Marine Reserve in Tasmania, a monthly manual eradication of *U. pinnatifida* sporophytes was carried out. As a result, the next generation, developed by zoospores or microscopic stages, consisted of a considerably reduced number of smaller thalli, few of which succeeded in maturing (Hewitt *et al.*, 2005).

11.3 Vectors

The transport mechanisms of alien seaweeds throughout the world are numerous. Hull fouling is considered the most ancient vector for the introduction of alien species in the marine system (Boudouresque & Verlaque, 2002a). Seaweeds can attach to vessels as juveniles, as encrusting and filamentous thalli, or as large developed thalli, and are able to survive the highly variable journey conditions. Mineur *et al.*, (2007) studied the hulls of 22 ships arriving in the commercial harbour of Sète (France, Mediterranean Sea) and found 31 seaweeds, mainly cosmopolitan species. The importance of recreational vessels in bays and coastal environments was investigated in California, since this region has been a hot spot for the introduction of alien species since the 1960s, suffering economic damage in excess of 2 trillion US dollars by 2010 (Ashton *et al.*, 2012). However, the most recent investigations showed that, contrary to what has been observed for alien animals (Canning-Clode *et al.*, 2013), hull fouling seems less important than aquaculture for the introduction of alien macroalgae. Nonetheless, the use of modern non-toxic paints and the high number of vessels mooring in marinas all over the world could enhance the risk of dispersal of these species after their introduction (Mineur *et al.*, 2008). Indeed, some of the more dessication-resistant species can survive transport attached to anchors, ropes, and chains (Hewitt *et al.*, 2007).

Today, the most likely vector for the introduction of alien seaweeds seems to be the importation of aquaculture organisms for different purposes (Hewitt *et al.*, 2007).

Ballast water is indicated as the main vector for the introduction of plankton species, but microscopic stages, propagules, and vegetative fragments of seaweeds are also able to survive the stress linked to ballast transport such as uptake, the ballast pump, and prolonged darkness (Flagella *et al.*, 2007). Ballast sediment is a less probable vector (Hewitt *et al.*, 2007).

Aquarium species, even when carefully controlled with quarantine periods, can accidentally escape from tanks and settle in the surrounding environment, as occurred for *Caulerpa taxifolia* (M. Vahl) C. Agardh in the Mediterranean Sea, California, and Australia (Hewitt *et al.*, 2007).

Finally, another vector is packing material, namely thalli used to maintain mollusc and live bait moisture during long routes. Once these thalli are thrown into seawater, they can settle and form new populations (Hewitt *et al.*, 2007).

11.4 Control and Management

Prediction of future invasions is not possible, but if suitable prevention and management are not implemented, the number of alien seaweeds will increase in coming years (Ashton *et al.*, 2012). Indeed, prevention of introduction is the most effective method in limiting biological invasions (Doelle *et al.*, 2007), but the correct management of human activities directly implicated in the spread of invasive species will be a strong constraint on further propagation (Lyons & Scheibling, 2009).

Different management actions are possible for intentional and unintentional introductions. In the first case, a precautionary risk assessment is necessary to fulfil the requirements of the ICES Code of Practice for Introductions and Transfers of Marine Organisms, in order to evaluate the possible damage that the introduced species and any associated alien species can cause. The knowledge of their biological and ecological features could allow us to avoid possible new damaging introductions and to make provisions for the possible spread of these species (Meinesz, 2007). Before introduction into the field, the first step must be a quarantine period — specimens must be held in segregation from which they cannot escape (Pickering *et al.*, 2007).

Concerning accidental introductions, the detection of possible candidate sites (e.g. harbours, marinas, aquaculture plants, public aquaria) and their successive monitoring should be regularly performed, since the early finding of alien seaweed species is important for effective management of the problem (Meinesz, 2007). Indeed, when these organisms have not yet formed consistent reproductive and spreading populations, it is almost certainly easier to eradicate them (Ashton *et al.*, 2012). For example, management of recreational boats, which are also a source of economic entries, should go beyond the common activities performed to avoid fouling settlement on hulls, and also inspect all the gear associated with the boat (Ashton *et al.*, 2012). Generally, boat owners are neither acquainted nor interested in the problem of alien introduction, so they do not the necessary precautions in their boat management (Ashton *et al.*, 2012). In this respect, the need for an adequate information campaign aimed at sea users and the general populace is clear, to make them aware of the problem and of its risks at all levels, facilitating the early detection of new introduced species (Aguilar-Rosas *et al.*, 2013). As an example, the prompt reply of a fisherman, informed through a brochure circulated to the population, led to the first detection of *Caulerpa taxifolia* in Tunisia (Johnson & Chapman, 2007; Meinesz, 2007). However, few examples of this kind of informed activity have been found. In California, some sporadic awareness campaigns were carried out after the finding of *Undaria pinnatifida* in some marinas (Ashton *et al.*, 2012). The Hawai'i Department of Land and Natural Resources, together with the U.S. Environmental Protection Agency, made a set of waterproof cards to hand out, not only to sea stakeholders but also to scholars, to help them in the identification of alien seaweeds (http://www.epa.gov/region09/water/oce/seaweed/alien.html). In Italy, the research project "Individuation and Monitoring of Alien Species in the Taranto seas (IMSAT)" produced a pamphlet about several categories of marine alien species, including seaweeds, which was circulated to all the Italian captaincies and to local stakeholders, to raise their awareness of this problem (Cecere *et al.*, 2005). RAC/SPA worked out an Action Plan concerning invasive species, creating informative booklets with guidelines for the control of introductions, including some of the more threatening seaweed species (http://www.rac-spa.org/publiclations#en11).

11.4.1 Policy and Laws

For effective prevention of bioinvasions, all current laws and practices (e.g. quarantine for imported live products, control of ballast water discharge, ban of potential invasive species) have to be fully implemented and enforced (Boudouresque & Verlaque, 2002b). For seaweeds specifically, there are currently no laws; only some general guidelines are present at a global scale, aimed at regulating the intentional introduction of some economically important species (Pickering *et al.*, 2007). However, several measures concerning alien species in general are present, and they can be effective for alien seaweed control. The Ballast Water Management Convention, issued in 2004 by the International Maritime Organization (IMO), addresses the hazardous introduction of "harmful aquatic organisms" by ship ballast water (Doelle *et al.*, 2007). For the control of hull fouling, only the adoption of anti-fouling paints and the cleaning of hulls out of water are recommended (Hewitt *et al.*, 2007). Australia and New Zealand were the first nations that realised the importance of a healthy sea, and formulated the governance of their maritime districts based on Ecologically Sustainable Development. Here, the quarantine of imported species and risk assessment became primary principles of sea management (Ashton *et al.*, 2012). At this moment, in the USA, the National Aquatic Invasive Species Act 2005 (NAISA) is effective for the management of aliens through partnership between the government and private stakeholders (Godwin *et al.*, 2006). In Europe, within the Marine Strategy Framework Directive (2008/CE/56, MSFD), alien species are considered one of the descriptors to be used in monitoring programs aimed at achieving the Good Environmental State (GES) designation by 2020. The rules about the introduction of alien species for aquaculture purposes (CE 708/2007) have been present for some time. Moreover, on 29th September 2014, the European Council adopted an ordinary legislative procedure, "Regulation of the European Parliament and of the Council on the prevention and management of the introduction and spread of invasive alien species" (COD 2013/0307). It was published in the Official Journal on 5th November (N. 1143/2014) and entered into force on 1st January 2015. Article 4 of the Regulation provides for drawing up *a list of invasive alien species of Union concern* to be reviewed every six years, in which all the species meeting fixed criteria have to be included (http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1415116378291&uri=OJ:JOL_2014_317_R_0003).

11.5 Conclusion

Over the last 30 years, the increase in commercial and touristic trade and the change in economic activities led to the rise of introductions of alien seaweeds, which have had, on balance, a negative impact on receiving systems (Schaffelke & Hewitt, 2007).

Nonetheless, from the analysis of the current available literature on three of the most spread alien seaweeds, the scarcity of pluriannual studies in the field to assess their actual negative or positive impacts on native communities is evident. Indeed, most of the studies were carried out in the laboratory or in mesocosms, and the reported impact was only a speculative extrapolation of results.

In addition, despite the heavy impact substantiated for a few alien invasive seaweeds, no real effective solution has been found for the prevention and the management of their introduction, either from science or policy. However, the noticeable proliferation of practices (e.g. increase of commercial trade, use of non-native aquaculture organisms) that have favoured the introduction of invasive seaweeds in most of the world seas underlines the urgent necessity of regulating such activities, not only at a national level but also and above all at an international level (Hewitt & Campbell, 2007). This is more valid in Europe where, among the state members, the free circulation of goods is warranted. In this way, goods (and thus alien species) coming from extra-European states, once entered into an EU state, can reach all others. According to descriptor 2 of the EU MSFD, *aliens must maintain a level at which they do not adversely alter the ecosystem*. However, the final goal should be to avoid their introduction in the first place, since the introduction of aliens is considered an irreversible phenomenon that, in the case of invasive species, can have effects on a geological scale (Boudouresque *et al.*, 2005).

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In a nutshell

- The number of introductions of alien seaweeds is continuously rising due to the expansion of commercial transoceanic trade.
- This phenomenon can be intentional, mainly concerning economically important species introduced for cultivation purposes, or accidental, concerning species either associated with other imported organisms or attached to vessel hulls.
- The main vector for the accidental introduction of seaweeds are molluscs transferred throughout the world for both aquaculture and food purposes.
- Introduced seaweeds, which have a negative impact, are called invasive. Their biological invasion can cause damage to native biodiversity, ecosystem function, and human health.
- No seaweed species can be defined as invasive in an absolute sense, because their behaviour changes in time and in space.
- Introduced seaweeds can also have positive effects, such as increasing epibiont diversity.
- Biological invasions by seaweeds can be effectively limited through the prevention of introduction and effective management of human activities that contribute to the spread of invasive species.
- No effective solution has been found for the prevention and management of alien seaweed introductions, either from science or policy.
- There is an urgent need for regulation at both national and, far more importantly, international levels.
- The education of both sea stakeholders and the general populace is strongly advisable to raise ecological awareness and vigilance.

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