Plastic as a Vector of Dispersion for Marine Species With Invasive Potential. A Review

José Carlos García-Gómez1,2,3*, Marta Garrigós2* and Javier Garrigós2*

1 Laboratorio de Biología Marina, Facultad de Biología, Universidad de Sevilla, Seville, Spain, 2 Área de Investigación I+D+i del Acuario de Sevilla, Seville, Spain, 3 Estación de Biología Marina del Estrecho, Ceuta, Spain

Plastic debris constitutes up to 87% of marine litter and represents one of the most frequently studied vectors for marine alien species with invasive potential in the last 15 years. This review addresses an integrated analysis of the different factors involved in the impact of plastic as a vector for the dispersal of marine species. The sources of entry of plastic materials into the ocean are identified as well as how they move between different habitats affecting each trophic level and producing hot spots of plastic accumulation in the ocean. The characterization of plastic as a dispersal vector for marine species has provided information about the inherent properties of plastics which have led to its impact on the ocean: persistence, buoyancy, and variety in terms of chemical composition, all of which facilitate colonization by macro and microscopic species along with its dispersion throughout different oceans and ecosystems. The study of the differences in the biocolonization of plastic debris according to its chemical composition provided fundamental information regarding the invasion process mediated by plastic, and highlighted gaps of knowledge about this process. A wide range of species attached to plastic materials has been documented and the most recurrent phyla found on plastic have been identified from potentially invasive macrofauna to toxic microorganisms, which are capable of causing great damage in places far away from their origin. Plastic seems to be more efficient than the natural oceanic rafts carrying taxa such as Arthropoda, Annelida, and Mollusca. Although the differential colonization of different plastic polymers is not clear, the chemical composition might determine the community of microorganisms, where we can find both pathogens and virulent and antibiotic resistance genes. The properties of plastic allow it to be widely dispersed in practically all ocean compartments, making this material an effective means of transport for many species that could become invasive.

Keywords: plastic debris, alien species, marine exotic species, plastic dispersion, marine ecosystem, non-indigenous species

INTRODUCTION

Marine ecosystems around the world are threatened by several factors related to human activity (Ibabe et al., 2020), such as biological invasions (Ojaveer et al., 2015). Invasive species generally have a strong influence on the invaded environment, altering the structure of the community and the functions of the ecosystem, through competition with native species (Bertness, 1984), introduction of pathogens (Rilov and Crooks, 2009b), or indirect changes in habitat conditions (Crooks, 2002).
The exponential increase in the rate of invasive alien species (IAS) over the last decades has stimulated the study of biological invasions (Seebens et al., 2017), especially in the marine environment, which has received less attention compared to the terrestrial one (Davis, 2000; Katsanevakis et al., 2014). In addition to traditional marine vectors (biofouling and ballast water), which gained importance with the development of commercial shipping (Carlton, 1987; Clarke Murray et al., 2014), new challenges were added to the study of dispersion factors, such as plastic materials (see Audrézet et al., 2020; previous and complementary article of this review, mainly focused on the biosecurity of marine plastic debris and the knowledge gaps and research priorities that exist on this topic), other materials derived from aquaculture or aquarium hobbies (Rilov and Crooks, 2009b; Walters et al., 2011).

Plastic is a potential dispersal vector of marine species (Rech et al., 2016). It is the most common marine debris, constituting 61–87% of all types of marine debris (Eriksen et al., 2014; Serra-Gonçalves et al., 2019), and is considered as one of the major threats to marine biodiversity (Avio et al., 2017). Plastic production has increased exponentially in the last 60 years, from 0.5 million tons in 1960, to almost 300 million tons in 2013 (PlasticsEurope, 2014) and 360 million tons in 2018 (PlasticsEurope, 2018). About 10% of plastic production has been introduced into marine ecosystems (Thompson, 2006) through land-based sources such as rivers, storm drains (Moore et al., 2011), urban runoff, sewage discharge, effluents from plastic manufacturing factories (Eerkes-Medrano et al., 2015), landfills or recycling points (Alomar et al., 2016), coastal areas due to the action of the wind, illegal dumping, fishing, and other human activities (Derraik, 2002). van Sebille et al. (2015) estimated that microplastics (MPs) in the oceans have reached 52.2 × 10^12 particles, 236,000 metric tons, mainly distributed in the centers of the subtropical gyres.

The global distribution, buoyancy, and high levels of colonization of plastic debris greatly facilitate the transport of microbial communities (Carson et al., 2013), algae, invertebrates, and fish (Goldstein et al., 2014) to non-native regions (Barnes, 2002). Marine plastic debris is not only a threat to marine wildlife, but also causes significant economic and ecological damage (Keswani et al., 2016) acting both as a vector for the primary introduction of alien species into remote regions, and as a secondary vector for the regional expansion of marine species (Rech et al., 2016; Audrézet et al., 2020).

Several gaps remain to be filled regarding the potential of plastic as a species vector. For example, the harmonization of methodological approaches to study marine litter in different environmental compartments (Galgani et al., 2019) or the impact caused by the secondary propagation, which is not yet sufficiently documented (National Oceanic and Atmospheric Administration Marine Debris Program, 2017). Also, understanding the biosecurity implications associated with plastics could be a vital step toward understanding, monitoring, and eventually mitigating its impacts on a global scale (Audrézet et al., 2020).

This work aims to identify the dispersal potential of plastic as a vector for alien species introductions and to compare it with other vectors, as well as to expose the qualitative composition of the communities that inhabit plastic debris. On the other hand, we attempt to synthesize the methodological aspects of the detection of AIS introduced through plastic debris and the prevention of their negative impacts.

**METHODOLOGY**

Scientific literature published in the last 30 years (1990–2020) was collected from Science Direct, Scopus, Web of Science, and Google Scholar scientific databases, and the most widely consulted publishers and/or scientific internet networks were Elsevier, Springer, ResearchGate, Wiley Online Library, Dialnet, and Academia. The keywords related to invasive species in the ocean, especially those carried by plastic debris, were used in the title and keywords field: “Alien Species,” “Ballast Water,” “Biofouling,” “Ecology,” “Ecosystem,” “Impact,” “Invasive Species,” “Marine,” “Management,” “Microplastics,” “Ocean,” “Plastic Debris,” “Rafting,” “Sea,” “Threat,” “Transport,” “Vector,” and “Waste.” The searches were conducted mostly in March 2020 on the full range of articles or reviews available at that time. The last search was made on April 20, 2020. This initial search yielded a total of 447 articles which included information on invasive and potentially invasive species in the ocean and different dispersal vectors. In this preliminary library, a pre-selection step was carried out according to the presence of at least one of three criteria: (1) articles focused on the impact caused by one or more invasive marine species; (2) articles focused on the management of the invasion of one or more marine species; or (3) articles that include both concepts. After applying these selection criteria, 228 articles were obtained, of which 48 were discarded after analysis because they were not directly related to the topic with respect to the sections considered in the manuscript. Therefore, most of the information presented in this paper was extracted from 180 scientific publications. In addition, other articles named in the literature and previously known to the authors due to their high topic relevance were used for the review.

Selected articles were classified according to the dispersion vector(s) (Plastic Debris, Boat hulls (biofouling), Climatic Events, Ballast Water, Aquaculture, or General), their publication date (1990–2005 or 2006–2020), and the aspect addressed: Impact (I), Management (M) or Impact+Management (I+M). Impacts included articles focused on describing the impacts produced by alien species, and Management included articles focused on the management of these impacts. We separated the last 30 years into two bands to appreciate the differences in the efforts made by scientists regarding different topics in the near past and at present. On the other hand, the label “General” was included for those papers that covered more than one vector.

For the invasive or potentially invasive species listed in Table 1, it was specified whether they were sessile or no sessile, in order to draw conclusions about the biology of the species inhabiting plastic. Also, it was specified the transport vector for which they were identified (Plastic Debris, Boat hulls (biofouling), Climatic Events, Ballast Water, Aquaculture, Aquariums, or Transoceanic Channels/Swimming). The native
and non-native locations of the invasive and potentially invasive species were indicated.

Moreover, other relevant information was extracted from the selected and related articles such as plastic as a vector, different types of plastic and how their characteristics affect the colonization of macro and microscopic marine species, recurrent species transported by plastics, associated microorganisms dispersion and species and dispersal patterns of plastic in the ocean and how they can influence horizontal and vertical transport.

**PLASTIC DEBRIS COMPARED TO OTHER DISPERSAL VECTORS**

With respect to the total number of articles, the labels that yielded the highest number of selected articles were “Boat hulls (biofouling)” and “Ballast Water” including I, M, and I + M, with 40 and 31 papers, respectively, followed by “Plastic Debris, Aquaculture and Climate Events” (21, 21, 15, respectively) (Figure 1).

In the last 15 years, the most frequent labels were “Plastic Debris-Impact,” and “Biofouling – Management” with 19 articles each. No articles were selected between 1990 and 2005 for the labels “Plastic Debris” and “Aquaculture.” There was also a great difference in the number of research papers on the management of invasive species from the dispersal vectors “Boat hulls (biofouling)” and “Ballast Water,” and the vectors “Plastic Debris,” “Aquaculture,” and “Climatic Events.”

Of the 216 exotic species identified in the present study (Table 1), 68% were considered to have been introduced through maritime transport, divided into the categories “Boat hulls (biofouling)” and “Ballast Water,” followed by dispersal as a consequence of the “Aquaculture” (16%), and “Plastic debris” (5%) (Figure 2).

This result is to be expected, as commercial shipping as a cause of IAS dispersal has been cited long before other vectors such as plastic (e.g., Carlton, 1987). Although it is a more recent problem, we consider that the studies on plastics as an IAS vector were quite important between 2005 and 2020. Furthermore, it is expected that the number of papers on plastic as a vector of species will increase in the coming years, as its production increases every year and it is currently an emergent topic.

**CHARACTERIZATION OF PLASTIC AS A VECTOR**

Plastic debris abundance (Winston et al., 1997), artificial origin (Glasby et al., 2007; Pinochet et al., 2020), and properties can affect its potential to act as a vector of IAS: durability, buoyancy (Schoener and Rowe, 1970), size, and structural complexity of the surface determine colonization by marine organisms and the succession of the community associated with plastic debris, with differences in the sessile and mobile organisms (Kiessling et al., 2015).

The increasing introduction of plastic pollution into the ocean increases the chances for alien species to become invasive. For example, the bryozoan *Electra tenella* [Hickins, 1880; this name is currently not accepted and it is *Arbopercula tenella* (Hickins, 1880)] previously identified on natural rafts, may be increasing in abundance and distribution due to the increasing amounts of plastic entering the Caribbean currents and the Gulf Stream (Winston et al., 1997). Natural rafts (eg, wood, pumice, and marine vegetation) are generally characterized by low or patchy abundance, limited longevity, and relatively high habitability, due to high surface roughness, structural complexity, and biodegradability (Gil and Pfaller, 2016). Compared to natural rafts, the abundance of plastic debris is increasing (Ebbesmeyer and Ingraham, 1992), and its longevity generally exceeds that of natural debris, taking decades or even centuries to be degraded (Gregory, 1999). The durability of plastic along with its buoyancy in comparison to organic materials (Schoener and Rowe, 1970) allows a greater dispersal potential for organisms that colonize plastic debris (Barnes, 2002; Barnes
| INVASIVE and potential invasive species | Plastics | Boat hulls (biofouling) | Climate events | Ballast water | Aquaculture | Aquariums | Transoceanic channels/swimming | Native location | Non-native or invaded location | References |
|----------------------------------------|----------|------------------------|----------------|--------------|-------------|-----------|-----------------------------|----------------|-----------------------------|------------|
| Algae (34)                             |          |                        |                |              |             |           |                              |                |                             |            |
| *Acrothamnion preissii* E.M.Wollaston, 1968 | X        | X                      | X              | X            |             |           | Indo-Pacific (Australia)    | Mediterranean Sea | Bonanno and Orlando-Bonaca, 2019 |
| *Agardhiella subulata* (C.Agardh) Kraft and M.J. Wynne, 1979 | X        |                        |                |              |             |           | Atlantic North America     | United Kingdom   | Eno et al., 1997               |
| *Antithamnionella spirographidis* (Schiffner) E.M. Wollaston, 1968 | X        |                        |                |              |             |           | Mediterranean Sea           | United Kingdom   | Eno et al., 1997               |
| *Antithamnionella ternifolia* (J.D.Hooker and Harvey) Lyle, 1922 | X        |                        |                |              |             |           | Australia                   | United Kingdom   | Eno et al., 1997               |
| *Asparagopsis armata* Harvey, 1855      |          |                        |                | X            | X            |           | Western Australia New Zealand | European coasts Northeast Atlantic Mediterranean Sea South Africa Middle East Indo-Pacific | Pinteus et al., 2018 |
| *Bonnemaisonia hamifera* Hariot, 1891  |          |                        |                |              | X            |           | X                           | Japan            | Northwest Pacific Europe      | Katsanevakis et al., 2014 |
| *Caulerpa cylindracea* Sonder, 1845     |          |                        |                | X            | X            |           | Indo Pacific                | Mediterranean Sea | Bonanno and Orlando-Bonaca, 2019 |
| *Caulerpa Olivieri* Dostál, 1929        | X        |                        |                | X            | X            |           | Mediterranean Sea           | Bahamas          | Williams, 2007                 |
| *Caulerpa taxifolia* (M.Vahl) C.Agardh, 1817 | X        |                        |                |              |             |           | Pacific Ocean               | Mediterranean Sea | Occhipinti-Ambrogi and Savini, 2003 |
| *Codium fragile tomentosoides* (1) (van Goor) P.C.Silva, 1955 | X        |                        |                | X            | X            |           | Japan                       | Northwest Atlantic | Williams, 2007                 |
| *Codium fragile atlanticum* (A.D.Cotton) P.C.Silva, 1955 |          |                        |                |              |             |           | Pacific coast of Japan      | United Kingdom   | Eno et al., 1997               |
| *Colpomenia peregrina* (2) (Sauvageau) Hamel, 1937 | X        |                        |                | X            |             |           | Pacific coast of North America | United Kingdom   | Eno et al., 1997               |
| *Durvillaea antarctica* (Charnisso) Hariot, 1892 | X        |                        |                |              |             |           | Chile Southern New Zealand South Atlantic | King George Island (Antarctica) | Fraser et al., 2018 |

(Continued)
| INVASIVE and potential invasive species | Plastics | Boat Hulls (biofouling) | Climate events | Ballast water | Aquaculture | Aquariums | Transoceanic channels/ swimming | Native location | Non-native or invaded location | References |
|----------------------------------------|----------|------------------------|----------------|--------------|-------------|-----------|---------------------------------|----------------|-------------------------------|------------|
| Eucheuma denticulatum (N.L.Burman) Collins and Hervey, 1917 | X | | X | | | | Sulu Sea | Indian Ocean | Williams, 2007 |
| Grateloupia doryphora (Montagne) M.Howe, 1914 | | | X | | | | Pacific North America | United Kingdom | Eno et al., 1997 |
| Grateloupia filicina var. luxurians (3) A.Gepp and E.S.Gepp, 1906 | | | X | | | | Japan | United Kingdom | Eno et al., 1997 |
| Grateloupia imbricata Holmes, 1896 | X | | | | | | Japan Korea | Portugal | Chainho et al., 2015 |
| Grateloupia lanceolata (4) (Okamura) Kawaguchi, 1997 | X | | | | | | East of Asia | Portugal | Chainho et al., 2015 |
| Grateloupia turuturu Yamada, 1941 | | | X | | | | Pacific ocean | Portugal | Chainho et al., 2015 |
| Halophila stipulacea (Forskål) Ascherson, 1867 | | | | X | | | Indo-Pacific | Mediterranean Sea | Hernández-Delgado et al., 2020 |
| Kappaphycus alvarezii (Doty) Doty ex P.C.Silva, 1996 | | | | | | | Sulu Sea (Philippines) | Southwest Pacific Indian Ocean | Williams, 2007 |
| Lomentaria clavellosa (Lightfoot ex Turner) Gaillon, 1828 | X | | X | | | | Northeast Atlantic | North America | Mathieson et al., 2008 |
| Lophocladia lallemandii (Montagne) F.Schmitz, 1893 | X | | | | X | | Indo-Pacific | Northern Coast Ibiza | García-Gómez et al., 2020b |
| Mastocarpus papillatus (C.Agardh) Kützing, 1843 | | X | | | | | North Pacific | Chile | Castilla and Neill, 2009 |
| Monostroma oxyspermum (5) (Kützing) Doty, 1947 | | | X | | | | Northeast Atlantic | Northwest Pacific | Ani et al., 2002 |
| Neosiphonia harveyi (6) (Bailey) M.-S.Kim, H.-G.Choi, Guiry and G.W.Sanders, 2001 | X | | | | X | | Japan North-Pacific | Pacific coast of Japan | Argentina United Kingdom | Eno et al., 1997; Schwindt et al., 2014 |
| Polysiphonia harveyi (6) Bailey, 1848 | X | | | | | | | | |
| Pikea californica Harvey, 1853 | X | | | | | | North America | United Kingdom | Eno et al., 1997 |
| Table 1 (Continued) |
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| **INVASIVE and potential invasive species** | **Plastics** | **Boat hulls (biofouling)** | **Climate events** | **Ballast water** | **Aquaculture** | **Transoceanic channels/serpentine** | **Native location** | **Non-native or invaded location** | **References** |
| Polysiphonia morrowii Harvey, 1857 | X | X | X | X | | | Northeast Asia | Chile | Castilla and Neill, 2009 |
| Rugulopteryx okamurae* (E.Y.Dawson) I.K.Hwang, W.J.Lee and H.S.Kim, 2009 | X | X | X | | | | Pacific northern | Strait of Gibraltar (Cádiz, Spain) Thau Lagoon (France) Western Mediterranean | Huang, 1994; Verlaque et al., 2009; García-Gómez et al., 2018 |
| Sargassum filicinum (7) Harvey, 1860 | X | | | | | | Japan and Korea | California (UNITED STATES) | Miller et al., 2006 |
| Solieria chordalis (C.Agardh) J. Agardh, 1842 | X | X | X | | | | Northern France | United Kingdom | Eno et al., 1997 |
| Undaria pinnatifida (Harvey) Suringar, 1873 | X | | X | | | | Northwest Pacific | Spain France United Kingdom Belgium The Netherlands New Zealand Australia Argentina | Epstein and Smale, 2017 |
| Womersleyella setacea (Hollenberg) R.E.Norris, 1992 | X | X | X | | | | Pacific | Mediterranean Sea | Williams, 2007 |
| **Porifera (4)** | X | X | | X | | | Mediterranean Sea | Portugal | Chainho et al., 2015 |
| Crambe crambe (Schmidt, 1862) | X | X | | | | | Philippines | Pearl Harbor (Oahu, Hawaii) | Godwin, 2003; Therriault et al., 2018 |
| Gelliodes fibrosa (8) (Wilson, 1925) | X | | | | | | Brazil | Portugal | Chainho et al., 2015 |
| Paraleucilla magna Klaatu, Monteiro and Borovjic, 2004 | X | | | | | | North Pacific | Chile | Castilla and Neill, 2009 |
| Stelletta clarella de Laubenfels, 1930 | X | X | | | | | Mediterranean Sea | Portugal | Chainho et al., 2015 |
| **Cnidaria (16)** | X | X | | X | | | Eastern Atlantic Mediterranean Sea | Portugal | Chainho et al., 2015 |
| Aiptasia diaphana (9) (Rapp, 1829) | X | | | | | | Black Sea Norest Atlantic | Caspian Sea | Korsun et al., 2012 |
| Amelia aurita (Linnaeus, 1758) | X | X | | | | | Baltic Sea | Portugal | Chainho et al., 2015 |
| Blackfordia virginica Mayer, 1910 | X | X | | | | | West Pacific | Northeast Pacific | Williams, 2007 |
| Cladonema radiatum Dujardin, 1843 | X | X | | | | | East Pacific | Ilha Grande Bay (Brazil) | Mantelatto et al., 2018 |
| Clavularia viridis Quoy and Gaimard, 1833 | X | | | | | | Indo-Pacific | | |

(Continued)
| INVASIVE and potential invasive species | Plastics | Boat hulls (biofouling) | Climate events | Ballast water | Aquaculture | Aquariums | Transoceanic channels/ swimming | Native location | Non-native or invaded location | References |
|----------------------------------------|----------|-------------------------|----------------|---------------|-------------|-----------|---------------------------------|----------------|--------------------------------|------------|
| *Cordylophora caspia* (Pallas, 1771)   | X        | X                       | X              | X             |             |           | Caspian Sea Black Sea           | Portugal       | Caspian Sea Black Sea           | Chainho et al., 2015 |
| *Diadumene lineata* (Verrill, 1869)   |          |                         | X              |               |             |           | Northwest Pacific (Japan)       | Northwest Atlantic | Williams, 2007; Gregory, 2009; Miller et al., 2018 |
| *Garveia franciscana* (10) (Torrey, 1902) |          |                         | X              |               |             |           | Indo-Pacific                     | Mediterranean Sea | Marchini et al., 2015b |
| *Gonionemus vertens* A. Agassiz, 1862 | X        |                         | X              | X             |             |           | North Pacific Portugal           | Northwest Atlantic United Kingdom | Eno et al., 1997; Williams, 2007 |
| *Haliplanella lineata* (11) (Verrill, 1869) |          |                         | X              |               |             |           | Pacific Japan                    | United Kingdom   | Eno et al., 1997 |
| *Oculina patagonica* de Angelis, 1908 |          |                         | X              |               |             |           | South West Atlantic              | Mediterranean Sea | Fine et al., 2001 |
| *Rhizostoma pulmo* (Macri, 1778)      |          |                         |                |               |             |           | Southern North Sea               | Black Sea       | Boran, 2017 |
| *Rhophilema nomadica* Galli, Spanier and Ferguson, 1990 |          |                         |                |               |             |           | Indo-Pacific                     | Mediterranean Sea | Bonanno and Orlando-Bonaca, 2019 |
| Sansia spp.                           |          |                         |                |               |             |           | Indo-Pacific                     | Ilha Grande Bay (Brazil) | Mantelatto et al., 2018 |
| *Tubastraena coccinea* (Ehrenberg, 1834) |          |                         |                |               |             |           | Unknown (widespread distribution) | Southwest Atlantic | Creed et al., 2017 |
| *Tubastraena tagusensis* Wells, 1982  |          |                         |                |               |             |           | Galapagos archipelago             | Southwest Atlantic | Creed et al., 2017 |
| Ctenophora (2)                        |          |                         |                |               |             |           |                                 |                 |                                 |            |
| *Beroe ovata* Bruguière, 1789         |          |                         |                |               |             |           | East Atlantic (North and South America) | Black Sea Denmark | Shiganova et al., 2014 |
| *Mnemiopsis leidyi* A. Agassiz, 1865  |          |                         |                |               |             |           | West Atlantic                     | Black Sea       | Shiganova et al., 2019 |
| Platyhelminthes (1)                   |          |                         |                |               |             |           |                                 |                 |                                 |            |
| *Koinosystochus ostreophagus* (Hyman, 1955) |          |                         |                |               |             |           | Northwest Pacific                | Strait of Georgia (Canada) | Gartner et al., 2016 |
| Nematoda (1)                          |          |                         |                |               |             |           |                                 |                 |                                 |            |
| *Angulicola crassus* (12) Kuwahara, Námi and Itagaki, 1974 |          |                         |                |               |             |           | Taiwan                          | United Kingdom   | Eno, 1996 |
| Mollusca (44)                         |          |                         |                |               |             |           |                                 |                 |                                 |            |
| *Arcuatula senhousia* (Benson, 1842)  |          |                         |                |               |             |           | Indo-Pacific                     | Mediterranean Sea | Bonanno and Orlando-Bonaca, 2019 |
| *Batillaria atramentaria* (G. B. Sowerby II, 1855) |          |                         |                |               |             |           | Asia                            | California (UNITED STATES) | Grosholz et al., 2015 |

(Continued)
| INVASIVE and potential invasive species | Plastics | Boat hulls (biofouling) | Climate events | Ballast water | Aquaculture | Aquariums | Transoceanic channels/ swimming | Native location | Non-native or invaded location | References |
|----------------------------------------|----------|------------------------|----------------|--------------|-------------|-----------|--------------------------------|----------------|-------------------------------|-------------|
| Chaetopleura angulata (Spengler, 1797) |          | X                      |                | X            | X           |           |                                | Brazil         | Portugal                       | Chainho et al., 2015 |
| Chama macerophylla Gmelin, 1791        |          |                        |                |              |             |           |                                |                |                               |             |
| Crassostrea gigas (Thunberg, 1793)     |          | X                      |                | X            |             |           |                                | Asian Pacific Ocean | New Zealand               | Chainho et al., 2015 |
| Crassostrea virginica (Gmelin, 1791)   |          | X                      |                | X            |             |           |                                | Northeast America | North Sea                   | Gollasch, 2002     |
| Crepidula fornicta (Linnaeus, 1758)   |          |                        |                |              |             |           |                                | Atlantic coast of North America | Norway                   | Minchin and Gollasch, 2005 |
| Crepidula onyx G. B. Sowerby I, 1824  |          |                        |                |              |             |           |                                | Northwest Pacific | Northeast Pacific           | Miller et al., 2018   |
| Dreissena polymorpha (Pallas, 1771)    |          |                        |                |              |             |           |                                | Caspian Sea Black Sea | St Clair lake (North America) | Hebert et al., 1991 |
| Ensis americanus (13) Gould, 1870      |          |                        |                | X            |             |           |                                | Atlantic North America | United Kingdom           | Eno et al., 1997     |
| Halolit rufescens Swainson, 1822       |          |                        |                |              |             |           |                                | North Pacific | Chile Peru                   | Castilla and Neill, 2009 |
| Hexaplex trunculus (Linnaeus, 1758)    | X        |                        |                | X            |             |           |                                | Mediterranean Sea | Portugal                    | Chainho et al., 2015 |
| Lopha cristagalli (Linnaeus, 1758)     |          |                        |                |              |             |           |                                | Indo-Pacific | Southwestern New Zealand | Gregory, 2009     |
| Lyrodus mediiobata (Edmonson, 1942)    |          |                        |                |              |             |           |                                | Indo-Pacific Ocean | West coast of India        | Anil et al., 2002   |
| Lyrodus takanothimensis (Roch, 1929)   |          |                        |                |              |             |           |                                | Northwest Pacific | Northeast Pacific           | Miller et al., 2018   |
| Magallana angulata (Lamarck, 1819)     |          |                        |                |              |             |           |                                | Pacfic Ocean (New Zealand) | North Sea               | Gollasch, 2002       |
| Magallana gigas (Thunberg, 1793)       | X        |                        |                |              |             |           |                                | Pacfic Ocean | Southern Portuguese coast    | Rech et al., 2018b   |
| Mercenaria mercenaria (Linnaeus, 1758) |          |                        |                |              |             |           |                                | Indo-Pacific Ocean | Mediterranean Sea Cantabrian Coast | Mirailes et al., 2018; Bonanno and Orlando-Bonaca, 2019 |
| (Continued)                            |          |                        |                |              |             |           |                                | West Atlantic | Great Britain                | Williams, 2007     |
| INVASIVE and potential invasive species | Boat hulls (biofouling) | Climate events | Ballast water | Aquaculture | Aquariums | Transoceanic channels/ swimming | Native location | Non-native or invaded location | References |
|----------------------------------------|-------------------------|----------------|---------------|-------------|-----------|--------------------------------|----------------|-----------------------------|------------|
| *Muscus senhousia* (15) (Benson, 1842) | X                       |                |               |             |           | West Pacific                    | California     | Black Sea, Sea of Azov      | Williams, 2007 |
| *Mya arenaria* Linnaeus, 1758           | X                       |                |               |             |           | Northern Atlantic               |                | Black Sea, Sea of Azov      | Occhipinti-Ambrogi and Savini, 2003 |
| *Mytilus arenaria* (16) (d’Orbigny, 1846) | X                       |                |               |             |           | Atlantic South America          | South-east North America |                | Spinuzzi et al., 2013 |
| *Mytilus galloprovincialis* Lamarck, 1819 | X                       |                |               |             |           | Japan                          | Pearl Harbour (Hawaii) | Therriault et al., 2018 |
| *Nassarius costellifera* (17) (A. Adams, 1853) | X                       |                |               |             |           | North Atlantic North Pacific Baltic Sea | Cantabrian Coast | Mralles et al., 2018 |
| *Nassa tora dunlopi* E. P. Wright, 1864 | X                       |                |               |             |           | Japan                          | Cochin (India) | Goa (India) | Ani et al., 2002 |
| *Ostrea lurida* Carpenter, 1864        | X                       |                |               |             |           | Pacific North America           | North Sea      |                | Gofasch, 2002 |
| *Perna viridis* (Linnaeus, 1758)       | X                       |                |               |             |           | Tropical Indo-Pacific           | Florida Colombian Caribbean | Spinuzzi et al., 2013; Gracia and Rangel-Buitrago, 2020 |
| *Philine auriformis* Suter, 1909        | X                       |                |               |             |           | Asia                           | San Francisco (UNITED STATES) | Godwin, 2003; Therriault et al., 2018 |
| *Potamopyrgus antipodarum* (Gray, 1843) | X                       |                |               |             |           | New Zealand                    | Portugal Baltic Sea | Leppäkoski and Olenn, 2000; Chainho et al., 2015 |
| *Rapana venosa* (Valenciennes, 1846)   | X                       |                |               |             |           | Sea of Japan                    | Black Sea Adriatic Sea | Occhipinti-Ambrogi and Savini, 2003 |
| *Ruditapes philippinarum* (A. Adams and Reeve, 1850) | X                       |                |               |             |           | Indo-Pacific                    | Portugal        | Braga et al., 2017 |
| *Saccostrea cucullata* (Born, 1778)    | X                       | X              |               |             |           | Indo-Pacific                    | South Brazilian coast | do Amaral et al., 2020 |

(Continued)
| Invasive and potential invasive species | Plastics | Boat hulls (biofouling) | Climate events | Ballast water | Aquaculture | Aquariums | Transoceanic channels/ swimming | Native location | Non-native or invaded location | References |
|-----------------------------------------|----------|------------------------|---------------|--------------|-------------|-----------|-------------------------------|----------------|-----------------------------|------------|
| Scapharca inaequivalvis (19) (Bruguière, 1789) | X | | | | | | Indo-Pacific | Black Sea Adriatic Sea | Occhipinti-Ambrogi and Savini, 2003 |
| Senilia senilis (Linnaeus, 1758) | X | | | | | | North east Atlantic | North Sea | Gotfiasch, 2002 |
| Teredo fulleri (Clapp, 1924) | X | | | | | | Gulf of Mannar (Southeast India) | Okha (West India) | Anil et al., 2002 |
| Teredo navalis Linnaeus, 1758 | X | | | | | | Northeast Atlantic | Florida (UNITED STATES) | Miller et al., 2018 |
| Theora lubrica Gould, 1861 | X | X | | | | | Inland Sea (Qatar) | San Francisco Bay (UNITED STATES) | Carlton, 1996 |
| Tonicia atrata (20) (Linnaeus, 1767) | X | X | | | | | Europe | Portugal | Chainho et al., 2015 |
| Urosalpinx cinerea (Say, 1822) | X | X | | | | | North America | United Kingdom | Eno, 1996 |
| Xenostrobus securis (Lamarck, 1819) | X | | | | | | Western Australia New Zealand | North Sea | Gotfiasch, 2002 |
| Annelida (21) | | | | | | | | | |
| Branchiomma bairdi (McIntosh, 1883) | X | | | | | | Caribbean Sea | Portugal | Chainho et al., 2015 |
| Clymenella torquata (Leidy, 1855) | X | | | | | | Western Atlantic | United Kingdom | Eno et al., 1997 |
| Eulalia viridis (Linnaeus, 1767) | X | | | | | | North Atlantic | Strait of Georgia (Canada) | Gartner et al., 2016 |
| Eumida sanguinea (Orsted, 1843) | X | | | | | | Northeast Atlantic | Strait of Georgia (Canada) | Gartner et al., 2016 |
| Ficopomatus enigmaticus (Fauvel, 1923) | X | X | | | | | Indian Ocean | Black Sea | Occhipinti-Ambrogi and Savini, 2003 |
| Goniadella gracilis (Verrill, 1873) | X | | | | | | North America | United Kingdom | Eno et al., 1997 |
| Hydroides dianthus (Verrill, 1873) | X | X | | | | | Atlantic North America | United Kingdom | Eno et al., 1997; Katsanevakis et al., 2014 |
| Hydroides elegans (Haswell, 1883) [nomen protectum] | X | | | | | | Indo-Pacific Northwest Pacific | Australia | Bryan et al., 2004 |
| Hydroides ezoensis Okuda, 1934 | X | X | | | | | Japan | United Kingdom Tropical North Pacific | Eno et al., 1997 |
| Hydroides sanctaebricius Kroyer in Mörch, 1863 | X | | | | | | Caribbean Sea | Northern Australia | Lewis et al., 2006 |
| Janua brasiliensis (21) (Grube, 1872) | X | | | | | | Tropical areas (e.g., Brazil) | United Kingdom | Eno et al., 1997 |

(Continued)
| INVASIVE and potential invasive species | Plastics | Boat hulls (biofouling) | Climate events | Ballast water | Aquaculture | Aquariums | Transoceanic channels/ swimming | Native location | Non-native or invaded location | References |
|----------------------------------------|----------|------------------------|---------------|--------------|-------------|-----------|-------------------------------|----------------|-------------------------------|------------|
| Marenzelleria viridis (Verrill, 1873)  |          | X                      |               | X            |             |           |                               |                | North America                  | Baltic Sea  |
| Mercierella enigmatica (22) (Fauvel, 1923) |          |                        |               |              |             |           |                               |                | Australia                      | Indian Ocean|
| Neodexiospira brasiliensis (Grube, 1872) |          |                        |               |              |             |           |                               |                | South America                  | Northwest Atlantic Great Britain |
| Parougia caeca (Webster and Benedict, 1884) |          | X                      |               |              |             |           |                               |                | North America                  | Johnstone Strait (Canada)          |
| Pileolaria berkeleyana (Ronea, 1942)   |          |                        |               | X            | X           | X         |                               |                | Japan                          | United Kingdom         |
| Polydora cornuta Bosc, 1802            |          | X                      |               | X            |             |           |                               |                | Unknown                        | Black Sea                          |
| Pseudopolydora kempii japonica         |          |                        |               | X            |             |           |                               |                | Japan                          | Northwest Pacific       |
| Sabaco elongatus (Verrill, 1873)       |          | X                      |               |              |             |           |                               |                | West Atlantic                   | Northwest Pacific       |
| Sabella spallanzanii (Gmelin, 1791)    |          |                        |               | X            |             |           |                               |                | Mediterranean Sea               | New Zealand |
| Streblospio benedicti Webster, 1879    |          |                        |               | X            |             |           |                               |                | West Atlantic                   | Northwest Pacific       |
| Arthropoda (51)                        |          |                        |               |              |             |           |                               |                |                               |            |
| Acarina (Acartiura) omori Bradford, 1976 |          | X                      |               |              |             |           |                               |                | North Pacific                   | Chile                  |
| Acarina (Acanthacartia) tonsa Dana, 1849 |          |                        |               | X            |             |           |                               |                | Indo-Pacific                    | Portugal            |
| Ammotoidea hilgendorf (Bohn, 1879)     |          | X                      |               |              |             |           |                               |                | Japan                          | United Kingdom         |
| Amphibalanus amphiocrine (Darwin, 1854) |          |                        |               | X            |             |           |                               |                | Unknown                        | Cantabrian Coast       |
| Amphibalanus improvisus (Darwin, 1854)  |          |                        |               | X            |             |           |                               |                | Western Atlantic                 | Strait of Georgia (Canada, Northwest Pacific) |

(Continued)
| INVASIVE and potential invasive species | Plastics | Boat hulls (biofouling) | Climate events | Ballast water | Aquaculture | Aquariums | Transoceanic channels/ swimming | Native location | Non-native or invaded location | References |
|----------------------------------------|----------|------------------------|---------------|--------------|-------------|-----------|-------------------------------|----------------|-------------------------------|------------|
| Amphibalanus reticulatus (Utinomi, 1967) | X        | X                      |               | X            | X           |           |                               | Japan          | Southern Brazil                | Kauano et al., 2016 |
| Amphiotea valida Smith, 1873            | X        | X                      |               | X            | X           |           |                               | Japan          | Strait of Georgia (Canada)     | Williams, 2007    |
| Austrominius modestus (Darwin, 1854)   |          |                        |               |              |             |           |                               |                | Australia New Zealand          |                       |
| Balanus amphitrite (23) Darwin, 1854   | X        |                        |               |              |             |           |                               | Japan Korea     | North Sea                      | Gollasch, 2002    |
| Balanus campbelli (24) Fihol, 1866      | X        |                        |               |              |             |           |                               | New Zealand     | North Sea                      | Gollasch, 2002    |
| Balanus eburneus (25) Gould, 1841       | X        |                        |               |              |             |           |                               | North America   | North Sea                      | Gollasch, 2002    |
| Balanus perforatus (26) Bruguère, 1789  | X        |                        |               |              |             |           |                               | Northeast Atlantic | North Sea                      | Gollasch, 2002    |
| Balanus variegatus (27) Darwin, 1854    | X        |                        |               |              |             |           |                               | Fare East Australia India | North Sea                      | Gollasch, 2002    |
| Callinectes sapidus Rathbun, 1896       |          |                        | X             |              |             |           |                               | Western Atlantic Ocean | Portugal                      | Chainho et al., 2015 |
| Caprella drepanochir Mayer, 1890        | X        |                        |               |              |             |           |                               | North Pacific    | Strait of Juan de Fuca (Canada) | Gartner et al., 2016 |
| Caprella mutica Schurin, 1935           | X        | X                      | X             | X            |             |           |                               | Northwestern Pacific Ocean (Japan) | Strait of Georgia (Canada) | Gartner et al., 2016 |
| Caprella scaura Templeton, 1836         | X        | X                      | X             | X            |             |           |                               | Indo Pacific     | Girona (Spain)                 | Martinez and Adarraga, 2008 |
| Carcinus maenas (Linnaeus, 1758)        | X        |                        |               |              |             |           |                               | Northeast Atlantic | North America South Africa    | Grosholz and Ruiz, 1995 |
| Centropages abdominalis Sato, 1913      | X        | X                      |               |              |             |           |                               | North Pacific    | Chile                         | Castilla and Neill, 2009 |
| Cercopagis pengoi (Ostrovoumov, 1891)    |          |                        | X             |              |             |           |                               | Caspian Sea      | Baltic Sea                     | Leppäkoski and Olenin, 2000 |
| Cilicaea latreillei Leach, 1818         | X        |                        |               |              |             |           |                               | Japan Korea      | New Zealand                    | Brine et al., 2013  |
| Diamydis lagunaris Ariani and Wittmann, 2000 |          |                        | X             |              |             |           |                               | Mediterranean Sea Black Sea | Portugal                      | Chainho et al., 2015 |

(Continued)
| INVASIVE and potential invasive species | Plastics | Boat hulls (biofouling) | Climate events | Ballast water | Aquaculture | Aquariums | Transoceanic channels/ swimming | Native location | Non-native or invaded location | References |
|----------------------------------------|----------|------------------------|----------------|--------------|-------------|-----------|---------------------------------|----------------|-------------------------------|------------|
| *Dynamene bidentata* (Adams, 1800)     |          | X                      |                |              |             |           |                                 | Northeast Atlantic | North Sea                      | Gollasch, 2002 |
| *Elminius kingii* Gray, 1831           |          | X                      |                |              |             |           |                                 | South America     | North Sea East cost of Canada  | Gollasch, 2002 |
| *Elminius modestus* (28) Darwin, 1854  |          | X                      |                |              |             |           |                                 | New Zealand       | United Kingdom Shetland Islands | Eno et al., 1997; Barnes and Milner, 2004 |
| *Elminius simplex* Linzey (1942)       |          | X                      |                |              |             |           |                                 | Indian Ocean Australia | North Sea East cost of Canada | Gollasch, 2002 |
| *Endeis nodosa* Hilton, 1942           |          | X                      |                |              |             |           |                                 | Northwest Pacific  | Tropical Eastern Atlantic       | Miller et al., 2018 |
| *Eriocheir sinensis* H. Milne Edwards, 1853 |          | X                      |                |              |             |           |                                 | Japan China        | United Kingdom                | Eno et al., 1997 |
| *Hemigrapsus penicillatus* (De Haan, 1835 [in De Haan, 1833-1850]) |          | X                      |                |              |             |           |                                 | Fare East (Japan, China, Korea) | North Sea French Atlantic coast | Gollasch, 2002 |
| *Hemigrapsus sanguineus* (De Haan, 1835 [in De Haan, 1833-1850]) |          | X                      |                |              |             |           |                                 | Japan             | Hawaii Northeast Pacific       | Therriault et al., 2018 |
| *Hesperibalanus fallax* (Broch, 1927)  |          | X                      |                |              | X           |           |                                 | Atlantic Coast of tropical Africa | South Portugal      | Rech et al., 2018b |
| *Hyas araneus* (Linnaeus, 1758)        |          | X                      |                |              | X           |           |                                 | North Atlantic Arctic Ocean | Antarctic Peninsula | Tavares and De Melo, 2004 |
| *Ianiropsis serricaudis* Gurjanova, 1936 |          | X                      |                |              |             |           |                                 | Northwest Pacific  | North America                 | Miller et al., 2018 |
| *Incisocallope derzhavini* (Gurjanova, 1938) |          | X                      |                |              |             |           |                                 | Northeast Pacific  | Strait of Juan de Fuca (Canada) Strait of Georgia (Canada) | Gartner et al., 2016 |
| *Ligia oceanica* (Linnaeus, 1767)      |          | X                      |                |              | X           |           |                                 | Northeast Atlantic  | Portugal                      | Chainho et al., 2015 |
| *Liocarcinus navigator* (Herbst, 1794) |          | X                      |                |              |             |           |                                 | Eastern Atlantic Mediterranean Sea | Adriatic Sea       | Tutman et al., 2017 |

(Continued)
| INVASIVE and potential invasive species | Plastics | Boat hulls (biofouling) | Climate events | Ballast water | Aquaculture | Aquariums | Transoceanic channels/swimming | Native location | Non-native or invaded location | References |
|----------------------------------------|----------|-------------------------|----------------|--------------|-------------|-----------|--------------------------------|----------------|--------------------------------|------------|
| *Megabalanus coccopoma* (Darwin, 1854) |          | X                       |                |              |             |           |                                | Pacific Central South America | San Diego (California) | Spinuzzi et al., 2013 |
| *Melita nitida* S.I. Smith in Verril, 1873 |          | X                       |                |              |             |           |                                | North America | Strait of Georgia (Canada) | Gartner et al., 2016 |
| *Metapenaeus monoceros* (Fabricius, 1798) |          |                         | X              |              |             |           |                                | Indo-Pacific Ocean | Mediterranean Sea | Bonanno and Orlando-Bonaca, 2019 |
| *Monocorophium acherusicum* (Costa, 1853) |          |                         |                |              |             |           |                                | Eastern Atlantic | Strait of Juan de Fuca (Canada) | Gartner et al., 2016 |
| *Monocorophium insidiosum* (Crawford, 1937) |          |                          | X              |              |             |           |                                | Eastern Atlantic | Strait of Juan de Fuca (Canada) | Gartner et al., 2016 |
| *Oithona davisae* Ferrari F.D. and Orsi, 1984 |          |                         |                |              |             |           |                                | North Pacific | Chile | Castilla and Neill, 2009 |
| *Paracaprella pusilla* Mayer, 1890 |          |                         |                |              |             |           |                                | Western Atlantic | Panama Mediterranean Sea | Ros et al., 2013 |
| *Paracaprella tenuis* Mayer, 1903 |          |                          | X              |              |             |           |                                | Pacific North America Gulf of Mexico | North Sea | Golasch, 2002 |
| *Penaeus japonicus* Spence Bate, 1888 |          |                         |                |              |             |           |                                | Indo-Pacific | Mediterranean Sea | Bonanno and Orlando-Bonaca, 2019 |
| *Planes minutus* (Linnaeus, 1758) |          |                         |                |              |             |           |                                | Indian ocean Atlantic ocean | Adriatic Sea | Tutman et al., 2017 |
| *Pyromaia tuberculata* (Lockington, 1877) |          |                         |                |              |             |           |                                | Southern California (UNITED STATES) | San Francisco (UNITED STATES) Japan Korea New Zealand | Carlton, 1996 |
| *Rhithropanopeus harrisii* (Gould, 1841) |          | X                       | X              | X            |             |           |                                | West Atlantic | Portugal | Chainho et al., 2015 |
| *Sphaeroma walkeri* Stebbing, 1905 |          |                          | X              |              |             |           |                                | Indian Ocean | Hong Kong | Lewis and Coutts, 2010 |
| *Striatabalanus amaryllis* (Darwin, 1854) |          |                         |                |              |             |           |                                | Indian Ocean West Pacific | West Africa | Kerckhof et al., 2010 |
| *Temora turbinata* (Dana, 1849) |          |                         |                |              |             |           |                                | Indian Ocean | Southwest Atlantic | Soares et al., 2018 |
| *Bryozoa* (15) |          |                          |                |              |             |           |                                |                  |                  |                        |
| *Bowerbankia gracilis* (16) Lediy, 1855 |          |                          |                |              |             |           |                                | Western Atlantic | California (UNITED STATES) | Williams, 2007 |
| *Bugula flabellata* (17) (Thompson in Gray, 1848) |          | X                       | X              | X            |             |           |                                | South Pacific South Atlantic | Chile | Castilla and Neill, 2009 |

(Continued)
| INVASIVE and potential invasive species | Plastics | Boat hulls (biofouling) | Climate events | Ballast water | Aquaculture | Aquariums | Transoceanic channels/ swimming | Native location | Non-native or invaded location | References |
|----------------------------------------|----------|------------------------|----------------|--------------|-------------|-----------|--------------------------------|----------------|-------------------------------|------------|
| Bugula neritina (Linnaeus, 1758)       | X        |                        | X             |              |             |           | Pacific Ocean                  | Chile          | Castilla and Neill, 2009     |            |
| Cryptosula palliata (Moll, 1803)       |          |                        | X             |              |             |           | Northwest Pacific               | Northeast Pacific | Miller et al., 2018          |            |
| Disporaria novaehollandiae (d’Orbigny, 1853) |          |                        | X             |              |             |           | Northwest Pacific               | Hawaiian Island | McCuller and Carlton, 2018   |            |
| Jellyella eburnea (Hincks, 1891)       | X        |                        | X             |              |             |           | Western Pacific                 | Central Pacific Eastern Pacific | McCuller and Carlton, 2018 |            |
| Jellyella tuberculata (Bosc, 1802)     | X        |                        | X             |              |             |           | Western Pacific                 | Central Pacific Eastern Pacific | McCuller and Carlton, 2018 |            |
| Membranipora membranacea (Linnaeus, 1767) |          |                        | X             |              |             |           | Atlantic Ocean Pacific          | Artic Ocean     | Barnes and Milner, 2004      |            |
| Savignyella lafontii (Audouin, 1826)   |          |                        | X             |              | X           |           | Mediterranean Sea               | North Sea       | Gollasch, 2002               |            |
| Schizoporella japonica Ortmann, 1890   | X        | X                      | X             | X            | X           |           | Japan                           | California (UNITED STATES) Columbia (Canada) Northeast Pacific | Williams, 2007; Gartner et al., 2016; Miller et al., 2018 |            |
| Thalamoporella evelinae Marcus, 1939    | X        |                        | X             |              |             |           | Brazil                          | Florida (UNITED STATES) | Winston et al., 1997         |            |
| Tricellaria inopinata d’Hondt and Occhipinti Ambrogi, 1985 |          |                        | X             |              |             |           | Pacific ocean                   | Portugal        | Chainho et al., 2015         |            |
| Watersipora cucullata Busk, 1854        | X        |                        | X             |              |             |           | Northeast Pacific               | New Zealand     | Lewis and Coutts, 2010        |            |
| Watersipora subtorquata (d’Orbigny, 1852) |          |                        | X             |              |             |           | Unknown                         | Portugal        | Chainho et al., 2015         |            |
| Zoobotryon verticillatum (18) (Dele Chiaje, 1822) |          |                        | X             | X            |             |           | Caribbean Sea                   | California (UNITED STATES) Portugal | Williams, 2007; Chainho et al., 2015 |            |
| Entoprocta (2)                         |          |                        | X             |              |             |           |                                |                |                               |            |
| Barentsia benedeni (Foettinger, 1887)  |          |                        | X             |              |             |           | Northeast Atlantic               | Black Sea       | Rilov and Crooks, 2009a      |            |
| Barentsia ramosa (Robertson, 1903)     |          |                        | X             |              |             |           | California (UNITED STATES)      | Indian Ocean    | Anil et al., 2002            |            |
| Echinodermata (2)                      |          |                        | X             | X            |             |           |                                |                |                               |            |
| Asterias amurensis (Lutken, 1871)      | X        | X                      |                |              |             |           | Northern Pacific (Japan)        | South Australia | Godwin, 2003; Therriault et al., 2018 |            |

(Continued)
TABLE 1 | Continued

| INVASIVE and potential invasive species | Plastics | Boat hulls (biofouling) | Climate events | Ballast water | Aquaculture | Aquarums | Transoceanic channels/ swimming | Native location | Non-native or invaded location | References |
|----------------------------------------|----------|------------------------|----------------|--------------|-------------|----------|---------------------------------|----------------|---------------------------------|------------|
| *Ophiothela mirabilis* Verrill, 1867   | X        |                        |                |              |             |          |                                 | Indo-Pacific   | Ilha Grande Bay (Brazil)         | Marteletto et al., 2018 |
| *S. Tunicata* (16)                     |          |                        |                |              |             |          |                                 |                |                                 |            |
| *Ascidia aspersa* (Müller, 1776)       | X        |                        |                |              |             |          |                                 | Northeastern Atlantic | Atlantic coast of North America New Zealand Southern Australia India | Lynch et al., 2016 |
| *Asterocarpa humilis* (Hecker, 1878)   | X        |                        |                |              |             |          |                                 | South Pacific   | Chile                           | Pinochet et al., 2017 |
| *Botryloides violaceus* Oka, 1927      | X        |                        |                |              |             |          |                                 | West Pacific    | Northwest Atlantic Columbia (Canada) | Williams, 2007; Gartner et al., 2016 |
| *Botryllus schlosseri* (Pallas, 1766)  | X        |                        |                |              |             |          |                                 | Northeast Atlantic | East Atlantic Columbia (Canada) | Williams, 2007; Gartner et al., 2016 |
| *Ciona intestinalis* (Linnaeus, 1767)  | X        |                        |                |              |             |          |                                 | North Atlantic   | Chile Iceland                    | Castilla and Neill, 2009; Micael et al., 2020 |
| *Oavelina dellavalle* (Zirpolo, 1925) | X        |                        |                |              |             |          |                                 | Northeast Atlantic | Portugal                        | Chainho et al., 2015 |
| *Corella eumyota* Traustedt, 1882      |          |                        |                | X            | X           |          |                                 | Southern Ocean   | Portugal                        | Chainho et al., 2015 |
| *Didemnum vexillum* Kott, 2002         | X        |                        |                |              |             |          |                                 | Japan           | Northwest Pacific Ocean Hawaii   | Therriault et al., 2018 |
| *Distaplia corolla* Monniot F, 1974    | X        |                        |                |              |             |          |                                 | West Atlantic Ocean | Portugal                        | Chainho et al., 2015 |
| *Herdmania momus* (Savigny, 1816)      | X        |                        |                |              |             |          |                                 | Indo-Pacific     | Mediterranean Sea                | Bonanno and Orlando-Bonaca, 2019 |
| *Molgula ficus* (Macdonald, 1859)      |          |                        |                |              |             |          |                                 | South Pacific    | Chile                           | Castilla and Neill, 2009 |
| *Molgula manhattensis* (De Kay, 1843)  | X        |                        |                |              |             |          |                                 | North America    | Strait of Juan de Fuca (Canada) Strait of Georgia (Canada) | Gartner et al., 2016 |
| *Perophora viridis* Verrill, 1871      | X        |                        |                |              |             |          |                                 | Western-Atlantic | Portugal                        | Chainho et al., 2015 |
| *Pycnoclavella taurenensis* Brunetti, 1991 | X        |                        |                |              |             |          |                                 | Mediterranean Sea | Portugal                        | Chainho et al., 2015 |
| *Styela canopus* (Savigny, 1816)       | X        |                        |                |              |             |          |                                 | West Pacific     | Northwest Atlantic               | Williams, 2007    |

(Continued)
| Invasive and potential invasive species | Plasmas | Boat hulls (biofouling) | Climate events | Ballast water | Aquaculture | Aquaria | Transoceanic channels/ swimming | Native location | Non-native or invaded location | References |
|---------------------------------------|---------|------------------------|----------------|---------------|-------------|---------|--------------------------------|----------------|-------------------------------|------------|
| **Styela clava** Herdman, 1881         |         | X                      |                |               |             |         |                                | Asian Pacific Ocean | Great Britain                | Davis and Davis, 2007 |
| **Vertebrates** (7)                   |         |                        |                |               |             |         |                                |                 |                               |            |
| Lagocephalus sceleratus (Gmelin, 1789) |         |                        | X              |               |             |         | Indo-Pacific                     | Mediterranean Sea   | Bonanno and Orlando-Bonaca, 2019 |
| Mugil soiuy (32) Basilewsky, 1855      |         |                        |                |               |             |         | Amur river Sea of Japan           | Sea of Azov        | Occhipinti-Ambrogi and Savini, 2003 |
| Neogobius melanostomus (Pallas, 1814) |         |                        | X              |               |             |         | Caspian Sea                      | Baltic Sea         | Holmes et al., 2019             |
| Pterois miles (Bennett, 1828)         |         |                        |                |               |             |         | Indo-Pacific                     | Mediterranean Sea   | Bonanno and Orlando-Bonaca, 2019 |
| Pterois volitans (Linnaeus, 1758)      |         |                        | X              | X             | X           |         | Indian West Pacific              | East coast of North America Caribbean | Padilla and Williams, 2004 |
| Sargocentron rubrum (Forskål, 1775)   |         |                        |                | X             |             |         |                                | Indo-Pacific         | Mediterranean Sea           | Bonanno and Orlando-Bonaca, 2019 |
| Siganus rivulatus Forskål and Niebuhr, 1775 |         |                        | X          |               |             |         |                                | Indo-Pacific         | Mediterranean Sea           | Bonanno and Orlando-Bonaca, 2019 |
| **Total:** 216                        | 17      | 128                    | 18             | 84            | 50          | 9       | 6                               |                  |                               |            |

Sessile species: 112

Mobile species: 104

Plastic and boat hulls are highlighted because of their importance in our study. 216 species were included, classified as sessile (pink cells) and no sessile species (blue cells) and sorted mainly by phylum (except the group Algae, subphylum Tunicata and the group Vertebrates). Next to each group, the number of species in the group is indicated in parentheses. The species name coincides with the name used in the citation. Species whose currently accepted name has changed are indicated by numbers in parentheses, and the currently accepted name is clarified at the end of the table. Accepted names: (1) Codium fragile subsp. fragile (Suringer) Hariot, 1889 (2) Colpomenia sinuosa var. peregraui Sauvageau, 1927 (3) Grateloupiapunctata Holmes, 1912 (4) Psychemorepita lanceolata (K.Okamura) Y.Yamada ex S.Kawabata, 1954 (5) Gayralia oxysperma (Kützing) K.L.Vinogradova ex Scagel et al., 1989 (6) Melanothamnus harveyi (Bailey) Diaz-Tapia and Maggs, 2017 (7) Sargassum horemi (Tumer) C.Agardh, 1820 (8) Gellodes wilsoni Carballo, Aquilar-Camacho, Knapp and Bell, 2013 (9) Exaptasia diaphana (Rapp, 1829) (10) Calyptpsapid cernula Clarke, 1882 (11) Diadumene lineata (Verrill, 1869) (12) Anguillicolia (Anguillicoloidea) crassus Kuwahara, Niimi and tagaki, 1974 (13) Ensis leei M. Huber, 2015 (14) Spisula discors (Gray, 1837) (15) Arcuatula senhousia (Benson, 1842) (16) Mytella striata (Hanley, 1843) (17) Nassarius margaritifer (Dunker, 1847) (18) Ocinebrilus ornatus (Récluz, 1851) (19) Anadara inaequivalvis (Bruguiera, 1789) (20) Paphiophora (Paphiophora) aurata (Spalowsky, 1795) (21) Neodexiospira brasiliensis (Grube, 1872) (22) Piccopomatus enigmaticus (Fauvel, 1923) (23) Amphibalanus amphitrite (Darwin, 1854) (24) Notomegabalanus campbelli (Fihol, 1895) (25) Amphibalanus ebuneus (Gould, 1841) (26) Perforatus perforatus (Bruguiera, 1789) (27) Amphibalanus vanegatus (Darwin, 1854) (28) Austrominulis modestus (Darwin, 1854) (29) Amathia gracilis (Leidy, 1855) (30) Bugulina fibellata (Thompson in Gray, 1849) (31) Amathia verticillata (delle Chiaje, 1822) (32) Planiliza haematobrachia (Temminck and Schlegel, 1845). * García-Gómez et al. (2018) cite and photograph the species on nets, and these nets are made of nylon, like the piece illustrated in Figure 3D of this work. After 2018, the species have been observed (pers. obs.) on sunken plastic bags and bottles.
Bugula species of the genus et al. (2020) found that the settlement of the larvae of two invasive reefs but not on artificial structures (Glasby et al., 2007). Pinochet (5 mm–20 cm) compared to MPs of 300 \( \mu \text{m} \).

eukaryotic richness in polyethylene (PE) of mesoplastic size 2018). Debroas et al. (2017) observed a higher bacterial and (Simberloff, 1976; Gil and Pfaller, 2016; Garcia-Vazquez et al., 2018).

greater biological diversity, which is consistent with the classic species-area relationships inherent in the biogeography of islands (Simberloff, 1976; Gil and Pfaller, 2016; Garcia-Vazquez et al., 2018). Debroas et al. (2017) observed a higher bacterial and eukaryotic richness in polyethylene (PE) of mesoplastic size (5 mm–20 cm) compared to MPs of 300 \( \mu \text{m} \)--5 mm, mainly PE. However, it is necessary to consider the complexity of the debris materials, since those with greater structural complexity (for example, groups of tangled ropes) support greater diversity (Goldstein et al., 2014). Plastic debris of all sizes often has limited structural complexity and smooth, rigid surfaces (e.g., buoys, containers, balls, liners). These characteristics can limit the habitability of plastic waste for many species, since a wide variety of organisms require shelter to persist (Gil and Pfaller, 2016).

Even floating harbor pontoons, which carry well-established biofouling communities, can be an important vector for the massive expansion of native species in the face of extreme events that destroy them, such as tsunamis (Wang et al., 2016), displacing them thousands of kilometers away (Figures 3A–D).

Gil and Pfaller (2016) studied the relationship between the area and the structural complexity of marine plastic debris and the colonization of species. The study revealed contrasting patterns for the richness of sessile and mobile taxa. Regarding the number of sessile taxa on debris, the increase in surface had a significant positive effect, while the cover of barnacles of the genus Lepas had a significant negative effect. However, regarding the number of mobile taxa on the debris, the increase in surface area had a trivial positive effect, while the number of barnacles had a significant positive effect. These results suggest that barnacles of the genus Lepas act as base species in communities on plastic debris, providing a complex structural habitat on otherwise structurally limited plastic debris. In agreement with these data, Astudillo et al. (2009) carried out a study on biota inhabiting buoys in the sea and observed that the number of mobile species on buoys was positively related to the number and biomass of sessile species. Thus, benthic species which colonize plastic surfaces are considered eco-engineers, since they provide a habitat for mobile species that otherwise would not be able to colonize these surfaces (Astudillo et al., 2009).

**Differential Colonization in the Different Types of Plastic Polymers**

The five main classes of plastic polymers, which comprise about 90% of polymer production, are polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), and polyethylene terephthalate (PET), with the latter being the most abundant in the ocean (Andrady and Neal, 2009).

While many authors have observed no evidence that the type of polymer is relevant for the composition of the macrobiota associated with plastics, Gündoğdu (2017) have found that the type of plastic (PE, PET, and PP) shows significant differences with respect to the diversity and abundance of species. On the other hand, it is commonly accepted that the difference in structural and/or chemical properties (plasticizers and colorants) observed among polymer families influences bacterial communities and dynamics (De Tender et al., 2015). Pinochet et al. (2020) observed that the bryozoan larvae of two invasive species of the genus Bugula showed preferences for colonizing PS and polycarbonate (PC) substrates within the polymer possibilities (PP, PVC, PET, and PC). Furthermore, antifouling treatments applied to different plastic materials, such as nylon fishing nets, could influence the community of organisms adhering to them (Núñez et al., 2006).

Although the reason for association with certain polymers is not clear, some authors have indicated that it might be due to the biofilm that develops on each polymer (Shin et al., 2013; Lagos et al., 2016; Morohoshi et al., 2018). According to...
Oberbeckmann et al. (2014) the composition of the polymer not only influences the abundance of microorganisms associated with polymers, but also shapes the structure of the biofilm community, which could play a role in the establishment of other species associated with the biofilm (Shin et al., 2013; Lagos et al., 2016; Morohoshi et al., 2018).

**Macrobiota Transported by Plastics**

Barnes (2002) highlighted the importance of marine debris as a distribution vector for marine species and estimated that it doubled the probability of transport of the species. After analyzing more than 200 pieces of debris from 30 different islands, he concluded that the most abundant groups were bryozoans, barnacles, polychaetes, hydroids and molluscs. Astudillo et al. (2009) found in the Southeastern Pacific 134 species in a total of 40 sampled buoys, mostly belonging to the Arthropoda, Annelida, and Mollusca phyla, 4 of them classified as invasive on the Chilean coast (Castilla et al., 2005): *Ciona intestinalis* (Linnaeus, 1767), *Bugula neritina* (Linnaeus, 1758), *B. flabellata* [Thompson in Gray, 1848; this name is currently not accepted and it is *Bugulina flabellata* (Thompson in Gray, 1848)] and the macroalgae *Codium fragile* (Suringar) Hariot, 1889 (frequencies of 73, 82, 59 and 9%, respectively). Later, in 2014, Goldstein et al. (2014) found 95 taxa in 242 pieces of plastic debris, most of them from the phylum Arthropoda, followed by Mollusca and Cnidaria. These data are consistent with the results obtained in our study (Table 1), as the phylum observed on plastic were Arthropoda (6), Bryozoa (4), Mollusca (4), Annelida (1) and Cnidaria (1), and the group Algae (1).

Some recurrent characteristics have been noted in the biology and ecology of species associated with plastic debris in the sea, such as cosmopolitan distributions, suspensivorous feeding (Astudillo et al., 2009) and sessile with short-lived larval development without natural potential means of dispersal (Barnes, 2002).

Kiessling et al. (2015) found 335 taxa associated with plastic garbage items in the ocean and stranded on the coast. In a study in the Atlantic Ocean, Barnes and Milner (2004) found several species of barnacles with a high incidence; the balanomorph *Semibalanus balanoides* (Linnaeus, 1767) were present in marine debris at all arctic and subarctic study sites; the invasive species *Elminius modestus* Darwin, 1854 [this name is currently not accepted and it is *Austrominius modestus* (Darwin, 1854)] was also found on plastic items.
Plastic as a Vector for the Dispersal of Microorganisms and Associated Diseases

Plastics, including MPs and NPs, adsorb organic and inorganic nutrients from water (Frère et al., 2018), which, along with its physical properties and widespread distribution provides a unique and stable habitat (Zettler et al., 2013; Oberbeckmann et al., 2015; Keswani et al., 2016), thus attracting bacteria, viruses, plankton, and other microorganisms which adhere to its surface (Frère et al., 2018), and enhancing their dispersion to different oceanic regions (Zettler et al., 2013; Oberbeckmann et al., 2015; Keswani et al., 2016). This adhesion is facilitated by the complexity of plastic surfaces, such as roughness and braiding (Núñez et al., 2006).

Zettler et al. (2013) introduced the term “plastisphere” to define a community of microorganisms associated with marine plastic debris found on the surface of seawater. “Plastisphere” differs from the bacterial populations found in other marine ecosystems, both in the water column and in other natural substrates (Zettler et al., 2013; Harrison et al., 2014; Dussud et al., 2018; Curren and Leong, 2019) and host a diverse community, including heterotrophs, autotrophs, predators, and symbionts, which generally begin with microbial colonization and biofilm conformation, which at the same time facilitate the settlement of other species, for example bryozoans (Bryant et al., 2016). Oberbeckmann et al. (2014) show that microbial communities in plastic change in structure and composition with respect to geographic location, season and type of polymer, but that there are also similarities between these plastic communities, such as the predominance of the phyla Proteobacteria and Bacteroidetes (Zettler et al., 2013; Oberbeckmann et al., 2014; Frère et al., 2018; Curren and Leong, 2019) and some microalgal species such as diatoms and dinoflagellates (Carson et al., 2013).

Different cases of dissemination of potentially toxic species have been documented, including pathogens and invasive algae, which can invade new habitats and modify their structure, becoming a threat to the ecosystem (Zettler et al., 2013; Kirstein et al., 2016). The toxic bacterial genus Vibrio has been commonly detected in MPs (Zettler et al., 2013; Frère et al., 2018; Curren and Leong, 2019); Kirstein et al. (2016) confirmed the presence of Vibrio spp. in 13% of all MP particles collected in the sea, identifying the potentially pathogenic species V. parahaemolyticus (Fujino et al., 1974) Sakazaki et al., 1963 and V. fluvialis Lee et al., 1981. Masó et al. (2003) detected members of the potentially harmful dinoflagellate genera Ostreopsis, Coolia, and Alexandrium in plastic debris floating in Mediterranean coastal waters. These infectious organisms can reach their hosts through the ingestion of plastic (Harrison et al., 2011; Zettler et al., 2013).

Several authors found antibiotic resistance genes (ARG; Miller et al., 2009; Laganà et al., 2019), metal resistance genes (MRG; Yang et al., 2019) and virulence genes (Radisic et al., 2020) in different species of bacteria in marine environments. Radisic et al. (2020) findings of virulence genes and new ARG variants in the fish pathogen Aeromonas salmonicida (Lehmann and Neumann, 1896; Griffin et al. 1953) isolated from plastic debris in Norway showed their potential for causing infections.

Audrézet et al. (2020) highlight the importance of the study of the succession of plastisphere communities and the different factors that influence the transmission of microorganisms mediated by plastic through the combination of molecular and microscopic approaches, and the use of genetic markers.

Therefore, there is concern that MP pollution, which is increasing in the marine environment, may cause serious marine ecological effects, influence the dynamics of its population and, ultimately, the emergence of pathogens (Frère et al., 2018; Shen et al., 2019). The introduction of MPs colonized by non-native microbial communities is likely to alter microbial communities and genetic exchange in natural water and consequently affect the ecological function of microbial communities (Miao et al., 2019).

SPATIOTEMPORAL DISPERSION PATTERNS OF PLASTIC DEBRIS IN THE MARINE ENVIRONMENT AND VULNERABLE AREAS

Plastic horizontal dispersion in the ocean is driven by different large-scale processes, such as the action of ocean currents, wind, tides (Figure 4; Law et al., 2010; Kim et al., 2015) and extreme
meteoro logical events, such as hurricanes (Wang et al., 2019; Lo et al., 2020) and tsunamis (Wang et al., 2016). Sea state, wind (Astudillo et al., 2009; Thiel et al., 2011), and particle size and type (Reisser et al., 2015) influence the duration of transport. A Plastic particle from the east coast of the United States may reach the subtropical gyre of the Atlantic North in less than 60 days (Law et al., 2010). Six years after the 2011 tsunami in Japan, Carlton et al. (2017) documented 289 living species on the coasts of North America and Hawaii in marine debris originating after the catastrophe, among which plastic debris was abundant. On the ocean surface, downwind and slow current habitats are potential sinks for plastic debris (Browne et al., 2010). Currently, 5 ocean gyres have been identified, located in the North Atlantic, South Atlantic, South Indian, South Pacific, and North Pacific (Eriksen et al., 2014), which accumulate on their surfaces at least 79 thousand tons of plastic (Lebreton et al., 2018). Moreover, the appearance of another patch in the Barents Sea has been predicted (van Sebille et al., 2012). These areas can accommodate quantities of up to 21,290 tons of plastic in the North Pacific gyre (Law et al., 2010). In addition, in the convergence regions, surface water is pumped down to depths of a few hundred meters (van Sebille et al., 2020).

The vertical transport of plastic is both size- and density-dependent. MPs are more abundant than larger plastic debris, both on the sea's surface and in the water column (Kooi et al., 2017). On the other hand, plastic materials with a density lower than water (LD) (1.02 g/cm³) are usually found on the surface and in neustonic environment (Moore et al., 2011), while those with a higher density (HD) reach the marine benthic environments (Moret-Ferguson et al., 2010; Ballent et al., 2012).

During plastic debris stay in the marine environment, their density can change over time due to the physical/chemical/biological degradation or biofouling attachment Figure 4 (Moret-Ferguson et al., 2010) of suspended matter, contamination by epiphytes or the formation of microbial biofilms (Lobelle and Cunliffe, 2011; Collignon et al., 2014; Bagaev et al., 2017). Increased density could cause the debris to sink, to be transported by underlying currents (Engler, 2012), trapped by turbulent currents of the benthic boundary layer, resuspended by deep currents, or finally to settle onto the seafloor (Bagaev et al., 2017; Figure 4). In many cases, sedimentation is facilitated by oceanographic processes (Wang et al., 2016) such as dense shelf water cascading (Canals et al., 2006), severe coastal storms (Sanchez-Vidal et al., 2012), offshore convection (Durrieu de Madron et al., 2013), and saline subduction (Talley, 2002). Predicting this vertical mixing could be essential, as it affects the horizontal drifting patterns and ecological impacts of plastic pollution (Reisser et al., 2015). Plastic concentrations have been shown to decrease exponentially with depth (Reisser et al., 2015). However, Woodall et al. (2014) reported an abundance of MPs on the seafloor four orders of magnitude greater than in surface water gyres, while Peng et al. (2018) reported abundant MP particles in the Mariana Trench, the deepest part of the world's ocean.

Plastic debris is widely distributed throughout our oceans and colonize from latitudes near the equator to the poles (Obbard et al., 2014), with the tropical regions being the areas where it is most frequent and predominant (Barboza et al., 2019). Regardless of the geographical region, the most vulnerable areas with respect to the colonization of exotic species transported by this debris are those where endemisms abound and endangered species are present (Gregory, 2009; Thevenon et al., 2014).

Therefore, given the spatial “cosmopolitanism” of plastic materials and their increasing abundance in the marine environment, generalist invasive species (or with invasive potential) in the surface waters of all oceans which can be transported by this vector, constitute an increasing threat—within the bathymetric range to which they are adaptive—especially to pristine and highly biodiverse ecosystems, with particular relevance to Marine Protected Areas.

### EARLY DETECTION AND SURVEILLANCE OF AIS IN MARINE PLASTIC DEBRIS

Rech et al. (2018a) found that the frequency of a specific taxon attached to plastic litter in a coastal area can be predicted based on the characteristics of biological communities associated with each litter material and the composition of beach litter. This approach, after being tested in other regions, may contribute as a simple and cost-effective tool for risk assessment in the future (Rech et al., 2018a). On the other hand, Fazey and Ryan (2016a,b) showed that small samples of plastic litter lost buoyancy due to biofouling much faster than larger ones, providing the first estimates of the longevity of different sizes of plastic debris at the surface of the ocean. This finding could be used to improve model predictions of the distribution and abundance of floating plastic debris globally.

Ports are often export areas for native generalist species and entry areas for alien species (Mineur et al., 2006; Keller et al., 2010; Airoldi et al., 2015; López-Legentil et al., 2015; Ferrario et al., 2017). A sport or recreational vessel whose hull is made of fiberglass-reinforced polyester can import or export native and alien species. But also, by accumulation and subsequent sinking, ports and marinas can import and export plastic trash with alien species. In many cases the plastic sinks (especially bags), because of the weight of the biofouling, remain at shallow depths (especially in ports and marinas, which tend to accumulate plastic garbage on their bottoms). For their control and environmental monitoring, a modification of the SBPQ (Sessile Bioindicators Permanent Quadrats) method could be applied, as recently proposed by García-Gómez (2015) and García-Gómez et al. (2020a) for the early detection of alien species and environmental impacts of a local nature (e.g., urban discharges) or global (climate change) in rocky natural habitats. It is a non-invasive method focuses on the monitoring of preselected sensitive (indicators) sessile target species associated with rocky coralligenous habitats using permanent quadrats in underwater sentinel stations. It could be adapted to plastic panels (completed with other types of non-plastic panels) which are susceptible to colonization by opportunistic sessile species that could become invasive, and act as “traps” for the early
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FIGURE 4 | Debris made of high-density polyethylene (HDPE), such as plastic bottles which could be transported through large areas and be vectors for potentially invasive marine species (1) or result in micro and nanoplastic material through physical degradation, photodegradation, or biodegradation (2). Plastic bags composed of low-density polyethylene (LDPE) which usually settle in the water column, while plastic fishing nets, in many cases constituted by nylon, tend to sink and settle on the seafloor. Both plastic bags and fishing nets are susceptible to physical degradation and biodegradation. Plastic particles which could succumb to bioturbation (5), describe vertical movements (3,4) and be simultaneously ingested by animals from all oceanic stratum being dispersed by them (6), as well as sink and stay at the seafloor due to their original density or to increase by processes such as biofouling (7). Steps 1, 2, and 3 of “Horizontal Dispersion,” which are the most frequently involved in biological invasions. To a lesser degree, steps 3 and 4 involve “Vertical Dispersion.”

detection of alien species. In this regard, the installation of underwater sentinel stations should be tested at various inland points of ports, with plastic panels of at least five panels per point, of 25 cm × 25 cm, with different roughness and nature (e.g., polyamide or nylon, polyester, polyethylene, high density polyethylene and polypropylene), which serve to recognize the species which establish easily on this type of material and those which are more frequent and with a structural and adaptive profile of higher risk for invasion. This method could contribute to the early detection of alien species with invasive potential, and to the implementation of immediate mitigation and/or eradication measures.

ADDITIONAL CONSIDERATIONS

From the foregoing, it can be deduced that plastic debris represents a ubiquitous vector with great potential for transporting both sessile and mobile species associated with it, capable of traveling long distances because plastic, due to its composition, is not biodegradable and, therefore, very durable over time.

We could ask ourselves which species of those transported by plastic (or that could be transported by this type of substrata) may have a greater risk of invasion. They would be sessile generalist arborescent species (e.g., seaweeds, hydrozoans, bryozoans) that, according to Bradshaw et al. (2003), are common components of fouling communities. So, they can provide food, shelter or hiding conditions for other mobile species that can travel with them (both non-native and native). About this, Marchini et al. (2015a) reported three mobile NIS associated with the introduced sessile species Amathia verticillata ( = Zoobotrion verticillatum) (Bryozoa) and suggested this species as substrate for transport between ports, facilitating its distribution. Also, Gavira-O’Neill et al. (2018) found 19 species associated with the invasive bryozoan Tricellaria inopinata—in list of “100 Worst Invasives” in the Mediterranean (Streftaris and Zenetos, 2006)—between them the
three mobile introduced species *Caprella scaura*, *Monocorophium sextonae* (Amphipoda), and the *Paracercis sculpta*, adding that these species represented over half of the quantified individuals and discussing the possibility of a potential case of “invasional meltdown”—expression by Simberloff and Von Holle (1999)—during which introduced species provide suitable habitat for other non-native species, favoring their establishment. Other studies also support this hypothesis for *T. inopinata* as a host for other mobile species introduced from other zoological groups, such as isopods and nudibranchs (Keppel et al., 2012; Hobbs et al., 2015). So, such arborescent sessile species (hosts of mobile fauna) are those that need to occupy the substrate surfaces of the bottom (even as epibionts) and, therefore, those that can generate the greatest environmental impact on the native sessile biota.

In order to improve biosecurity, the best mechanism is prevention and, in this sense, it is important to start acting against this ongoing problem; for example, through protocols for the sighting (from small boats and large ships) of accumulations of plastic adrift within 20 miles off the coasts, where the presence of accumulations of floating with well-established biofouling is detected. In the same way, ports and marinas must be involved in environmental surveillance for the early detection of alien species before they can become widespread.

Actions to manage the problem should be put into place, such as the collection of floating plastic by cleaning boats employed in coastal areas at risk of the entry of plastic accumulations due to winds and/or currents. International regulations or legal provisions must be implemented in this regard. Collaboration on the part of society must also be encouraged. Environmental education and the emerging “Citizen Science” movement (Wiggins and Crowston, 2011) should be stimulated and coordinated from public administrations, as well as large industries, companies or institutions that have large coastal infrastructures. In addition, large industries and companies should also participate in mitigating the problem under the influence of the emerging philosophy of “Working with nature” (PIANC, 2014; Martin et al., 2017; Nebot et al., 2017), which has generated an awareness of respect for nature, by which it is intended to act with it and not against it, collaborating in environmental monitoring and surveillance studies of threatened species naturally established in port breakwaters (García-Gómez et al., 2010, 2014) and, in the present case, for the early detection of alien species with invasive potential.

### CONCLUSION

1. The number of articles published of plastic debris as a vector for the introduction of alien species has increased enormously in recent years. This increase could be related to the increase in annual plastic production, which results in a greater threat, in addition to a growing interest in the problem on the part of the scientific community and, therefore, the greater number of research papers related to it.

2. Several of the biological characteristics of marine species commonly associated with plastic, such as the short life cycle and larval development, are also characteristics of a large portion of the known invasive species; so these species that travel on plastic debris across the ocean could generally be perceived as a major threat to their destination.

3. A wide variety of organisms colonize plastic materials, both microorganisms (e.g., species of the genus *Vibrio* or different species carrying virulent and antibiotic resistance genes) and macrofauna species (e.g., algae or bryozoan species). This fact increases the threat to ocean life caused by plastic and turns it into a means for spreading disease.

4. There are large gaps in knowledge about the functioning of plastic objects as vectors and the lack of studies on colonization processes on different plastic polymers by marine species generate contradictions between different authors. Despite the great advances produced today in the knowledge of plastic debris in the ocean, greater research are necessary to mitigate the threat of biological invasions linked to this type of pollutant.

### REFERENCES

Airolidi, L., Turon, X., Perkol-Finkel, S., and Rius, M. (2015). Corridors for aliens but not for natives: effects of marine urban sprawl at a regional scale. *Diver. Distrib.* 21, 755–768. doi: 10.1111/ddi.12301

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### AUTHOR CONTRIBUTIONS

MG and JG made Figures 1, 2, and 4. JG-G provided the photographs of Figure 3. All authors decided the consensus on the structure of the manuscript and accomplished the literature search, and participated for the conclusion and formal aspects.

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Aliani, S., and Molcard, A. (2003). “Hitch-hiking on floating marine debris: macrobenthic species in the Western Mediterranean Sea,” in *Migrations And Dispersal Of Marine Organisms*, eds A. Ingólfsson, E. “lafsson, G. V. Helgason, J. Svavarsson, K. Gunnarsson, and M. B. Jones (Dordrecht: Springer Netherlands), 59–67. doi: 10.1023/b:hydr.0000008480.95045.26
Alomar, C., Estarellas, F., and Deudero, S. (2016). Microplastics in the Mediterranean Sea: deposition in coastal shallow sediments, spatial variation and preferential grain size. Mar. Environ. Res. 115, 1–10. doi: 10.1016/j.marenvres.2016.01.005
Andrady, A., and Neal, M. (2009). Applications and societal benefits of plastics. Philos. Trans. R. Soc. B Biol. Sci. 364, 1977–1984. doi: 10.1098/rstb.2008.0304
Anil, A., Venkat, K., Sawant, S., Dileepkumar, M., Dhargalkar, V., Ramaiah, N., et al. (2002). Marine bioinvasion: concern for ecology and shipping. Curr. Sci. 83, 214–218.
Astudillo, J., Bravo, M., Dumont, C., and Thiel, M. (2009). Detached aquaculture buoys in the SE Pacific: potential dispersal vehicles for associated organisms. Aquat. Biol. 5, 219–231. doi: 10.3354/ab00151
Audrézet, F., Zaito, A., Lear, G., Wood, S., Tremblay, L., and Pochon, X. (2020). Tsunami-driven rafting: transoceanic species dispersal and implications for marine biogeography. Science 357, 1402–1406. doi: 10.1126/science.aao1498
Carlton, J. (1996). Pattern, process, and prediction in marine invasion biology. Biol. Conserv. 78, 97–106. doi: 10.1016/0300-9091(96)00020-1
Carlton, J., Chapman, J., Geller, J., Miller, J., Carlton, D., McCuller, M., et al. (2017). Plastic-associated microorganisms of the North Pacific Gyre. Mar. Pollut. Bull. 126, 126–132. doi: 10.1016/j.marpolbul.2013.07.054
Castilla, J., Uribe, M., Bahamonde, N., Clarke, M., Desquesney-Faúndez, R., Kong, I., et al. (2005). Down under the southeastern Pacific: marine non-indigenous species in Chile. Biol. Invasions 7, 213–232. doi: 10.1007/s10530-004-0198-5
Castilla, J. C., and Neill, P. E. (2009). “Marine bioinvasions in the southeastern pacific: status, ecology, economic impacts, conservation and management,” in Biological Invasions in Marine Ecosystems. Ecological Studies (Analysis and Synthesis), Vol. 204, eds G. Rilov and J. A. Crooks (Heidelberg, BE: Springer). doi: 10.1353/psc.2002.0016
Chaihin, P., Fernandes, A., Arsov, A., Ávila, S., Canning-Clode, J., Castro, J., et al. (2015). Non-indigenous species in Portuguese coastal areas, coastal lagoons, estuaries and islands. Estuarine Coastal Shelf Sci. 167, 199–211. doi: 10.1016/j.ecss.2015.06.019
Clarke Murray, C., Gartner, H., Gregg, E., Chan, K., Pakhomov, E., and Therriault, T. (2014). Spatial distribution of marine invasive species: environmental, demographic and vector drivers. Diver. Distrib. 20, 824–836. doi: 10.1111/ddi.12215
Collignon, A., Heeq, J., Galgani, F., Collard, F., and Goffart, A. (2014). Annual variation in neustonic micro- and meso-plastic particles and zooplankton in the Bay of Calvi (Mediterranean–Corsica). Mar. Pollut. Bull. 79, 293–298. doi: 10.1016/j.marpolbul.2013.11.023
Cook, E., Jahnke, M., Kerckhof, F., Minchin, D., Faasse, M., Boos, K., et al. (2007). European expansion of the introduced amphipod Caprella mutica Schurin, 1935. Aquat. Invasions 2, 411–421. doi: 10.3391/ai.2007.2.4.11
Creed, J., Junqueira, A., Fleury, B., Mantelatto, M., and Oigman-Pszczol, S. (2017). The Sun-Coral Project: the first social-environmental initiative to manage the biological invasion of Tubastrea spp. in Brazil. Manag. Biol. Invasions 8, 181–195. doi: 10.3391/mibi.2017.8.2.06
Crooks, J. (2002). Characterizing ecosystem-level consequences of biological invasions: the role of ecosystem engineers. Oikos 97, 153–166. doi: 10.1034/j.1600-0706.2002.970201.x
Crooks, E., and Leong, S. (2019). Profiles of bacterial assemblages from microplastics of tropical coastal environments. Sci. Total Environ. 655, 313–320. doi: 10.1016/j.scitotenv.2018.11.250
Davis, M., and Davis, M. (2007). The distribution of styela clava (Tunicata, R. philippinarum) shellfish species living in the Bay of Calvi (Mediterranean–Corsica). Mar. Pollut. Bull. 54, 145–146. doi: 10.1016/j.marpolbul.2007.07.016
Davis, M. E. (2000). Invasion Biology. New York, NY: Oxford University Press. De Tender, C., Devriese, L., Maes, S., Ruttink, T., and Dawyndt, P. (2015). Bacterial Community Profiling of Plastic Litter in the Belgian Part of the North Sea. Environ. Sci. Technol. 49, 12215. doi: 10.1021/acs.est.5b03093
Debros, D., Mone, A., and Ter Halle, A. (2017). Plastics in the North Atlantic garbage patch: a boat-microbe for hitchhikers and plastic degraders. Sci. Total Environ. 59, 1222–1232. doi: 10.1016/j.scitotenv.2017.05.059
Derraik, J. (2002). The pollution of the marine environment by plastic debris: a review. Mar. Pollut. Bull. 44, 842–852. doi: 10.1016/s0025-326x(02)00220-5
Dumont, C., and Thiel, M. (2009). Detached aquaculture buoys in the SE Pacific: potential dispersal vehicles for associated organisms. Aquat. Biol. 5, 219–231. doi: 10.3354/ab00151
Estrada, P., Freeman, B., and Dyer, S. (2016). “Bivalve biofouling as an emerging source of plastic pollution,” in Microplastics in the Marine Environment, ed. C. Sheppard (Coventry: University of Warwick), 305–328. doi: 10.1086/707505
Estrada, P., Fiorentino, F., and Dyer, S. (2016). “Bivalve biofouling on plastic debris,” in Marine Environments: Physical Processes, Ecological Responses, and Future Research. doi: 10.1016/j.marpolbul.2017.08.040
Fernandes, A., Arsov, A., Ávila, S., Canning-Clode, J., Castro, J., et al. (2015). Non-indigenous species in Portuguese coastal areas, coastal lagoons, estuaries and islands. Estuarine Coastal Shelf Sci. 167, 199–211. doi: 10.1016/j.ecss.2015.06.019
García-Gómez et al. Marine Species Dispersion by Plastic
organic particles and surrounding seaways. *Environ. Pollut.* 236, 807–816. doi: 10.1016/j.envpol.2017.12.027

Ebbesmeyer, C., and Ingraham, W. (1992). Shoe spill in the North Pacific. *Eos Trans. Am. Geophys. Union* 73, 361–361. doi: 10.1029/91EO10273

Eerkens-Medrano, D., Thompson, R., and Aldridge, D. (2015). Microplastics in freshwater systems: a review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. *Water Res.* 75, 63–82. doi: 10.1016/j.watres.2015.02.012

Engler, R. (2012). The complex interaction between marine debris and Toxic chemicals in the Ocean. *Environ. Sci. Technol.* 46, 12302–12315. doi: 10.1021/es3027105

Eno, N. (1996). Non-native marine species in British waters: effects and controls. *Aquat. Conserv. Mar. Freshw. Ecosyst.* 6, 215–228. doi: 10.1002/(sici)1099-0755(199612)6:4<215::aid-aqc191>3.0.co;2-q

Eno, N. C., Clark, R. A., and Sanderson, W. G. (1997). *Non-Native Marine Species in British Waters: A Review and Directory*, Peterborough: JNCC.

Epstein, G., and Smale, D. (2017). Undaria pinnatifida: a case study to highlight challenges in marine invasion ecology and management. *Ecol. Evol.* 7, 8624–8642. doi: 10.1002/2ece.33430

Fujino, T., Sakazaki, R., and Tamura, K. (1974). Designation of the type strain of *Garcia-Gomez* et al. *Marine Species Dispersion by Plastic: A Guide on Environmental Monitoring of Rocky Seabeds*.

Ferrario, J., Caroni, S., Anna Occhipinti-Ambrogi, A., and Marchini, A. (2017). *Colonization of low-density polyethylene microplastics in coastal sediment between microorganisms and marine microplastics: a call for research.*

Fazio, F., and Ryan, P. (2016a). Biofouling on buoyant marine plastics: an experimental study into the effect of size on surface longevity. *Environ. Pollut.* 210, 354–360. doi: 10.1016/j.envpol.2016.01.026

Fazio, F., and Ryan, P. (2016b). Debris size and buoyancy influence the dispersal distance of stranded litter. *Mar. Pollut. Bull.* 110, 371–377. doi: 10.1016/j.marpolbul.2016.06.039

Ferrario, J., Caronni, S., Anna Occhipinti-Ambrogi, A., and Marchini, A. (2017). Role of commercial harbours and recreational marinas in the spread of non-indigenous fouling species. *Biofouling* 33 (N8), 651–660. doi: 10.1080/08927014.2017.1351958

Fine, M., Zebrowski, H., and Loya, Y. (2001). Oculina patagonica: a non-lessepsian exotic alga. *J. Exp. Mar. Biol. Ecol.* 302, 139–146. doi: 10.1016/S0022-0981(01)00171-7

Fraser, C., Morrison, A., Hogg, A., Macaya, E., van Sebille, E., Ryan, P., et al. (2016). Rapid bacterial colonization of polyethylene plastic debris: does habitat creation facilitate biotic invasions? *Mar. Biol.* 164, 1141–1143. doi: 10.1007/s00227-014-2432-8

García-Gómez, J., Sempere-Valverde, J., Ostalé-Valriberas, E., Martínez, M., Olaya-Ponzon, L., González, A., et al. (2018). *Rugulopteryx okamureae* (E.Y. Dawson) I.K. Hwang, W.J. Lee & H.S. Kim (Dictyotales, Ochrophyta), alga exótica “explosiva” en el estrecho de Gibraltar. Observaciones preliminares de su distribución e impacto. *Almaraura* 48, 97–113.

García-Vázquez, E., Cani, A., Diem, A., Ferreira, C., Geldhof, R., Marquez, L., et al. (2018). Leave no traces – Beached marine litter shelters both invasive and native species. *Mar. Pollut. Bull.* 131, 314–322. doi: 10.1016/j.marpolbul.2018.04.037

Gartner, H., Murray, C., Frey, M., Nelson, J., Larson, K., Ruiz, G., et al. (2016). Non-indigenous invertebrate species in the marine fouling communities of British Columbia, Canada. *Bioinvasions Rec.* 5, 205–212. doi: 10.3391/bir.2016.5.4.03

Gavira-O'Neill, K., Guerra-García, J., Moreira, J., and Ros, M. (2018). Mobile epifauna of the invasive brachyuran Tricellaria inopinata: is there a potential invasive meltdown? *Mar. Biodivers.* 48, 1169–1178. doi: 10.1002/mib.10563-5

Gil, M., and Pföller, J. (2016). Oceanic barnacles act as foundation species on plastic debris: implications for marine dispersal. *Sci. Rep.* 6:19987. doi: 10.1038/srep19987

Glasy, T., Connell, S., Holloway, M., and Hewitt, C. (2007). Nonindigenous biota on artificial structures: could habitat creation facilitate biological invasions? *Mar. Biol.* 151, 887–895. doi: 10.1007/s00227-006-0552-5

Godwin, L. (2003). Hull fouling of maritime vessels as a pathway for marine invasions. *Biofouling* 19(sup1), 123–131. doi: 10.1007/s10530-003-0017-2

Goldstein, M., Carson, H., and Eriksen, M. (2014). Relationship of diversity and habitat area in North Pacific plastic-associated rafting communities. *Mar. Biol.* 161, 1441–1453. doi: 10.1007/s00227-014-2432-8

Gollasch, S. (2002). The importance of ship hull fouling as a vector of species introductions into the North Sea. *Biofouling* 18, 105–121. doi: 10.1080/0892701031000061750

Gregory, M. (1999). Plastics and South Pacific Island shores: environmental implications. *Ocean Coastal Manag.* 42, 603–615. doi: 10.1016/s0964-5691(99)00306-8

Gregory, M. (2009). Environmental implications of plastic debris in marine settings—entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. *Philos. Trans. R. Soc. B Biol. Sci.* 364, 2013–2025. doi: 10.1098/rstb.2008.0265

Grosholz, E., Crafton, R., Fontana, R., Pasari, J., Williams, S., and Zabin, C. (2015). Polyethylene plastic debris: a vector for marine invasions in California. *Biol. Invasions 17*, 1471–1484. doi: 10.1007/s10530-014-0808-9

Grosholz, E., and Ruiz, G. (1995). Spread and potential impact of the recently introduced European green crab, *Carcinus maenas*, in central California. *Mar. Biol.* 122, 239–247.

Gündoğdu, S. (2017). Fouling assemblage of benthic plastic debris collected from Mersin Bay, NE Levantine coast of Turkey. *Mar. Pollut. Bull.* 124, 147–154. doi: 10.1016/j.marpolbul.2017.07.023

Harrison, J., Sapp, M., Schratzberger, M., and Osborn, A. (2011). Interactions between microorganisms and marine microplastics: a call for research. *Mar. Technol. Soc. J.* 45, 12–20. doi: 10.4031/mts45.2.2

Harrison, J., Schratzberger, M., Sapp, M., and Osborn, A. (2014). Rapid bacterial colonization of low-density polyethylene microplastics in coastal sediment microcosms. *BMC Microbiol.* 14:232. doi: 10.1186/s12866-014-0232-4

Hebert, P., Wilson, C., Murdoch, M., and Lazar, R. (1991). Demography and ecological impacts of the invading mollusc *Dreissena polymorpha*. *Can. J. Zool.* 69, 405–409. doi: 10.1139/z91-063

Hernández-Delgado, E., Toledo-Hernández, C., Ruiz-Díaz, C., Gómez-Andújar, N., Medina-Mutijú, J., Canals-Sílinder, M., et al. (2020). Hurricane impacts and the resilience of the invasive Sea Vine, *Halophila stipulacea*: a case study from Puerto Rico. *Estuaries Coast.* 43, 1263–1283. doi: 10.1002/est2.011132019f108e3

Hobs, N.-V., Lazo-Wasem, E., Faasle, M., Cordell, J., Chapman, J., Smith, C., et al. (2015). Going global: the introduction of the Asian isopod *Lanisopus*...
serricaudus Gurjanova (Crustacea: Peracarida) to North America and Europe. *Aquat. Invasions* 10, 177–187. doi: 10.3391/ai.2015.10.2.06

Holmes, M., Kotta, J., Persson, A., and Sahlin, U. (2019). Marine protected areas modulate habitat suitability of the invasive round goby (*Neogobius melanostomus*) in the Baltic Sea. *Estuarine Coast. Shelf Sci.* 229:106380. doi: 10.1016/j.ecss.2019.106380

Horta, P., and Oliveira, E. (2000). Morphology and reproduction of Anotrichum yagii (*Ceramiales, Rhodophyta*) – a new invader seaweed in the American Atlantic? *Phycologia* 39, 390–394. doi: 10.2216/0031-8884-39–5–390.1

Huang, Z. G. (1994). *Marine Species and Their Distributions in China’s Seas*. Beijing: China Ocean Press.

Ibáñez, A., Rayón, F., Martínez, J., and García-Vazquez, E. (2020). Environmental DNA from plastic and textile marine litter detects exotic and nuisance species nearby ports. *PLoS One* 15:0228811. doi: 10.1371/journal.pone.0228811

Katsanevakis, S., Wallentinus, I., Zenetos, A., Leppäkoski, E., Çinar, M., Oztürk, B., et al. (2014). Impacts of invasive alien marine species on ecosystem services and biodiversity: a pan-European review. *Aquat. Invasions* 9, 391–423. doi: 10.3391/ai.2014.9.4.01

Kauano, R., Roper, J., and Rocha, R. (2016). Small boats as vectors of marine invasion: experimental test of velocity and desiccation as limits. *Mar. Biol.* 164:27. doi: 10.1007/s00227-016-3057-x

Keller, R., Drake, J., and Drew, J. (2010). Linking environmental conditions and ship movements to estimate invasive species transport across the global shipping network. *Diver. Distrib.* 16, 93–102. doi: 10.1111/j.1472-4641.2010.00696.x

Keppl, E., Sigovini, M., and Tagliapietra, D. (2012). A new geographical record of Polycera hedgesiethi Er. Markos, 1964 (*Nudibranchia: Polyceridae*) and evidence of its established presence in the Mediterranean Sea, with a review of its geographical distribution. *Mar. Biol. Res.* 8, 969–981. doi: 10.1080/17451000.2012.706306

Kerckhoff, F., Haelters, J., and Degraer, S. (2010). The barnacles Chirona (*Striatobalanus*) amaryllis (Darwin 1854) and *Megabalanus coccopoma* (Darwin 1854) (Crustacea, Cirripedia): two invasive species new to tropical West African waters. *African J. Mar. Sci.* 32, 265–268. doi: 10.2989/1814232x.2010.501573

Keswani, A., Oliver, D., Gutierrez, T., and Quilliam, R. (2016). Microbial hitchhikers on marine plastic debris: human exposure risks at bathing waters and beach environments. *Mar. Environ. Res.* 118, 10–19. doi: 10.1016/j.marenvres.2016.04.006

Kiesling, T., Gutow, L., and Thiel, M. (2015). “Marine litter as habitat and dispersal vector,” in *Marine Anthropogenic Litter*, eds M. Bergmann, L. Gutow, and M. Thiel (Cham: Springer). doi: 10.1007/978-3-319-20690-8

Kim, J., Chae, D., Kim, S., Choi, S., and Woo, S. (2015). Factors influencing the spatial variation of microplastics on high-tidal coastal Beaches in Korea. *Arch. Environ. Contam. Toxicol.* 69, 299–309. doi: 10.1007/s00244-015-1515-6

Kirstein, L., Kirkmiz, S., Wichels, A., Garin-Fernandez, A., Erler, R., Löder, M., et al. (2016). Dangerous hitchhikers? Evidence for potentially pathogenic Vibrio spp. on microplastic particles. *Mar. Environ. Res.* 120, 1–8. doi: 10.1016/j.marenvres.2016.07.004

Kooi, M., Nes, E., Scheffer, M., and Koelmans, A. (2017). Ups and Downs in the Ocean: effects of biofouling on vertical transport of microplastics. *Environ. Sci. Technol.* 51, 7963–7971. doi: 10.1021/acs.est.6b04702

Korsun, S., Fahrni, J., and Pawlowski, J. (2012). Invading Aurelia aurita has invaded the Caribbean. *Mar. Biol.* 159, 1061–1069. doi: 10.1007/s00227-012-1886-9

Laganà, P., Caruso, G., Corsi, I., Bergami, E., Venuti, V., Majolino, D., et al. (2019). Distinct community structure and microbial functions of biofilms colonizing marine plastic debris on beaches in Hong Kong. *Sci. Total Environ.* 716:137172. doi: 10.1016/j.scitotenv.2020.137172

Lobelle, D., and Cunliffe, M. (2011). Early microbial biofilm formation on marine plastic debris. *Mar. Pollut. Bull.* 62, 197–200. doi: 10.1016/j.marpolbul.2010.10.013

López-Legentil, S., Legentil, M., Erwin, P., and Turon, X. (2015). Harbor networks as introduction gateways: contrasting distribution patterns of native and introduced ascidians. *Biol. Invasions*. 17, 1623–1638. doi: 10.1007/s10530-014-0821-x

Lynch, S., Darmody, G., O’Dwyer, K., Gallagher, M., Nolan, S., McAllen, R., et al. (2016). Biology of the invasive ascidian Ascidia amnis aspera in its native habitat: Reproductive patterns and parasite load. *Estuarine Coast. Shelf Sci.* 181, 249–255. doi: 10.1016/j.ecss.2016.08.048

Mantelatto, M., Silva, A., Louzada, T., McFadden, C., and Creed, J. (2018). Invasion of aquarium origin soft corals on a tropical rocky reef in the southwest Atlantic, Brazil. *Mar. Pollut. Bull.* 130, 84–94. doi: 10.1016/j.marpolbul.2018.03.014

Marchini, A., Ferrari, J., and Minchin, D. (2015a). Marinas may act as hubs for the spread of the pseudo-indigenous bryozoan Amathia verticillata (*Dellechia*, 1822) and its associates. *Sci. Mar.* 79, 355–365. doi: 10.3989/scimar.04238.03a

Marchini, A., Ferrari, J., Sfriso, A., and Occhipinti-Ambrogi, A. (2015b). Current status and trends of biological invasions in the Lagoon of Venice, a hotspot of marine NIS introductions in the Mediterranean Sea. *Biol. Invasions* 17, 2943–2962. doi: 10.1007/s10530-015-0922-3

Martin, J., Baptist, E. E., van Eekelen, P. J. T., Dankers, B., Grasmeijer, T., van Kessel, D. S., et al. (2017). “Working with nature in wadden sea ports,” in *Proceeding of the Coasts & Ports 2017 Conference*, (Cairns), 7.

Marchini, J., and Adarraga, J. (2008). First record of invasive caprellid Caprella *scaura* Templeton, 1836ensus lato (Crustacea: Amphipoda: Caprellidae) from the Iberian Peninsula. *Aquat. Invasions* 3, 165–171. doi: 10.3391/ai.2008.3.2.6

Masó, M., García, E., Pagés, F., and Camp, J. (2003). Drifting plastic debris as a potential vector for dispersing Harmful Algal Bloom (HAB) species. *Sci. Mar.* 67, 107–111. doi: 10.3989/scimar.2003.67n1107

Mathieson, A., Pederson, J., and Dawes, C. (2008). Rapid assessment surveys of fouling and introduced seaweeds in the Northwest Atlantic. *Rhodora* 110, 406–478. doi: 10.3119/07-4.1

McCuller, M., and Carlson, I. (2018). Transoceanic rafting of Bythozoa (Cycllostomata, Cheilostomata, and Ctenostomata) across the North Pacific Ocean on Japanese tsunami marine debris. *Aquat. Invasions* 13, 137–162. doi: 10.3391/ai.2018.13.1.11

Miao, L., Wang, P., Hou, J., Yao, Y., Liu, Z., Liu, S., et al. (2019). Distinct community structure and microbial functions of biofilms colonizing microplastics. *Sci. Total Environ.* 650, 2395–2402. doi: 10.1016/j.scitotenv.2018.09.378

Micali, J., Rodrigues, P., Halldórsson, H., and Gislason, S. (2020). Distribution and abundance of the invasive tunicate Ciona intestinalis (Linnaeus, 1767) in Icelandic harbours. *Reg. Stud. Mar. Sci.* 34:101039. doi: 10.1016/j.rsma.2020.101039
Mikkelsen, P., and Bieler, R. (2008). "Seashells of Southern Florida. Living Marine Mollusks of the Florida Keys and Adjacent Regions." Princeton: Princeton University Press.

Miller, J., Gillman, R., Carlton, J., Murray, C., Nelson, J., Otani, M., et al. (2018). "Trait-based characterization of species transported on Japanese tsunami marine debris: effect of prior invasion history on trait distribution." Mar. Pollut. Bull. 132, 90–101. doi: 10.1016/j.marpolbul.2017.12.064

Miller, K., Engle, J., Uwai, S., and Kawai, H. (2006). First report of the Asian seaweed Sargassum filicinum Harvey (Fucales) in California, USA. Biol. Invasions 9, 609–613. doi: 10.1007/s10530-006-09060-2

Miller, R., Gammon, K., and Day, M. (2009). Antibiotic resistance among bacteria isolated from seawater and penguin fecal samples collected near Palmer Station, Antarctica. This article is one of a selection of papers in the Special Issue on Polar and Alpine Microbiology. Can. J. Microbiol. 55, 37–45. doi: 10.1139/w08-119

Minchin, D., and Gollasch, S. (2005). "Vector pathways and the spread of exotic species in the sea." ICES Coop. Rep. 271:25.

Mineur, F., Johnson, M., Maggs, C., and Stegenga, H. (2006). Hull fouling on transoceanic gene flow. Mar. Pollut. Bull. 53, 204–210. doi: 10.1016/j.marpolbul.2006.07.020

Mironov, S., Law, K., Proskurowski, G., Murphy, E., Peacock, E., and Mineur, F., Johnson, M., Maggs, C., and Stegenga, H. (2006). "Hull fouling on dispersal vector for hitchhiking invasive species." Mar. Environ. 257:113571. doi: 10.1016/j.envpol.2019.113571

Mortreux, J., van der Weg, B., and Lamberti, A. (2009). "Vertical distribution of buoyant plastics at sea: an observational study in the Atlantic Ocean." Mar. Pollut. Bull. 59, 87–106. doi: 10.1016/j.marpolbul.2008.10.019

Mortreux, J., van der Weg, B., and Lamberti, A. (2009). "Vertical distribution of buoyant plastics at sea: an observational study in the Atlantic Ocean." Mar. Pollut. Bull. 59, 87–106. doi: 10.1016/j.marpolbul.2008.10.019

Munari, L., Assirelli, M., and Bartolomeo, F. (2015). "Classification of non-indigenous species based on their impacts: considerations for application in marine management." PLoS One 10:e0133033. doi: 10.1371/journal.pone.0133033

Ojaveer, H., Galil, B., Campbell, M., Carlton, J., Canning-Clode, J., Cook, E., et al. (2015). "Classification of non-indigenous species based on their impacts: considerations for application in marine management." PLoS One 10:e0133033. doi: 10.1371/journal.pone.0133033

Ojaveer, H., Galil, B., Campbell, M., Carlton, J., Canning-Clode, J., Cook, E., et al. (2015). "Classification of non-indigenous species based on their impacts: considerations for application in marine management." PLoS One 10:e0133033. doi: 10.1371/journal.pone.0133033

Padilla, D., and Savin, S. (2004). "Beyond ballast water: aquarium and ornamental trades as sources of invasive species in aquatic ecosystems." Front. Ecol. Environ. 2, 131–138. doi: 10.1890/1540-9295(2004)002[0131:bbwaau]2.0.co;2

Peng, X., Chen, M., Chen, S., Dasgupta, S., Xu, H., Ta, K., et al. (2018). "Microplastics contaminate the deepest part of the world's ocean." Geochim. Perspect. Lett. 9, 1–5. doi: 10.7185/geochemlet.1829

Pettersen, A., White, C., and Marshall, D. (2016). "Metabolic rate covaries with fitness and the pace of the life history in the field." Proc. R. Soc. B Biol. Sci. 283:20160323. doi: 10.1098/rspb.2016.0323

PIANC (2014). "Sustainable Ports' a Guide for Port Authorities. Report n. 150." Available online at: http://www.pianc.org/editeds/articleshop.php?id=42014150 (accessed 30 September, 2016).

Pincetth, J., Leclerc, J., Brante, A., Daugiu-Thiebaut, C., Diaz, C., Tellier, F., et al. (2017). Presence of the tunicate Asteroepa humilis on ship hulls and aquaculture facilities in the coast of the Biobio Region, south central Chile. PeerJ 5:e3672. doi: 10.7717/peerj.3672

Pincetth, J., Urbina, M., and Lagos, M. (2020). "Marine invertebrate larval love plastics: habitat selection and settlement on artificial substrates." Environ. Pollut. 265:116209. doi: 10.1016/j.envpol.2020.116209

Pincetth, J., Urbina, M., and Lagos, M. (2020). "Marine invertebrate larval love plastics: habitat selection and settlement on artificial substrates." Environ. Pollut. 265:116209. doi: 10.1016/j.envpol.2020.116209

PlasticsEurope (2014). "Datos de Mercado: Plastics - the Facts 2014." Available online at: https://www.plasticsEurope.es/es/resources/market-data (accessed January 16, 2020).

PlasticsEurope (2014). "Datos de Mercado: Plastics - the Facts 2018." Available online at: https://www.plasticsEurope.es/es/resources/market-data (accessed March 19, 2018).

Przedzinska, E., López Gappa, J., Raffo, M., Tatián, M., Bortolus, A., Orensanz, J., Schoener, A., and Rowe, G. (1970). Pelagic Sargassum and its presence among the amphipod Paracaprella pusilla: a new alien crustacean in the Mediterranean Sea. Ocean Coast. Manag. 12, 551–556. doi: 10.1016/0029-0126(70)90010-0

Reich, S., Borrell, Y., and García-Vázquez, E. (2016). "Marine litter as a vector for non-native species: what we need to know." Mar. Pollut. Bull. 113, 40–43. doi: 10.1016/j.marpolbul.2016.08.032

Reich, S., Borrell Pichs, Y., and García-Vázquez, E. (2018a). Anthropogenic marine litter composition in coastal areas may be a predictor of potentially invasive rafting fauna. PLoS One 13:e0191859. doi: 10.1371/journal.pone.0191859

Reich, S., Salmina, S., Borrell Pichs, Y., and García-Vázquez, E. (2018b). "Dispersal of alien invasive species on anthropogenic litter from European mariculture areas." Mar. Pollut. Bull. 131, 10–16.

Reisser, J., Slat, B., Noble, K., de Plessis, K., Epp, M., Proietti, M., et al. (2015). "The vertical distribution of buoyant plastics at sea: an observational study in the North Atlantic Gyre." Biogeosciences 12, 1249–1256. doi: 10.5194/bg-12-1249-2015

Rilov, G., and Crooks, J. (2009a). "Europea enclosed and semienclosed Seas," in Biological Invasions in Marine Ecosystems, eds G. Rilov and J. Crooks (Berlin: Springer), 529–548.

Rilov, G., and Crooks, J. (2009b). "Marine bioinvasions: conservation hazards and vehicles for ecological understanding," in Biological Invasions in Marine Ecosystems, eds G. Rilov and J. Crooks (Berlin: Springer), 3–11. doi: 10.1007/978-3-540-79236-9_1

Ros, M., Vázquez-Luis, M., and Guerra-García, J. (2013). The tropical caprellid amphipod Paracarcella pusilla: a new alien crustacean in the Mediterranean Sea. Helgoland Mar. Res. 67, 675–685. doi: 10.1007/s10152-013-0353-4

Sanchez-Vidal, A., Canals, M., Calafat, A., Lastras, G., Pedrosa-Pámis, R., Menéndez, M., et al. (2012). "Impacts on the deep-sea ecosystem by a severe coastal storm." PLoS One 7:e30395. doi: 10.1371/journal.pone.0030395

Schoener, A., and Rowe, G. (1970). Pelagic Sargassum and its presence among the deep-sea benthos. Deep Sea Res. Oceanogr. Abstr. 17, 923–925. doi: 10.1016/0011-7471(70)90010-0

Schwindt, E., López Gappa, J., Raffo, M., Tatián, M., Bortolus, A., Orensanz, J., et al. (2014). "Marine fouling modes in invasions of Patagonia (Argentina) with implications for legislation and monitoring programs." Mar. Environ. Res. 99, 60–68. doi: 10.1016/j.marenres.2014.06.006
