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Pathways of introduction of marine alien species in European waters and the Mediterranean – A possible undermined role of marine litter

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Abstract

In recent assessments of pathways of introduction of alien marine species in European seas, shipping, corridors (Suez canal and inland corridors), aquaculture, and aquarium trade have been identified as the most important (in decreasing order). In the Mediterranean Sea, the same pathways have been identified as the main ones, with the Suez Canal being the most important. The role of marine litter as a vector of introduction or secondary spread of alien species in the Mediterranean has not been considered and studied so far. Primary introductions of alien species in the Mediterranean Sea by rafting on floating litter through the Suez Canal or the Gibraltar strait could have occurred. Furthermore, the huge amounts of floating plastic in the Mediterranean offer increased opportunities for many alien species to further spread in the Basin. Thirteen established aliens in the Mediterranean are known to be able to colonize floating litter. Furthermore, as inferred from their life cycle and traits, more than 80% of the known alien species in the Mediterranean could potentially use litter for further expanding their range (after their initial introduction).

Introduction

Mediterranean marine ecoregions are amongst the most impacted ecoregions globally (Halpern *et al*., 2008) due to increasing levels of human pressures that affect all levels of biodiversity (Coll *et al*., 2012; Micheli *et al*., 2013), to severe impacts from climate change (Lejeusne *et al*., 2010), and to biological invasions (Zenetos *et al*., 2010; 2012; Katsanevakis *et al*., 2013). Nearly 1,000 marine alien species have been introduced in the Mediterranean up to now CIESM Atlas Series (Galil *et al.*, 2002; Golani *et al.*, 2002; Verlaque *et al.*, 2015 in press; Zenetos *et al.*, 2003), of which more than half are considered to be established and spreading. Some of these species have become invasive and substantially modify the recipient ecosystems acting as ecosystem engineers, change community structure, affect food-web properties and ecosystem processes, impede the provision of ecosystem services, impact human health, and cause substantial economic losses (Grosholz, 2002; Wallentinus and Nyberg, 2007; Molnar *et al*., 2008).

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To address the problem of invasive species and to protect native biodiversity and ecosystem services, the Convention on Biological Diversity (CBD) has set the following target (Aichi Target 9): "By 2020, invasive alien species and pathways are identified and prioritized, priority species are controlled or eradicated, and measures are in place to manage pathways to prevent their introduction and establishment." In the European Union, this target has been adopted by the 'EU Biodiversity Strategy' (EU, 2011) and has led to the proposed new Regulation 'on the prevention and management of the introduction and spread of invasive alien species' (EU, 2013).

However, in the marine environment, eradication of invasive alien species is impossible in almost all cases, except in the very early stages of introduction (e.g. the eradication of *Caulerpa taxifolia* in California; Anderson, 2005). Prevention is by far more cost effective and environmentally desirable than post-introduction measures, which are both costly and of low probability of success. The only way to prevent new arrivals of alien marine species is by effectively managing the related pathways of introduction. Pathways and vectors of new arrivals (primary) and of further spread of established aliens (secondary) need to be first identified, and then proper management actions need to be decided.

Floating marine litter is a potentially important vector of primary introduction or of further (secondary) spread of alien species. The vast availability of anthropogenic rafting material (Galgani, this volume) can greatly assist the transport of species beyond their natural boundaries and their introduction to environments where they were previously absent (Winston, 1982; Barnes, 2002; Barnes and Milner, 2005; Barnes, this volume). Barnes (2002) estimated that human litter more than doubles the rafting opportunities for biota, assisting the dispersal of alien species. However, the role of marine litter for the introduction and spread of alien species has been understudied in the European Seas. Marine litter has not been included in any of the major recent assessments of pathways in Europe (Zenetos *et al*., 2012; Katsanevakis *et al*., 2013; Galil *et al*., 2014; Nunes *et al*., 2014).

The aim of this paper is to review our current knowledge on the pathways of introduction of alien marine species in Europe, focusing specifically in the Mediterranean, and to investigate the potential role of floating marine litter as a primary or secondary pathway.

Recent assessments of pathways of introduction in Europe

By critically reviewing related information in the scientific/grey literature and online resources, Katsanevakis *et al*. (2013) identified 1369 alien marine species in European seas, of which 92% were linked to the most probable pathway(s) of introduction (Fig. 1) the same percentage as found for the 986 alien species identified by Zenetos *et al*. (2012). Five categories of pathways of introduction were used in these assessments: 'shipping' (subdivided into 'ballasts' and 'fouling'), 'corridors' (subdivided into 'Suez', which is the only marine man-made corridor in Europe, and 'inland canals'), 'aquaculture' (subdivided into 'commodity' and 'contaminant'), 'aquarium trade' (also including escapes from public aquaria), and 'other' (including: live food/bait trade, floating objects, and import for military purposes).

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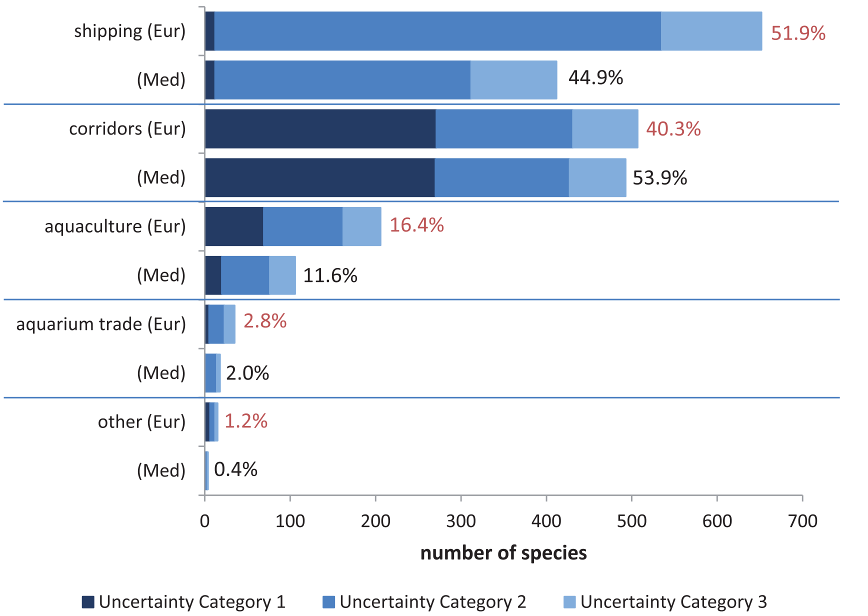

Figure 1. Number of marine alien species known or likely to be introduced by each of the main pathways, in Europe (Eur) and the Mediterranean (Med). Percentages add to more than 100% as some species are linked to more than one pathway (red percentages refer to the European total, black percentages to the Mediterranean total). Uncertainty categories: (1) there is direct evidence of a pathway/vector; (2) a most likely pathway/vector can be inferred; (3) one or more possible pathways/vectors can be inferred; (4) unknown (not shown in the graph). Modified from Katsanevakis *et al.* (2013) and Zenetos *et al.* (2012).

New introductions of alien species in Europe, and in the Mediterranean Sea in particular, have an increasing trend, reaching almost 200 new species introductions per decade (Fig. 2). Shipping and corridors are the two most important pathways in Europe and the Mediterranean Sea. Many more species are expected to invade the Mediterranean Sea through the Suez Canal, as it has been continuously enlarged and the barriers for the invasion of Red Sea species have substantially decreased (Katsanevakis *et al*., 2013). The increasing trend observed in new introductions by shipping is not expected to halt unless effective measures are taken, such as the ratification of IMO's (BWM Convention) (International Convention for the Control and Management of Ships' Ballast Water and Sediments). Nevertheless, introductions by hull-fouling, which was identified as the most common vector for marine alien species so far introduced in European seas (Katsanevakis *et al*., 2013), will remain or even increase due to the recent adoption of the IMO Anti-fouling Convention in 2004 and the banning of the most effective (i.e. most toxic) of the anti-fouling hull coatings.

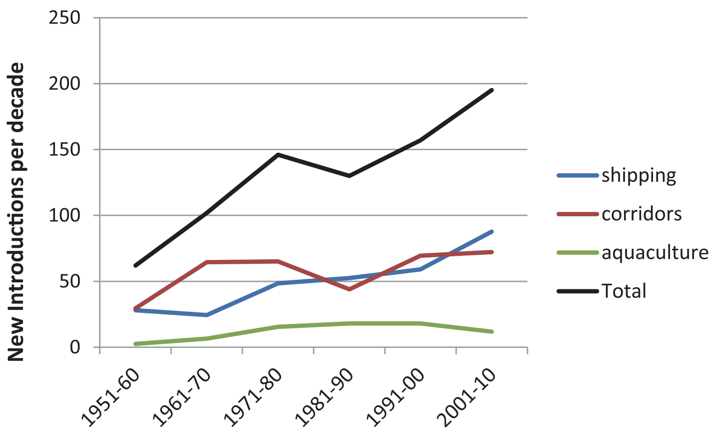

Figure 2. Trends in new introductions of alien marine species in the Mediterranean per decade (trends in total introductions and for the three most important pathways).

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Plastic surfers: a general overview

Many species may extend their distribution range through transport by floating rafts rather than through the active or passive dispersal of reproductive propagules (Highsmith, 1985; Aliani and Molcard, 2003; Barnes and Milner, 2005). Passive transport of juveniles or adult algae and invertebrates on natural floating debris (whether biotic or abiotic, such as trunks, seaweeds, seeds, volcanic pumice, cephalopods' sepion bones and buoyant corals) can last for years, with marine current-driven journeys covering vast distances across the ocean before landfall (De Vantier, 1992; Thiel and Gutow, 2005a, b).

With the onset of human travels at sea, especially commercial shipping, many marine organisms drastically increased their dispersal by travelling on vessel hulls or with ballast water. Nevertheless, over the past 4-5 decades anthropogenic floating litter offered a massive and historically unparalleled new opportunity for rafting species. During the last few decades, the availability of rafting material has increased dramatically, mostly because of the wide use of plastics, which currently constitute the larger percentage of floating litter (Katsanevakis, 2008).

Floating marine litter is commonly colonized by a wide variety of surfers, spanning almost all known taxa (e.g. bacteria, macro and micro-algae, barnacles, hydroids, bryozoa, sponges, polychaetes, sea-urchins, molluscs, and tunicates) (Carpenter *et al*., 1972; Carpenter and Smith, 1972; Winston, 1982; Minchin, 1996; Aliani and Molcard, 2003; Barnes and Fraser, 2003; Barnes and Milner, 2005; Katsanevakis, 2008). If favourable conditions are found in the new ground, the alien species may settle and become established. However, attributing a marine biological invasion to floating marine litter and not to other mechanisms is very difficult in most cases, and available data are generally insufficient. In the Mediterranean Sea, the role of marine litter as primary or secondary pathway of new introductions and translocations of species is largely neglected.

The impact of floating marine litter on biological invasions is difficult to measure and compare with other sources such as shipping or transportation on natural mobile hosts. Lewis *et al*. (2005) have questioned the extent to which floating marine litter may contribute to the introduction of exotic species in the Southern Ocean, and considered shipping as the most likely transport mechanism in that region. They stressed that floating litter follows already established passive dispersal routes, dependent on ocean currents and the wind, while ships create novel pathways, moving across currents and often visiting many locations over short periods of time. However, the availability of floating litter, mostly plastics, has become huge, offering substantial rafting opportunities for encrusting fauna and flora, especially in areas where there are only a few natural sources of flotsam. Marine litter should be considered as a serious potential vector for marine invasions, but further investigation is necessary.

Taxon-specific overview

The following review does not focus in the Mediterranean Sea and specifically on alien species. It intends to review the potential of species translocations via floating litter by reviewing taxa that have been reported to attach to drifting litter.

ALGAE and PLANTAE

Both unicellular and multicellular algae have been reported as living on plastic debris, including harmful algal bloom species. Masó *et al*. (2003) reported *Alexandrium taylori*, an *Ostreopsis* and a *Coolia* taxon living on plastic debris along the Catalan coast (north western Mediterranean), whilst diatoms have been often found on floating plastic spherules (*Cyclotella meneghiniana*, *Mastogloia angulata* and *Mastogloia hulburti*: see Carpenter and Smith, 1972). Pennate and centric diatoms have been also found by Carson *et al*. (2013b) between plastic-associated microorganisms of the North Pacific Gyre. Within Clorophyta, *Ulva rigida* has been reported from off Azores (Morton and Britton, 2000), and *Ulva* species have been also reported from off Chile, together with *Codium fragile* and *Bryopsis rhizophora* (Astudillo *et al*., 2009). The presence of several Rhodophyta living on floating plastics has been mostly stated, by genus only, by Winston *et al*. (1997): *Amphiroa*, *Fosliella*, *Jania*, *Lithophyllum* and *Mesophyllum*. To this list, Astudillo *et al*. (2009) added *Polysiphonia mollis*, *Antithamnion densum*, *Corallina officinalis* and a *Rhodymenia*

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and *Gelidium* species. Aliani and Molcard (2003) reported *Hydrolithon farinosum* and unidentified algae from the Mediterranean Sea, and also included a *Cystoseira* sp. and *Posidonia oceanica* (including the bryozoan *Electra posidoniae* on his leaves, see below). Astudillo *et al*. (2009) also included *Zostera tasmanica* as found on detached plastic buoys, as well as three Ochrophyta species (*Scytosiphon lomentaria*, *Hincksia granulosa* and *Ectocarpus acutus*).

BRYOZOA

Bryozoan species are indeed among the most common plastic debris colonizers due to their ability to encrust nearly all hard and even soft surfaces. Stevens *et al*. (1996) reported 47 species from New Zealand, whilst Rocha Farrapeira (2011) reported 19 taxa and Goldstein *et al*. (2014) at least 16 taxa. All of them included widespread aliens and species with pelagic cyphonautes larvae such as *Electra tenella* and *Jellyella tuberculata*. Winston (1982) also often reported *E. tenella* as the only bryozoan species on plastic debris cast up on beaches along the Atlantic coast of Florida. Gregory (1978) suggested that the cosmopolitan *J. tuberculata* may have crossed the Tasman Sea from Australia to New Zealand via rafting on plastic pellets. Barnes and Fraser (2003) listed 5 different bryozoan species (*Aimulosia antarctica*, *Arachnopusia inchoata*, *Ellisina antarctica*, *Fenestrulina rugula* and *Micropora brevissima*) on a plastic packaging band in the Southern Ocean, and Thiel and Gutow (2005) reported that the erect bryozoan *Bugula neritina* can be found on a wide variety of different substrata, including plastic surfaces. It has also been reported by Astudillo *et al*. (2009), together with six other taxa (including *Cryptosula pallasiana*, *Membranipora isabelleana* and *Bugula flabellata*), from detached plastic buoys sampled in the Bay System of Coquimbo (Chile). Aliani and Molcard (2003) listed four bryozoan species on floating debris (*Bowerbankia gracilis*, *Callopora lineata*, *Electra posidoniae* - see above in algae and plantae - and *Membranipora membranacea*). *Thalamoporella evelinae* is well known to have been introduced to the Atlantic by drift plastics (Winston *et al*., 1997; Derraik, 2002). Another common Caribbean and South Floridian bryozoan, *Schizoporella pungens*, was first found in the Indian River area on plastic drift in 2002. The following year it appeared on fouling panels in the Fort Pierce inlet, and since the summer of 2003 has been found on natural and artificial substrata in the inlet and adjacent Indian River Lagoon. Winston (2012) suggested that its rapid northward spreading may have been expedited by rafting.

ARTHROPODA

Cirripedia are common surfers. Within Sessilia, both *Amphibalanus amphitrite* and *Amphibalanus eburneus* have been found off Florida (Winston *et al*., 1997), whilst Morton and Britton (2000) reported *Coronula diadema* and *Xenobalanus globicipitis* from the Azores, and Astudillo *et al*. (2009) *Balanus laevis*, *Balanus flosculoidus* and *Austromegabalanus psittacus* from the Chilean shores. Barnes and Milner (2005) found *Semibalanus balanoides* and the alien *Austrominius modestus* on plastic debris in the Shetland Islands (north Atlantic Ocean). *A. amphitrite*, *A. eburneus*, *Balanus trigonus*, *Chelonibia patula*, *Conchoderma auritum*, *Coronula diadema* and *Striatobalanus amaryllis* have been listed by Rocha Farrapeira (2011) in his review of species associated with floating plastic debris off Brasil. Finally, Goldstein *et al*. (2014) listed *Megabalanus rosa* and *Chthamalus* species, among other crustaceans. Within Lepadiformes, *Dosima fascicularis*, *Lepas anatifera*, *Lepas anserifera*, *Lepas australis*, *Lepas hilli*, *Lepas pacifica* and *Lepas pectinata* are well known to be transported throughout plastics, often together with their main predator (see below in Mollusca), and can form very dense assemblages on floating substrata (Thiel and Gutow, 2005b; Barnes and Milner, 2005; Astudillo *et al*., 2009; Rocha Farrapeira, 2011; Goldstein *et al*., 2014). Astudillo *et al*. (2009) also reported 17 decapoda from detached buoys, although within Brachyura the most commonly reported species are the pelagic *Planes marinus* and *Planes minutus*, to which Goldstein *et al*. (2014) added *Planes major*. Several Amphipoda (*Calliopius laeviusculus*, *Dexamine thea*, *Phtisica marina* and *Caprella andreae*, *Jassa marmorata*, *Jassa slatteryi*, *Paradexamine pacifica*, *Elasmopus rapax*, *Caprella equilibra*, *Caprella verrucosa*, *Caprella scaura*, *Deutella venenosa*, *Paracaprella pusilla* and *Zeuxo marmoratus*), Isopoda (*Idotea balthica*, *Idotea metallica* and *Synidotea marplatensis*) and Pycnogonida have been also reported from floating plastic debris, but mostly on early detached buoys (see Thiel and Gutow, 2005b; Astudillo *et al*., 2009; Rocha Farrapeira, 2011; Goldstein *et al*., 2014).

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MOLLUSCA

Bivalves are common epibionts on floating plastic litter but gastropods may occur as well. Barnes and Fraser (2003) reported the gastropod *Laevilacunaria antarctica* on a plastic packaging band in the Southern Ocean, whilst Scarabino (2004) reported *Litiopa melanostoma* on a plastic tube. This species was also reported by Goldstein *et al*. (2014). Even vermetid gastropods may be associated with plastic debris, as reported in Breves and Skinner (2014) for *Petaloconchus varians*. Astudillo *et al*. (2009) reported 19 taxa on detached plastic buoys, including six different "opisthobranch" species. Aliani and Molcard (2003) also reported a *Doto* from the Mediterranean Sea. A usual species reported on plastic debris is the pelagic *Fiona pinnata*, often feeding on *Lepas* spp., that in turn are common cirripedia associated to both antropogenic and natural floating debris (see above in Arthropoda) (Aliani and Molcard, 2003; Scarabino, 2004; Thiel and Gutow, 2005b). Goldstein *et al*. (2014) also reported *Odostomia tenuisculpta*. It should have been transported in association with its bivalve prey. Bivalves attaching to plastic debris with byssal threads, such as Arcidae, Mitilidae, Anomiidae, Pectinidae or Pteridae have often been reported. *Semimytilus algosus*, *Brachidontes granulatus* and *Argopecten purpuratus* were found on detached plastic buoys (Astudillo *et al*., 2009), whilst Winston *et al*. (1997) reported *Anomia*, *Pinctada*, *Pteria* and *Isognomon* species. Also Gregory (2009) reported *Pinctada* from Bermuda, and *Pinctada imbricata* was found on floating plastic off Brasil (review in Rocha Farrapeira, 2011). Goldstein *et al*. (2014) listed an unidentified Arcidae, *Chlamys* and *Pinctada* species and *Mytilus galloprovincialis*. *Mytilus edulis* was also found on marine litter at several sites (review in Thiel and Gutow, 2005b). Even cemented species, such as Ostreidae and relatives, may be easily transported throughout floating plastic. Winston *et al*. (1997) reported the non-indigenous oyster *Lopha cristagalli* on plastics washed ashore in southern New Zealand, and a *Crassostrea* and a *Chama* species (Chamidae) in Florida. Goldstein *et al*. (2014) reported *Crassostrea gigas* on floating plastic.

CNIDARIA

Cnidarian polypoid phases or Anthozoa can be easily found on floating plastic debris. Several species of the genus Clytia (*Clytia gregaria*, *Clytia hemisphaerica* and *Clytia gracilis*) have been recorded as such (review in Thiel and Gutow, 2005b; Goldstein *et al*., 2014), while Aliani and Molcard (2003) also reported *Laomedea angulata*, *Obelia dichotoma*, *Eudendrium* sp. and *Gonothyraea loveni* from the Mediterranean Sea. In turn, a congeneric of the latter, *Gonothyraea hyalina*, has been found in the Sargasso Sea (Carpenter and Smith, 1972). Winston *et al*. (1997) also recorded a *Millepora* sp. and *Phyllangia americana* from off Florida, and the latter has been also recorded from off Brasil (see below). Jokiel (1984) reported a *Pocillopora* species. Hoeksema *et al*. (2012) reported trans-Atlantic rafting by the brooding reef coral *Favia fragum*. Astudillo *et al*. (2009) reported *Plumularia setacea*, an *Obelia* species and further hydrozoans, as well as the anthozoa *Anthothoe chilensis*, on detached buoys off Chile. Five cnidarians (*Aglaophenia latecarinata*, *Halecium nanum*, *Plumularia strictocarpa*, *Rhizogeton sterreri* and *Phyllangia americana*) have also been reported on floating plastic off Brasil (review in Rocha Farrapeira, 2011).

ANNELIDA

Several annellids have been reported on floating plastics. Winston *et al*. (1997) reported *Hydroides dianthus* and *Hydroides elegans* from off Florida and New Zealand, respectively. Aliani and Molcard (2003) listed *Nereis falsa* and *Spirobranchus polytrema*, whilst Rocha Farrapeira (2011) included *Hydroides dianthus* from off Brasil, a taxa well known as a worldwide invader. Three Spirorbinae species (*Spirorbis spirorbis*, *Spirorbis corrugatus* and *Circeis spirillum*) have also been recorded on plastic debris (see Thiel and Gutow, 2005b). Astudillo *et al*. (2009) listed 19 taxa from detached plastic buoys (including *Romanchella pustulata*, *Dodecaceria opulens*, *Autolytus simplex*, *Typosyllis magdalena*, *Platynereis australis*, *Pseudonereis gallapagensis*, *Halosydna patagonica* and *Steggoa magalhaensis*), whilst Goldstein *et al*. (2014) reported at least 14 taxa, including *Amphinome rostrata* and *Hipponoe gaudichaudi*.

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OTHER

Carson *et al*. (2013b) reported *Bacillus* and coccoid bacteria, as well as the radiolarian *Circorrhegma dodecahedra*, between plastic-associated microorganisms of the North Pacific Gyre. Goldstein *et al*. (2014) found different folliculinid ciliates belonging to the genus *Halofolliculina*, pathogens that cause skeletal eroding band (SEB) disease in corals, and suggested that floating plastic debris facilitated the dispersal of *Halofolliculina* to new areas. Other taxa found on plastic floating debris include Echinodermata (*Arbacia lixula*: Aliani and Molcard, 2003; *Patiria chilensis* and *Tetrapygus niger*: Astudillo *et al*., 2009), Foraminifera (*Acervulina* sp. and *Homotrema rubra*: Winston *et al*., 1997; *Planulina ornata*: Goldstein *et al*., 2014; *Rosalina globularis*: Jorissen, this volume), Porifera (*Halichondria panacea* and *Sycon* spp.: Goldstein *et al*., 2014), Platyhelminthes (Astudillo *et al*., 2009; Goldstein *et al*., 2014), Nemertinea (Astudillo *et al*., 2009) and Chordata (*Pyura chilensis*, *Ciona intestinalis* and *Diplosoma* sp.: Astudillo *et al*., 2009).

Marine litter as a pathway in the Mediterranean

Based on the present review of the capacity of many species to use floating litter as a means to extend their distribution, we assessed which of the species reviewed by Zenetos *et al*. (2012) could have potentially used or can use litter as a primary or secondary means of translocation. In many cases, plastic can be colonized more easily than metals painted by anti-fouling paints (e.g. vessel hauls), and thus species that have been reported to foul the hauls of vessels can, quite probably, colonize floating plastic as well. We defined three categories of increasing probability of litter acting as a primary or secondary vector for the assessed species:

- category 1: the species has been reported to attach to floating marine litter;
- category 2: shipping/fouling has been reported as a probable vector of introduction;
- category 3: the species could potentially attach to floating marine litter, as judged based on its life cycle and traits, e.g. shallow water byssed bivalves, bryozoans, ascidians, hard-substrate polychaetes, barnacles, hydrozoans with a polypod stage.

We found that 81% of the species having been reported to be introduced in the Mediterranean Sea by a different pathway, might have been introduced by marine litter or could use litter for further expanding their range (Categories 1, 2, and 3; Fig. 3). Category 1 included thirteen species: the alga *Codium fragile fragile*, the bryozoans *Electra tenella* and *Rhynchozoon larreyi*, the crustaceans *Caprella scaura*, *Jassa marmorata*, *Amphibalanus eburneus*, *Austrominius modestus*, and *Balanus trigonus*, the molluscs *Crassostrea gigas* and *Pinctada imbricata radiata*, and the polychaetes *Platynereis australis*, *Hydroides dianthus*, and *Hydroides elegans*.

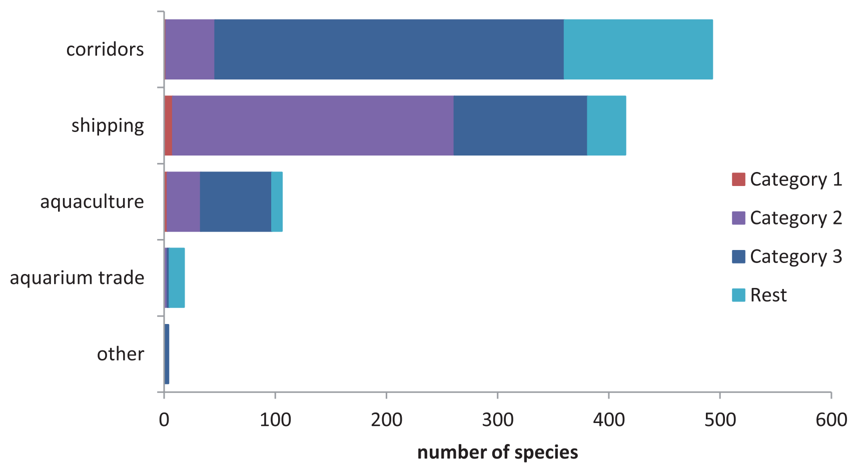

Figure 3. Number of alien marine species known or likely to be introduced by each of the main pathways (after Zenetos *et al*., 2012). For each pathway, the number of aliens that could have been initially introduced by marine litter or may potentially use marine litter as a means of secondary range expansion are indicated (Categories 1–3). For the definition of the three categories of uncertainty see the text.

The role of marine litter as a vector of primary introductions or translocations of alien species in the Mediterranean Sea appears largely underestimated and needs further investigation. In the absence of any such targeted survey in the Mediterranean, we may not properly assess the potentially important role of marine litter.