



Biological pollution in the Mediterranean Sea: invasive versus introduced macrophytes

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Abstract

The authors have listed 85 species of macrophytes that have probably been introduced to the Mediterranean. Among them, nine species can be considered as invasive, i.e., playing a conspicuous role in the recipient ecosystems, taking the place of keystone species and/or being economically harmful: *Acrothamnion preissii*, *Asparagopsis armata*, *Lophocladia lallemandii*, *Womersleyella setacea* (Rhodophyta), *Sargassum muticum*, *Styopodium schimperi* (Fucophyceae), *Caulerpa racemosa*, *Caulerpa taxifolia* and *Halophila stipulacea* (Plantae). These data fit well the Williamson and Fitter's "tens rule", which states that, on average, 1 out of 10 introduced species becomes invasive. Though some features (e.g. life traits, geographical origin) can increase the likelihood of a successful invasion, the success of invaders is far from being predictable. Since the beginning of the 20th century, the number of introduced species to the Mediterranean has nearly doubled every 20 years. Should these kinetics continue, and according to the tens rule, it can be expected that 5–10 newly introduced macrophytes shall become invasive in the next 20 years. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Mediterranean; Biological pollution; Macrophyte; Exotic species; Invasive species

1. Introduction

An introduced species is defined as a species that fulfills the four following criteria (Carlton, 1985; Ribera and Boudouresque, 1995; Williamson and Fitter, 1996; Boudouresque, 1999).

- (i) It colonizes a new area where it was not previously present.
- (ii) The extension of its range is linked, directly or indirectly, to human activity.
- (iii) There is a geographical discontinuity between its native area and the new area (remote dispersal). This means that the occasional advance of a species at the frontiers of its native range (marginal dispersal) is not taken into consideration. Such fluctuations (advances or withdrawals) may be linked to climatic episodes. Fluctuations of this type have been reported in *Fucus spiralis* Linnaeus from southern Portugal and in

Laminaria ochroleuca Pylae from Great Britain, for example (Parke, 1948; Fischer-Piette, 1959, 1963).

(iv) Finally, new generations of the non-native species are born in situ without human assistance, thus constituting self-sustaining populations: the species is established, i.e. naturalized. Based on this definition, the corn *Zea mais* in European terrestrial environments, and the sea mammal *Dugong dugon*, which has been observed only once along the Israeli coast and probably represents an isolated individual having entered the Mediterranean through the Suez canal (Por, 1978), are not introduced species.

The criteria for deciding whether or not a species has a probability of having been introduced are as follows:

- (i) The species is new to the area in question.
- (ii) There is a geographical discontinuity between the species' known range and the new station (see above).
- (iii) The new station is very localized; adjacent biotopes, which are similar to the one that has been colonized, are, for the time being, free of the species.

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- (iv) From an initial localized station, the species spread follows a logical pattern.
- (v) The introduced species has a tendency to pullulate.
- (vi) There is a potential introduction source close at hand (e.g. aquaculture farm, harbour, laboratory, aquarium).
- (vii) The new population possesses only part of the genetic variability exhibited by the species in its original range.
- (viii) When two populations of the same species with geographically discontinuous ranges are genetically identical, this is a strong indication that one of the two populations is introduced. Indeed, the separation and probable long-standing nature of their genetic isolation might lead one to expect differences (Zibrowius, 1991; Occhipinti-Ambrogi, 1994; Ribera and Boudouresque, 1995; Boudouresque, 1999).

In fact, the above criteria, which are rarely all met, only offer the means of assessing whether a species has a probability of having been introduced.

An invasive species is an introduced species that is ecologically and/or economically harmful, i.e. a pest (Williamson and Fitter, 1996; Clout, 1998). Within recipient ecosystems, this type of species acts as a new keystone species: it either has a strong impact on native keystone species or it takes their place.

The zebra-mussel *Dreissena polymorpha* Pallas, 1771 in the North American Great Lakes (Kiernan, 1993; Carlton, 1996a), the jellyfish *Mnemiopsis leydi* Agassiz, 1865 in the Black Sea (Konovalov, 1992; Travis, 1993; Carlton, 1996a; GESAMP, 1997) and the tropical green alga *Caulerpa taxifolia* (Vahl) C. Agardh in the Mediterranean (Meinesz and Hesse, 1991; Meinesz and Boudouresque, 1996; Boudouresque, 1997a, 1998) are invasive species.

2. Introduced species in the Mediterranean

Considering a species to be introduced is, in most cases, based on a level of probability. Here, we have listed only 85 species whose introduction to the Mediterranean presents a medium, high or very high probability. Furthermore, due to the poor knowledge of coastal habitats, it is not always possible to ascertain whether or not certain species, mentioned once or a few times, have actually become naturalized. As a result, it is clear that some of the species listed below may be either native or non-naturalized. In contrast, some cryptogenic species (see Carlton, 1996b), not listed below, may prove to be introduced. Also, species introduced to a part of the Mediterranean (e.g. *Desmarestia viridis*, Fucophyceae, in Thau Lagoon, France), but for which some populations may be native (e.g. *D. viridis* in the northern Adriatic), are

not taken into consideration here. The following updated list is mainly based upon the data of Boudouresque and Ribera (1994), Verlaque (1994), Ribera and Boudouresque (1995) and Verlaque (2001, unpublished data).

2.1. Rhodophyta

Acanthophora nayadiformis (Delile) Papenfuss, *Acrothamnion preissii* (Sonder) E.M. Wollaston, *Agardhiella subulata* (C. Agardh) Kraft et M.J. Wynne, *Agloothamnion feldmanniae* Halos, *Ahnfeltiopsis flabelliformis* (Harvey) Masuda, *Antithamnion amphigeneum* A. Millar (= *A. algeriense* M. Verlaque et Seridi), *A. pectinatum* (Montagne) Brauner ex Athanasiadis and Tittley¹, *Antithamnionella elegans* (Berthold) J.H. Price and D.M. John, *A. spirographidis* (Schiffner) E.M. Wollaston, *A. sublittoralis* (Setchell et Gardner) Athanasiadis, *A. ternifolia* (Hooker et Harvey) Lyle (= *A. sarniense* Lyle), *Apoglossum gregarium* (Dawson) M.J. Wynne, *Asparagopsis armata* Harvey (the sporophyte is known as *Falkenbergia rufolanosa* (Harvey) Schmitz), *A. taxiformis* (Delile) Trevisan, *Audouinella sargassicola* (Børgesen) Garbary, *A. spathoglossi* (Børgesen) Garbary, *A. subseriata* (Børgesen) Garbary, *Bonnemaisonia hamifera* Harriot, *Botryocladia madagascarensis* G. Feldmann, *Chondria pygmaea* Garbary et Vandermeulen, *Chondrus giganteus* Yendo f. *flabellatus* Mikami, *Chrysiomenia wrightii* (Harvey) Yamada, *Dasya sessilis* Yamada², *Galaxaura rugosa* (Ellis et Solander) Lamouroux, *Goniotrichopsis sublittoralis* Smith, *Gracilaria arcuata* Zanardini, *G. disticha* (J. Agardh) J. Agardh, *Grateloupia doryphora* (Montagne) Howe³, *G. filicina* (Lamouroux) C. Agardh var. *luxurians* Geep et Geep, *G. lanceolata* (Okamura) Kawaguchi, *Griffithsia corallinoides* (Linnaeus) Batters, *Herposiphonia parca* Setchell, *Heterosiphonia japonica* Yendo⁴, *Hypnea cervicornis* J. Agardh, *H. cornuta* (Kützting) J. Agardh, *H. esperi* Bory, *H. spicifera* (Suhr) Harvey (= *H. harveyi* Kützting), *H. nidifica* J. Agardh, *H. valentiae* (Turner) Montagne, *Laurencia okamurae* Yamada⁵, *Lithophyllum yessoense* Foslie, *Lomentaria hakodatensis* Yendo, *Lophocladia lallemandii* (Montagne) F. Schmitz, *Pleonosporium caribaeum* (Børgesen) R.E. Norris, *Plocamium secundatum* (Kützting) Kützting, *Polysiphonia harveyi* Bailey, *P. morrowii* Harvey, *Porphyra yezoensis* Ueda, *Prionitis*

¹ As *Antithamnion nipponicum* Yamada et Inagaki in Ribera and Boudouresque (1995).

² As *Dasya* sp. in Verlaque (2001).

³ Probably a misidentification for *Grateloupia turuturu* Yamada. See Verlaque (2001).

⁴ See Verlaque (2001) for taxonomic discussion: probably a *Dasyisiphonia* species.

⁵ As *Laurencia coronopus* J. Agardh in Ribera and Boudouresque (1995).

patens Okamura, *Pterosiphonia tanakae* Uwai et Masuda⁶, *Rhodophysema georgii* Batters, *Rhodothamniella codicola* (Børgesen) Bidoux et F. Magne, *Rhodymenia erythraea* Zanardini, *Sarconema filiforme* (Sonder) Kützing, *S. scinaoides* Børgesen, *Solieria dura* (Zanardini) Schmitz, *S. filiformis* (Kützing) Gabrielson, *Symphyclocladia* sp., *Womersleyella setacea* (Hollenberg) R.E. Norris (= *Polysiphonia setacea* Hollenberg).

2.2. Fucophyceae

Acrothrix gracilis Kylin, *Chorda filum* (Linnaeus) Stackhouse, *Colpomenia peregrina* (Sauvageau) Hamel, *Fucus spiralis* Linnaeus, *Laminaria japonica* Areschoug, *Leathesia difformis* (Linnaeus) Areschoug, *Padina boergesenii* Allender et Kraft (= *P. gymnospora* (Kützing) Vickers), *P. boryana* Thivy in Taylor, *Sargassum muticum* (Yendo) Fensholt, *Scytosiphon dotyi* Wynne, *Spathoglossum variabile* Figari et De Notaris, *Sphaerotrichia divaricata* (C. Agardh) Kylin, *Styopodium schimperi* (Buchinger ex Kützing) Verlaque et Boudouresque, *Undaria pinnatifida* (Harvey) Suringar.

2.3. Chlorophyta and Magnoliophyta

Caulerpa mexicana Sonder ex Kützing, *C. racemosa* (Forsskål) J. Agardh⁷, *C. scalpelliformis* (Brown ex Turner) C. Agardh, *C. taxifolia* (Vahl) C. Agardh, *Cladophora* cf. *patentiramea* (Montagne) Kützing, *Cladophoropsis zollingeri* (Kützing) Reinbold, *Codium fragile* (Suringar) Hariot ssp. *tomentosoides* (Goor) P.C. Silva, *Derbesia boergesenii* (Iyengar et Ramanathan) Mayhoub, *D. rhizophora* Yamada, *Halophila stipulacea* (Forsskål) Ascherson, *Monostroma obscurum* (Kützing) J. Agardh, *Ulva pertusa* Kjellman.

The check-list of the marine macrophytes (Rhodophyta, Fucophyceae, Chlorophyta and Magnoliophyta) of the Mediterranean encompasses 1285 species (Ribera et al., 1992; Gallardo et al., 1993; Boudouresque, 1997b; Gómez Garreta et al., 2001), of which 6.4% appear to be probably introduced.

3. Invasive species in the Mediterranean Sea

On average, 1 out of 10 imported species appears in the wild (settled species), one in ten of these settled species becomes established (introduced) and one out of ten introduced species becomes a pest (invasive) (Williamson and Fitter, 1996). According to these authors, adopting the value 10 in fact represents a range of be-

tween 5 and 20, which is close to the confidence limits of a binomial expectation of 0.1 in a sample of 100. This “tens rule” is satisfactory for British angiosperms, British Pinaceae, Australian pasture plants and United States terrestrial vertebrates and invertebrates. Deviations from the tens rule, e.g. British crop plants, Hawaiian birds, insects used in biological control and island mammals, are rather easily explained (Williamson and Fitter, 1996). The first question we address in this paper is: does the tens rule work in a marine environment, namely the Mediterranean Sea?

At least eight species can be assigned to the category of invasive organisms in the Mediterranean. They play a conspicuous role in the recipient ecosystems, becoming the dominant species and/or taking the place of keystone species: *Acrothamnion preissii* in western Italy (Piazzi et al., 1996), *Asparagopsis armata* (either in its gametophyte or tetrasporophyte stage) in the north-western basin (Sala and Boudouresque, 1997), *Lophocladia lallemandii* in the Balearic Islands (Patzner, 1998; E. Ballesteros, personal communication), *Womersleyella setacea* in western Italy, Corsica and the Aegean Sea (Airoldi et al., 1995a,b; Athanasiadis, 1997), *Sargassum muticum* in Thau lagoon, France (Gerbal et al., 1985), *Styopodium schimperi* in the eastern Mediterranean, especially along the Levantine coasts (Mayhoub and Billard, 1991; Verlaque and Boudouresque, 1991; Sartoni and De Biasi, 1999), *Caulerpa racemosa* in various localities throughout the Mediterranean (Panayotidis and Montesanto, 1994; Piazzi et al., 1994, 1997; Verlaque et al., 2000; Tolay et al., 2001) and *Caulerpa taxifolia* along the French and Italian Rivières (Verlaque and Fritayre, 1994; Villèle and Verlaque, 1995; Boudouresque, 1997a). An additional species, *Halophila stipulacea* in the Eastern Mediterranean, can be tentatively added to this list of invasive species (Biliotti and Abdelahad, 1990; Haritonidis and Diapoulis, 1990; Cancemi et al., 1994). A number of other species should probably be considered, but further research efforts are required if we are to adequately evaluate their ecological impact. In addition, most introductions are rather recent; so that the time elapsed may be too short for their possible invasiveness to become apparent. As far as the present day knowledge of introduced and invasive species in the Mediterranean is concerned, the data presented here fit the tens rule rather well.

The two additional questions which warrant mentioning are: why do some species become invasive and others not? and also, can we predict the invasiveness of an introduced species? Several common features, likely to account for their success, have been identified amongst invasive fresh water plants (Ashton and Mitchell, 1989; Pieterse, 1990):

- (i) Vegetative reproduction is usually the commonest, and often the only method of reproduction. As a re-

⁶ As *Pterosiphonia* sp. in Verlaque (2001).

⁷ According to Verlaque et al. (2000), Mediterranean citations of *C. racemosa* encompass three distinct taxa, which rank assessment (variety or species?) requires further investigations.

sult, one viable propagule is sufficient to start a new colony.

- (ii) Vegetative reproduction is prolific.
- (iii) Habitat requirements are flexible.
- (iv) They tolerate the stresses of environmental fluctuations and extremes.
- (v) There is a similarity between the native and recipient habitat.
- (vi) They are free from the predators and diseases characteristic of their native range.

In the same way, if one examines the life traits of the nine invasive plant species in the Mediterranean (Table 1), several more or less common features become apparent: many of these are large, perennial, lack a resting stage, present effective vegetative reproduction, possess toxic metabolites and are avoided by grazers. In addition, two functional-form groups are not represented (jointed calcareous and crustose plants). However, similar attributes, and even similar combinations of attributes, can be found in introduced species that have proven not to be invasive. As far as the route of access is concerned, invasive species have used diverse ways to enter the Mediterranean (Verlaque, 1994; Ribera and Boudouresque, 1995; Jousson et al., 1998): fouling on ship hulls (*Acrothamnion preissii*, *Asparagopsis armata*?, *Womersleyella setacea*), aquaculture (*Sargassum muticum*), the aquarium trade (*Caulerpa taxifolia*) and the Suez canal (*Styopodium shimperi*, *Caulerpa racemosa*?, *Halophila stipulacea*). In the same way, they originate

from various biogeographical areas, and not only from warm temperate seas similar to the Mediterranean: cold temperate seas (*Sargassum muticum*), warm temperate seas (*Asparagopsis armata*, *Acrothamnion preissii*) or tropical seas (*Womersleyella setacea*, *Styopodium shimperi*, *Caulerpa racemosa*, *C. taxifolia*, *Halophila stipulacea*). The success of several tropical algae is particularly surprising: in the Mediterranean, winter temperatures (9–17°C) fall largely below the lower limit of tropical temperatures (20°C). A significant example is that of *Caulerpa taxifolia*, a tropical green alga that is spreading in the coldest parts of the Mediterranean: the northwestern basin and northern Adriatic (Meinesz and Hesse, 1991; Meinesz and Boudouresque, 1996; Boudouresque, 1998). The strain which colonizes the Mediterranean, of unknown geographical origin at present (Jousson et al., 1998; but see Jousson et al., 2000), appears to be conspicuously cold resistant (Komatsu et al., 1997). Therefore, our data confirm the general agreement that some features (e.g. life traits, geographical origin, occurrence of a vector) can increase the likelihood of a successful invasion, but in no way guarantee its success. As yet, the success of invaders is far from being predictable (Ashton and Mitchell, 1989; Williamson and Fitter, 1996). It is a kind of “ecological roulette”, as coined by Carlton and Geller (1993). All things considered, the best forecasting tool to predict the invasiveness of a non-native species may be its invasiveness elsewhere in the world. For example, the success of the Japanese brown alga *Sargassum muticum* along

Table 1

Life traits of the Mediterranean populations of invasive macrophytes (listed above). Comparison with a set of non-invasive introduced species (below)

Species	Large sized	Perennial	Without a resting stage	Sexual reproduction	Vegetative multiplication	Defence metabolites	No or few predators	Functional form group
<i>Acrothamnion preissii</i>	–	?	+	–	+	+	?	Filamentous
<i>Asparagopsis armata</i>	+	–	–	+	+	++	+	Coarsely branched
<i>Lophocladia lallemandii</i>	–	?	–	+	–	+	+	Filamentous
<i>Womersleyella setacea</i>	–	–	+	–	+	?	+	Filamentous
<i>Sargassum muticum</i>	+	+	–	+	–	+	+	Thick leathery
<i>Styopodium shimperi</i>	+	+	–	?	–	+	?	Thick leathery
<i>Caulerpa racemosa</i>	+	+	–	+	+	+	+	Coarsely branched
<i>Caulerpa taxifolia</i>	+	+	+	–	+	++	+	Coarsely branched
<i>Halophila stipulacea</i>	–	+	+	+	+	–	–	Coarsely branched
<i>Antithamnion pectinatum</i>	–	–	–	–	+	?	?	Filamentous
<i>Audouinella sargassicola</i>	–	–	–	–	–	–	–	Filamentous
<i>Chrysymenia wrightii</i>	+	–	–	+	–	?	?	Coarsely branched
<i>Pleonosporium caribaeum</i>	–	–	–	+	–	–	–	Filamentous
<i>Colpomenia peregrina</i>	–	–	–	–	–	–	–	Coarsely branched
<i>Laminaria japonica</i>	+	–	–	+	–	–	+	Thick leathery
<i>Undaria pinnatifida</i>	+	–	–	+	–	–	–	Thick leathery
<i>Caulerpa mexicana</i>	+	+	–	+	+	+	?	Coarsely branched
<i>Codium fragile</i>	+	+	+	–	+	–	+	Coarsely branched

“Vegetative reproduction” means: dispersal of cuttings. ++ and += yes, – = no. Data from Rayss (1941, 1955), Cinelli and Sartoni (1970), Hulings (1979), McMillan et al. (1980), Caccamese et al. (1981), Littler and Littler (1984), Verlaque (1984), Boudouresque et al. (1985), Cormaci and Motta (1985), González Henríquez and Santos Guerra (1985), Ben Maiz et al. (1987), Verlaque and Riouall (1989), Verlaque and Boudouresque (1991), Frantzis and Gremare (1992), Guerriero et al. (1992), Meinesz (1992), Lundberg and Golani (1995), Airolidi and Cinelli (1996), Boudouresque et al. (1996), Sala and Boudouresque (1997), Forrest et al. (2001).

the Pacific coast of North-America should have warned European oyster farmers about a possible risk. In the same way, the spread of an aquarium strain of *Caulerpa taxifolia* in the Mediterranean has led several governments (Australia, France, Spain and USA) to ban its use in the aquarium trade in order to prevent it from escaping to new geographical areas (Jousson et al., 1998). This banning occurred too late in California, since the alga has already been introduced (Kaiser, 2000).

4. Conclusion

Although we cannot predict with certainty the success of individual invaders, there is no doubt that there are statistical regularities to invasions, as suggested by Williamson and Fitter (1996) and which are further supported by the Mediterranean data. Since the beginning of the century, the number of introduced species to the Mediterranean has nearly doubled every 20 years (Ribera and Boudouresque, 1995); should these kinetics continue, the number of introduced species will increase by about 80 species over the next 20 years. Although we cannot predict which species will be introduced, and which species will become invasive, it can be reasonably expected that 5–10 of them shall be invasive, with accompanying ecological and/or economical dire consequences.

We recommend that steps be taken at once to slow down the rate of introduction of non-native species. In particular, it seems necessary to implement national legislation, to set up quarantine conditions (aquaculture), to control the flow of ballast waters and the aquarium trade and to ban all species, which prove to be invasive in other parts of the world (“black list” or “dirty list”). Subsequently, it will be necessary to move from a “dirty list” to a “clean list” approach: only the species mentioned on the “clean list” will be allowed to be imported. In addition, it is clear that laws should be enforced and that particularly lax practices should be stopped.

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