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# Managing the risk of marine bioinvasion via biofouling: trends in methods of assessment, policy, and legislation

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## Abstract

Maritime shipping has been recognized as the main pathway of species transference throughout the world. Ballast water or fouling on vessels have become the main vectors of aquatic species transportation between coastal marine ecosystems, which can lead to significant social, economic, and ecological negative impacts. Approximately 55% of non-indigenous marine species can be associated with vessel biofouling. However, acting to prevent, detect, manage, and control bioinvasion via biofouling is relatively recent. To improve non-indigenous marine species management, several risk assessment frameworks have been proposed. This research undertook a systematic bibliographic review to investigate whether and how risk assessment has been used to manage marine bioinvasion via biofouling. We analyzed 410 scientific studies published until December 31, 2023, via the Scopus database, filtering them by keywords, title, and abstract. This study describes the parameters and methodologies to assess bioinvasion risks. Furthermore, it discusses the incorporation of risk assessments into global, regional, and country-level public policies, the latter based on countries that publish the most on the topic. This research highlights the scarcity of mandatory measures to manage biofouling, as well as the urgent need to standardize risk assessment methodologies and to incorporate the effects of climate change into these assessments. The development of advanced data analysis tools and a unified strategy to effectively address the complex challenge of marine bioinvasions is also suggested.

**Keywords:** Risk management, Non-indigenous species, Risk assessment, Marine bioinvasion, Legislation

## INTRODUCTION

Marine bioinvasions are one of the most important human-induced pressures threatening marine ecosystems (Ojaveer et al., 2018). These invasions have significantly increased in recent decades due to the dispersal of species associated with the rise in trade and maritime transport (Seebens et al., 2013). Ballast water and biofouling associated with commercial and oil vessels, recreational boats, and man-made submerged structures act as vectors to the introduction of invasive marine species (Carlton, 1989).

Biological invasions can negatively impact social and economic sectors (Ojaveer et al., 2015). The dispersion of non-indigenous species (NIS) can contribute to significant changes in the global biogeographic patterns (biodiversity and distribution) and lead to the development

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of homogeneous biological communities, with low species diversity (Capinha et al., 2015). The introduction and potential establishment of NIS generate high costs due to their damage to the ecosystem and cause a greater expenditure of economic resources that should be allocated to its control in the management of protected areas (Diagne et al., 2021; Ruiz et al., 2011). In some European countries and in the USA the invasive green algae *Caulerpa taxifolia* was quickly detected. In California, the government acted six months later, which enabled it to be eradicated in two years with an investment of US$ 7,000,000. In the Mediterranean, procrastination for years enabled the species to spread to several locations along the European coast (Simberloff et al., 2013).

Vector is the physical means by which NIS are transferred to non-native ecosystems (Creed et al., 2017. Thus, information about this displacement is very important to prevent and manage bioinvasions. According to Hewitt and Campbell (2010), approximately 55% of non-indigenous marine species can be associated with vessel biofouling. However, acting to prevent, detect, manage, and control bioinvasion via biofouling is relatively recent. These actions gained visibility around a decade ago, especially after the Guidelines for the Control and Management of Ships' Biofouling, published in 2011 and recently revised (see International Maritime Organization, 2011; 2023) and the 2012 Guidance for Minimizing the Transfer of Invasive Aquatic Species As Biofouling (Hull Fouling) for Recreational Craft, both published under the scope of the International Maritime Organization (IMO) (Davidson et al., 2016). Despite these recommendations, biofouling management associated with activities conducted at the sea are yet to be fully organized either at international or national levels. According to Davidson et al. (2016), points of concern regarding colonization, transfer, and possible establishment differ between the maritime industry, environmental managers, and scientists. Furthermore, there remains a discussion regarding the vessel hull areas that should be sampled and evaluated. Although niche areas differ from the horizontal and vertical hull surfaces of vessels in their heterogeneity and are considered hotspots for the accumulation of biofouling on vessels, industry studies tend to ignore niche areas in their methods (Coutts and Taylor 2004; Davidson et al., 2016; Thomason, 2009).

Evaluating and predicting the possible transfer of NIS configures a key task to reduce the environmental and socioeconomic impacts caused by bioinvasion worldwide (Campbell and Hewitt 2011; Hewitt et al., 2011; Davidson et al., 2016; Kacimi et al., 2021). However, there are no standardized measures to prevent/predict bioinvasions, mainly due to the variety of input parameters that can be considered. In this context, risk assessment can evaluate the probability and potential impact of risks, particularly in marine biosecurity. This involves five steps: defining objectives, recognizing hazards, evaluating risk likelihood, assessing consequences, and calculating overall risk (Campbell and Hewitt, 2011). Most risk assessment methodologies are divided into multi-criteria decision analysis and probabilistic modeling. Nevertheless, the parameters in these analyses are quite different depending on the adopted approach. The synergy of abiotic, biotic, and anthropogenic factors on marine bioinvasion is complex and may vary depending on the specific characteristics of the marine environment in question and the involved invasive species. Understanding and monitoring these factors is important to minimize the impact of invasive species on marine ecosystems. Nowadays, the main approaches consider several parameters related to the characteristics of vessels, (hull size, sailing speed, transport routes), geographic distances (biogeographic patterns), environmental factors (seawater temperature, salinity, etc.), species status, and impact potential (Hewitt et al., 2010).

This study investigates how global risk assessments of bioinvasion via biofouling have been approached regarding evaluated parameters and State adoption as a public policy to manage vessel biofouling.

## METHODS

A list of research articles published until December 31, 2023, was compiled using the Scopus database. We used the following terms as search parameters: "Risk assessment" OR "Risk analysis" AND "Biofouling" OR "Fouling" AND "Non-indigenous species" OR "Nonindigenous species" OR "Bioinvasion" AND "Marine" OR "Ocean" AND "Guidelines" OR "Act" OR "Law" OR "Plan" AND "Regulation" OR "Legislation" OR "Policy, applying each to the keywords, titles, or abstracts of the articles. Then, we accessed the list of references of each article and used the citation searching method to ensure that all relevant publications were considered (Rethlefsen et al., 2021). Based on the conceptual bibliographic analysis of 410 articles, we focused on risk assessment to manage bioinvasion via biofouling to investigate whether and how risk assessment has been used to manage marine bioinvasion via biofouling.

### Global developments

To investigate global trends and evolution, we evaluated two metrics based on the literature review: author keywords and scientific production per country. These aspects were analyzed based on the number of publications per year and percentage of publication in two periods (before 2011 and from 2011 to 2022). We selected 2011 because it was the publication year of the first IMO Guidelines on Biofouling (International Maritime Organization, 2011).

### Risk assessment methodologies

Based on the literature review, we conducted a screening to find, among the documents related to the description of methods, the primary approaches, techniques, and features to estimate/classify bioinvasion risk via biofouling. In total, six documents (Table 1) were selected in which we found three different assessment approaches: Statistical Modeling, Multi-Criteria Decision Analysis, and hybrid methods combining both.

### Policy and legislation

We also analyzed how risk assessment has been incorporated into the public policies and legislation on marine bioinvasion management via biofouling. First, we found 17 articles that contained the terms "guidelines," "act," "law," "plan," "regulation," "policy," and "legislation" in their title. As for country-level policy and legislation strategies, we focused on the countries that published the most on the subject. According to our results, these were the United States, the United Kingdom, New Zealand, and Australia, with more than 50 publications each. After reading the remaining 13 articles, we conducted a citation search to further knowledge about the strategies explored in the documents, searching legislation and government publications, as well as cited scientific articles.

For the bibliographic analysis of this section, some specific questions were raised: What types of legal acts provide regulations on biofouling? What is the scope of these regulations, considering environmental, economic, temporal, or geographical aspects (e.g. Which vectors are targeted? Which activities or actors are affected? Which areas does the standard apply to?) Finally, do these regulations impose obligations or do they only give recommendations?

## RESULTS AND DISCUSSION

### Risk assessment of marine bioinvasion via biofouling: key parameters

The parameters related to the risk of marine bioinvasion may vary depending on the methodology (Figure 1), but they can be organized according to four components:

1. **Introduction potential**

It is related to the intentional or unintentional human-mediated translocation of an organism to a region outside its natural biogeographic range (Hewitt et al., 2011). Introduction potential is based on how NIS can be introduced into the new environment. This component is also associated with specific characteristics from species, donor, and recipient regions, information about transportation such as anti-fouling system criteria), and vessel information (Hewitt et al., 2011).

2. **Establishment potential**

It is related to the process of survival and development of a self-sustaining population to a new environment. Establishment potential is estimated by biological characteristics and local environment conditions (Floerl and Coutts, 2009; Hewitt et al., 2011) that interfere with the ability of NIS to establish themselves in new environments.

3. **Impact potential**

Changes in the structure and functioning of ecosystems considering predation, competition for resources, diseases, and other factors. The impact potential is associated with species characteristics and reported status and estimated if the invasive species has been introduced elsewhere and what impact was recorded.

4. **Uncertainties**

uncertainty is usually associated with the available information about the invasive species, transportation, characteristics of donor/recipient regions, and associated impacts. Uncertainties can also fall on the methodology used to assess risk. All these aspects must be considered (Mandrak et al., 2012).

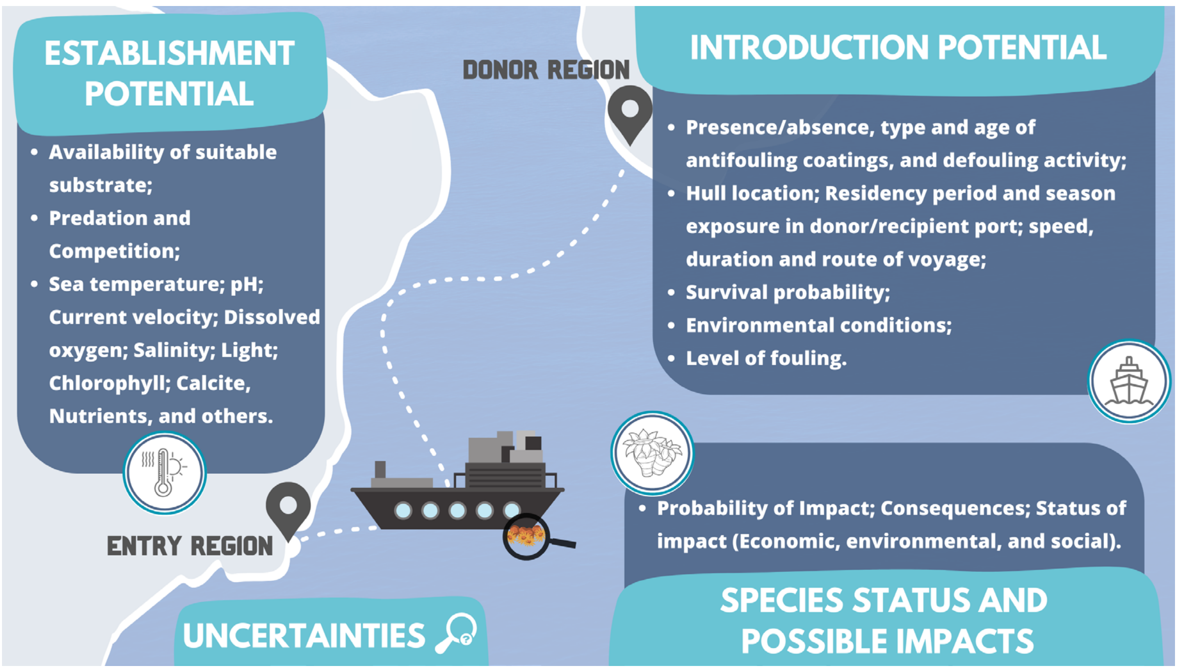


**Figure 1.** Key parameters for risk assessment of marine bioinvasion via biofouling

## Influence of the environmental parameters

Abiotic factors such as temperature, salinity, current velocity, nitrate, dissolved oxygen, calcite, iron, among others can influence the process of marine bioinvasion in several ways. For example, temperature can influence the rate of reproduction and growth of invasive and native species. Invasive species that can tolerate a wide range of temperatures may have a competitive advantage over native species that are more sensitive to temperature variations (Kacimi et al., 2021). Salinity can also influence the survival and reproduction of invasive species as some species may better tolerate variations in salinity than others (Kacimi et al., 2021). Currents can influence the dispersal and distribution of invasive species, enabling them to spread over long distances and colonize new areas (Coelho et al., 2022). Nutrient availability can also influence the survival and growth of invasive species, especially in coastal regions that are most affected by pollution and eutrophication (Yu et al., 2019). The availability of calcite is important for skeleton construction in several organisms (such as corals) (Carlos-Júnior et al., 2014). Dissolved oxygen can play an important role in the bioinvasion process since many invasive species have different oxygen needs than native species (Gobler and Baumann, 2016). Some invasive species can adapt to low-oxygen environments, whereas others may have higher oxygen needs. In marine environments, iron availability can limit the growth of some species, and the addition of iron can be used as a fertilizer to promote the growth of algae and other aquatic plants (Han et al., 2021). In summary, abiotic factors play a key role in marine bioinvasion, influencing the ability of invasive species to survive, grow, and reproduce in new environments and compete with native species.

Although chlorophyll is not an abiotic factor, it is strongly influenced by them. It plays no direct role in bioinvasion, but the changes that occur in the composition of the algal community in an ecosystem because of bioinvasion can affect the efficiency of photosynthesis in native species, which can, in turn, facilitate the NIS establishment process (Maltsev et al., 2021).

## Methodologies for risk assessment

We observed three most applied methods to assess the risk of NIS bioinvasion: multi-criteria decision analysis, statistical modeling, and hybrid methods.

Risk assessment is used to determine the likelihood of a particular event and its possible consequences (Hewitt et al., 2011). This process evaluates scientific and economic evidence to find potential invasive species and assess the level of invasion risk associated with a species or pathway (Roy et al., 2017). According to Roy et al. (2017), more than 70 tools have been developed during the last decades to assess the risk of marine bioinvasion, including ballast water and biofouling sources. These tools have been listed by Srėbalienė et al. (2019) and include the following terms: protocols, frameworks, kit, scheme, system, tool, index, and others.

Most methodologies to assess risk are related to the multi-criteria decision analysis approach (Table 1). This approach relies on data collected from several documents, such as inspection reports, online forms, questionnaires, and control spreadsheets as a basis for risk classification (Campbell and Hewitt, 2013; Hewitt et al., 2011). Thus, apart from on-site measured information, such as the level of fouling, these documents rate each event based on specific criteria. For example, Campbell and Hewitt (2011) show models to classify the risk of introducing organisms to the Australian coast that were built with multiple matrices, each associated with a criterion. The authors also included (a) information on the presence/absence of the evaluated species by location, (b) a probability matrix of event occurrence, (c) a consequence matrix according to potential impacts, and (d) a risk matrix.

**Table 1.** Summary of risk assessment methodologies (SM: Statistical modeling and MCDA: Multi Criteria Decision Analysis)

| Approach | Technique | Features | Type of document | Reference |
|---|---|---|---|---|
| MCDA | Inspection reports, questionnaires, or forms | Antifouling and defouling strategies, vessel information, abiotic factors | Legal document | IMO Biofouling guidelines review (2023) |
| SM | Environmental similarity and biogeographical dissimilarity | Level of fouling, species status, geographic distance and scale, abiotic factors | Research article | Kacimi et al. (2021) |
| MCDA | Inspection reports, questionnaires, or forms | Antifouling and defouling strategies | Legal document | Brazilian government (IBAMA, 2020) |
| Hybrid | Bioregion pathway and species-based exposure | Species status, vessel information, geographic distances | Research article | Azmi et al. (2014) |
| MCDA | Inspection reports, questionnaires, or forms | Species status, vessel information, propagule pressure, and impacts | Research article | Campbell and Hewitt (2013) |
| MCDA | Inspection reports, questionnaires, or forms | Species status, vessel information, and impacts | Legal document | Australian government (Campbell and Hewitt, 2011) |

Nevertheless, the IMO (2023) Biofouling Guidelines defend a preventive strategy against biofouling by evaluating biofouling risk profiles for both hull and niche areas along with monitoring several risk parameters throughout the operation of vessels.

A small part of the evaluated documents address risk analysis based on statistical models. For example, Kacimi et al. (2021) developed a model to estimate the risk of port-to-port invasion based on vessel trips to the port of Arzew in Algeria, which, in turn, is an adaptation of Seebens et al. (2020), focused on the transport of NIS by ballast water. This methodology considers that the invasion probability is the product of the probabilities of alien introduction and establishment. They used level of fouling, species occurrence, geographic, vessel, and abiotic factors data as features.

As for the hybrid approach, according to Azmi et al. (2014), many countries have limited information about species within their jurisdictional boundaries. To help solve it, they develop two risk models to find an effective marine biosecurity risk management approach in areas with scarce biological data.

## Global evolution of the research on risk assessment

Figure 2 shows that most listed documents are related to “non-indigenous species” (the term used in this study) and “invasive species” because these keywords are intrinsically connected to risk assessment and bioinvasions, as well as “biological invasions” and “risk assessment.” They are followed by the terms “biofouling” and “ballast water,” which are the main vectors to transport exotic species (Bailey et al., 2020; Diasamidze and Shotadze, 2019; Ojaveer et al., 2018). Regarding these last two topics, note that a shift in the evolution over the years occurred in 2019, when “biofouling” began to emerge on a greater number of documents than “ballast water”. The percentage of documents published from 2011 to 2022 for each keyword is shown in Figure 2b. It was calculated based on the ScientoPy library (Ruiz-Rosero et al., 2019)

Furthermore, note the presence of the term “climate change,” which, according to several studies (Capinha et al., 2015; Giakoumi et al., 2016; Mačić et al., 2018; Seebens et al., 2021), can facilitate increased bioinvasion worldwide. The terms “biosecurity” and “management” also emerge, which are related to policies, legislation, and overall risk analyses (Campbell and Hewitt, 2011).

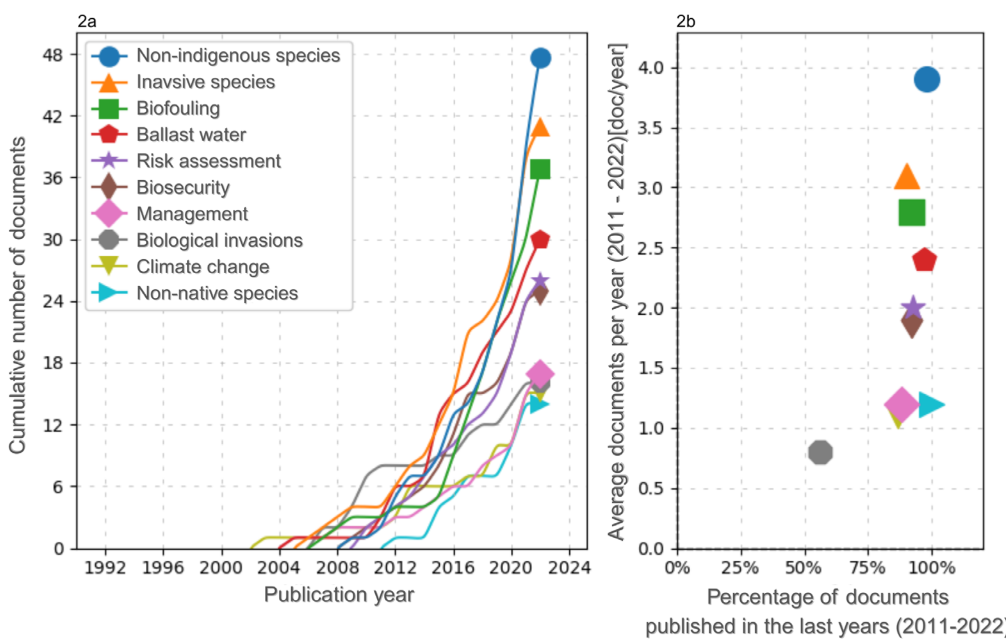


**Figure 2.** Number of documents and percentage of documents published from 2011 to 2022

To evaluate the development of international knowledge on risk assessment, we collected data on the number of publications from the 15 countries with the greatest production, as well as data on the percentage of documents published before 2011 and from 2011 to 2022 (Figure 3).

The results show that the United States has consistently stood at the forefront of publishing documents related to risk assessment (Figure 3). Also, the United Kingdom surpassed Australia in publications per year in 2016 and continues to outpace Australia (Figure 3).

Additionally, in 2022, note the formation of six groups with publication numbers that are relatively close (Figure 3). They are composed of (1) the United States; (2) the United Kingdom; (3) Australia and New Zealand; (4) Spain and Canada; (5) Italy and Germany; and (6) France, Portugal, Brazil, South Africa, Sweden, Greece, and Ireland.

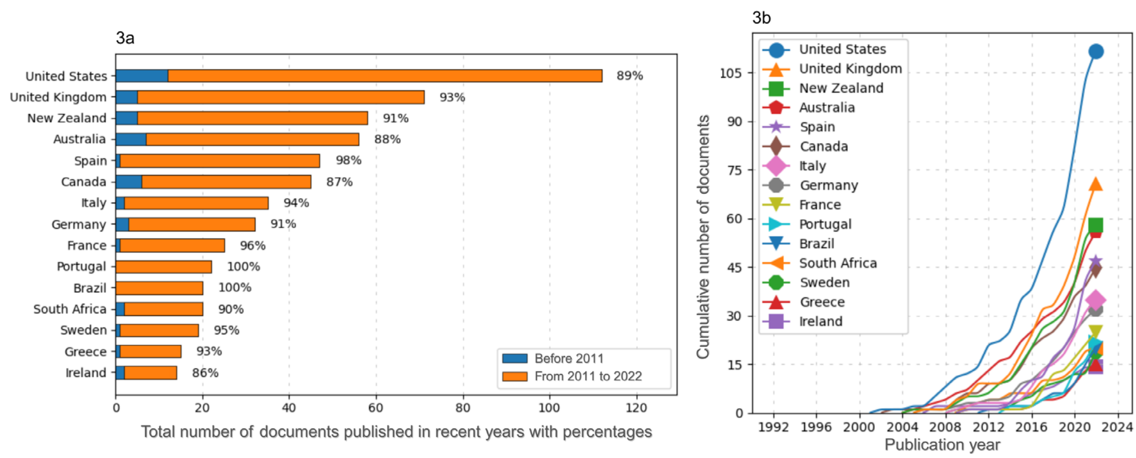


**Figure 3.** Trends in the research on risk assessment per country

## Policy, legislation, and other developments

We created a table to illustrate how risk assessment has been incorporated into public policies and legislation that address the management of marine bioinvasion via biofouling (see Table S2). As Ojaveer et al (2018) observed, policy documents and strategies to reduce the introduction and spread of NIS have been increasing since the second half of the 20th century after several high-profile invasions. However, they showed significant time lags, limited success, and a focus on only a subset of transfer mechanisms. Specifically regarding biofouling, this trend is even more recent, with a strong influence from the documents published by the IMO on the subject.

The remainder of this section summarizes our findings on the jurisdictional scale.

## Global efforts

From the 1980s — when the first international treaty concerned with the protection of the marine environment was signed — to the present day, this review found 13 legal documents related to the management of biofouling with a global mandate. Following the chronological order in which they were adopted, the most frequently cited are the United Nations Convention on the Law of the Sea – UNCLOS (Unite Nations, 1982), the Convention on Biological Diversity (CBD) Guiding Principles on Invasive Alien Species, and the IMO Guidelines on Biofouling. They will be discussed in detail below.

1. **United Nations Convention on the Law of the Sea (UNCLOS)**

UNCLOS, also known as the “constitution for the oceans” (Koh, 1982), dedicates an entire part of its document (Part XII) to the protection and preservation of the marine environment. As a legally binding treaty, it contains a general obligation on states (art. 192) and specified measures relating to certain sources of marine pollution, such as land-based pollution, atmospheric pollution, discharges, vessels, and installations (art. 194). Article 196 specifically addresses the introduction of NIS that “may cause significant and harmful changes in the marine environment,” establishing that “States shall take all necessary measures to prevent, reduce and control such introduction, whether accidental or intentional”.

Some limitations must be highlighted. First, although this no-harm imperative (*neminem laedere*) is mandatory, it only bears a due diligence obligation, which means States are obliged to take preventive measures. The document fails to prohibit damage itself (Winter, 2018). It focuses on pollution, abstaining from clear obligations to protect marine biodiversity beyond measures related to rare and fragile ecosystems, the habitats of threatened or endangered species (art. 195, para. 5), and fisheries resources (art. 61-68). Moreover, since UNCLOS fails to expressly link NIS introduction to pollution, the precise interpretation of the provision (and of the consequences it entails) remains under debate (Köck and Magsig, 2018).

2. **CBD COP guiding principles for the prevention, introduction, and mitigation of impacts of alien species that threaten ecosystems, habitats, or species**

The Convention on Biological Diversity (CBD), adopted in 1992, is the main international agreement in force on biodiversity protection. This mandatory framework convention is based on overarching objectives and principles that may be further elaborated via protocols and action-oriented documents (Eckardt et al., 2023). This calls on States to protect all ecosystems, habitats, and populations of species (see Winter, 2018 and Tanaka, 2015). Article 8 (h) calls each Contracting Party, as far as possible and as appropriate, "to prevent the introduction of, control or eradicate those alien species which threaten ecosystems".

Under this background, the CBD Guiding Principles on NIS were adopted at the 6th Conference of the Parties (COP 6) in 2002 (COP 6 Decision VI/23). It establishes 15 non-binding principles to guide governments and organizations to develop strategies that minimize the impacts due to invasive species. It adopts a "three-stage hierarchical approach" (see arts. 2, 13, 14, and 15), focusing on 1) taking measures to prevent the introduction or establishment of alien species, 2) eradicating invasive organisms, and 3) immediately implementing bioinvasion containment and control measures. Principle 7 expressly suggests conducting "risk analysis of the threats posed by alien species and their potential pathways of entry," whereas principle 11 encourages risk analyses of unintentional introductions promoted by specific activities, such as fishing, maritime transport, aquaculture, and tourism. It, therefore, prioritizes prevention as the best cost-benefit strategy, for which the management of the pathways of NIS introduction is given a central role (Shucksmith and Shelmerdine, 2015).

3. **IMO biofouling guidelines**

Under the slogan "safe, secure and efficient shipping on clean oceans," the International Maritime Organization (IMO), the specialized agency of the UN for maritime affairs, has paid special attention to marine pollution from vessels (International Maritime Organization, 2013). In the bioinvasion realm, ballast water was the first vector to be regulated by the IMO, first by the adoption of Guidelines in 1997, and then by signing the Ballast Water Management Convention in 2004, which only entered into force in 2017.

In 2001, the International Convention on the Control of Harmful Anti-fouling Systems on Ships was adopted. However, management of biofouling only began to be formally discussed by its Marine Environment Protection Committee (MEPC) in 2006, with its own document (Resolution MEPC 207(62)) approved in 2011 (Scianni et al., 2021). The 2011 IMO Biofouling Guidelines focused on developing and implementing vessel-specific Biofouling Management Plans and Biofouling Record Books to guide preventive and reactive biofouling management (Cunningham et al., 2019). The risk assessment of marine bioinvasion was mentioned in the session dedicated to in-water inspection, cleaning, and maintenance. This was a foreseeable measure for States to evaluate the risk of in-water cleaning activities and minimize potential threats, which may include biological, environmental, geographical, and sanitary aspects (Art. 7.6).

The IMO Biofouling Guidelines were followed by several related IMO efforts, for example , the 2012 Guidance for Minimizing the Transfer of Invasive Aquatic Species as Biofouling (Hull Fouling) for Recreational Craft and the 2013 Guidance for Evaluating the 2011 Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species (Scianni et al., 2021). In 2018, the Subcommittee on Pollution Prevention and Response was assigned to conduct a review of the document (Scianni et al., 2021), which was concluded at the 80th MEPC session, with the adoption of Resolution MEPC 378(80) from July 2023. In its recently published version, Appendix I suggests a proactive risk assessment approach for hull and niche areas based on monitoring various risk parameters during vessel operation. This includes the identification of the niche areas most susceptible to biofouling (risk areas), definition of the risk profile for biofouling accumulation of the vessel, and establishment of a system for monitoring risk parameters.

We also highlight the legal strategies adopted by other regulatory texts of global reach that are less disseminated in the literature, but which were also found in our review. This is the case of the Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement) and the World Organization for Animal Health (WOAH) Aquatic Animal Health Code, pioneers in indicating risk analyses to prevent damage caused by biofouling. In 1994, the SPS Agreement had set binding requirements (e.g., use of science, risk assessment, minimal impacts on trade, transparency) to establish national regulations to protect human, animal, and plant (Lodge et al., 2016), whereas, in 1995, the WOAH Aquatic Animal Health Code had included a specific section giving instructions on how to conduct risk analysis (Ojaveer et al., 2018). Finally, we find the Kunming-Montreal Global Biodiversity Framework (GBF), adopted in December 2022, during the 15th UN Biodiversity Conference (CBD COP 15). Although not mandatory, it deserves to be mentioned for the boldness of its Target 6, which aims at "reducing the rates of introduction and establishment of other known or potential invasive alien species by at least 50 per cent by 2030, and eradicating or controlling invasive alien species, especially in priority areas, such as islands" (see decision CBD/COP/DEC/15/4).

## Regional developments: the European Union strategy

In the regional international sphere, the European Union, officially created in 1992 with the signing of the Maastricht treaty, stands out as a lawmaker on bioinvasions. However, as Ojaveer et al. (2018) observes, still under the mantle of the European Community, article 11.1(b) from the Convention on the Conservation of European Wildlife and Natural Habitats, from 1979, already required contracting parties "to strictly control the introduction of non-indigenous species" (Council of Europe). In 1992, the Habitats Directive (Council of the European Communities, 1992) called on states to regulate the introduction of NIS, to avoid damage to natural habitats, fauna, and flora (Art. 22(b)).

As for aquatic environments, the Aquaculture regulation (EC n. 708/2007) went further by establishing directives to manage permits as a necessary condition for authorizing the introduction of exotic or absent species. The procedure is based on guidelines supported by data generated from risk assessment, aiming to issue permits associated with low invasion risks. The European Marine Strategy Framework Directive (2008/56/EC) is among the mandatory instruments and is specifically aimed at the marine environment (European Comissiom, 2008). Although mandatory, it belongs to the EU secondary law (see Treaty on the Functioning of the European Union – TFEU – art. 288), which means that Member States must transpose them by defining the form and methods that are applicable into their national legal systems to be effective at national level (Ojaveer et al., 2018). This recognizes the marine environment as a precious heritage and defines the aim to maintain biodiversity and dynamic and diverse oceans and clean, healthy, and productive seas. As part of the framework, it provided for achieving or maintaining good environment status by 2020 (art. 1), it committed states to adopt strategies to protect, preserve, prevent, and restore the marine environment and defined a series of qualitative descriptors for determining good environmental status (Köck and Magsig, 2018). Descriptor 2 is dedicated to NIS that were introduced by human activities, which should be kept "at levels that do not adversely alter the ecosystems" (European Comission, Annex I, 2008).

The most important document for invasive species management came in 2014, with Regulation (EU) n. 1143 of the European Parliament and of the Council of 22 October 2014 (European Comission, 2014). This established the List of invasive alien species of Union concern, drawn up from risk assessments that must involve consideration of risks and benefits of introduction (art. 5 (h)) (Köck 2015). The species of organisms listed there can no longer be imported, kept, bred, purchased, used, exchanged, and released (art. 7). Moreover, this document includes guides and determinations on the analysis of pathways of introduction (art. 13), setting up surveillance systems (art.14 ff.) and eradicating the yet to be established NIS "of Union concern" (art. 17 ff.), along with the necessary requirements for applying the program to combat and monitor NIS in practice (art. 3 ff.) (Köck and Magsig, 2018).

The EU Regulation on NIS (EU 1143) has a supplementary document devoted to NIS risk assessment, the Commission Delegated Regulation (EU) 2018/968, which was published in 2018. This described the common elements and a risk assessment methodology to submit requests for the inclusion of invasive alien species on the Union list.

## Country-level initiatives

Our findings pointed to the United States, the United Kingdom, New Zealand, and Australia, respectively, as the main publishers concerning risk assessment to manage bioinvasion via biofouling. Although the United Kingdom, formed by England, Scotland, Wales, and Northern Ireland, ranked second, the case of the Shetland Islands was the only one to stand out in the searched articles (see Appendix 1). Therefore, we will discuss in detail the strategies developed by the United States of America (US), New Zealand, and Australia since they have been considered as precursors of a relatively solid system of standards on the matter, contributing to the implementation of international targets and recommendations and to their design (Lodge et al., 2016).

1. **United States of America**

Since the 1990s, the United States developed federal legislations concerned with the negative impacts of NIS on its coastal waters. The first, the Non-Indigenous Aquatic Nuisance Prevention and Control Act, responded to the introduction of zebra mussels and other species into the Great Lakes region via ballast water. In 1996, it was amended to include the National Invasive Species Act of 1996, which granted authority to the United States Coast Guard to prevent the introduction and spread of aquatic nuisance species, including via hull fouling (Scianni et al., 2021). Since March 2017, it requires the removal of fouling organisms from the vessel hull, piping, and tanks regularly and dispose of any removed substances in accordance with local, state, and federal regulations (see 33 CFR 151, Subpart D, Section 2050 (f)).

Under the purview of the U.S. Environmental Protection Agency, the National Pollutant Discharge Elimination System, under the provisions of the Clean Water Act, establishes the basic structure to regulate discharges of pollutants into the waters of the United States. This sets requirements regarding the issuing of permits for in-water cleaning, hull coatings, anchor chains, seawater piping, hull cleaning, as well as routine or upon request inspections and reports (see title 33, § 1251 et seq. of the U. S. Code). In 2018, the Vessel Incidental Discharge Act (see § 1322) was adopted, aiming to provide national standards of performance for marine pollution control devices for discharges incidental to the normal operation of vessels, including the discharge of biofouling from a vessel during a period in which the vessel is undergoing not active cleaning activities (called "passive biofouling"). However, the U.S. Environmental Protection Agency only adopted their final Vessel Incidental Discharge Act standard of performance in September 2024, and the U. S. Coast Guard still has two years to develop the corresponding implementation, compliance, and enforcement regulations so that it can become effective.[1] Note the rapid risk assessment protocols developed by the US Fish and Wildlife Service. The entity is responsible for finding injurious wildlife the importation of which should be barred. Although the procedures also respond to climate change, they fail to exclusively apply to marine species (Lodge et al., 2016).

Therefore, when focusing on the marine environment, one must look upon the initiatives in California. In 2007, an amendment placed a mandate on the California State Lands Commission to develop and adopt biofouling management regulations (Scianni et al, 2021). The Biofouling Management to Minimize the Transfer of Non-indigenous Species from Vessels arriving at California Ports as part of the California Code of Regulations entered into force in October 2017. This is applicable for vessels over 300 registered gross tons capable of carrying ballast water, placing requirements such as biofouling

1. See: https://www.epa.gov/vessels-marinas-and-ports/vessel-incidental-discharge-act-vida.

management plans and record books (such as the 2011 IMO Biofouling Guidelines but with specific conditions) as well as annual vessel reporting. Vessels that incur violations during their first inspection after becoming subject to requirements have a 60-day grace period to correct the found deficiencies. If uncorrected, the vessel will receive a Notice of Violation (see Title 2, Division 3, Chapter 1, Article 4.8). As Scianni et al (2021) highlights, this flexibility is a helpful tool to increase awareness and encourage compliance since California has a compliance rate of over 99% after grace period expiration and subsequent inspection.

2. **New Zealand**

New Zealand is also a world-leading country regarding its biosecurity system, which is based in effective and proactive legislation and policy to manage invasive species. The legal framework is provided by the Biosecurity Act 1993 and encourages national and regional government collaboration, as well as affected parties' and stakeholders' engagement (Georgiades et al., 2020).

Under this framework, the Craft Risk Management Standard for Biofouling on Vessels Arriving to New Zealand became effective in 2014. It placed NZ as the first country to institute a standard for biofouling that is applicable to all classes of international vessels. Risk assessments were conducted by the competent public body during its development and risk rating for vessel profiling is part of its implementation (Georgiades et a.l, 2020). It established the "clean hull" obligation, which means to follow the defined thresholds according to the duration of the stay in the country. During the first four years, compliance with the requirements was voluntary, becoming mandatory in 2018 (Scianni et al., 2021). As of October 2023, all biosecurity requirements for biofouling, except for ballast water risks associated with a vessel, emerge in the updated CRMS for Vessels (Ministry for Primary Industries, 2023).

After the 2012 amendments, the Biosecurity Act 1993 enabled national and regional pest management plans to manage NIS biofouling (Georgiades et al., 2020). This changed the focus in the management approach by enabling agencies to declare invasive or harmful species as "pests" and place rules on the vectors rather than on the species themselves to reduce bioinvasions risk (Cunningham et al., 2019). The Fiordland Marine Regional Pathway Management Plan in the Fiordland Marine Area (Southland, New Zealand) was its first national plan to be developed and implemented (Cunningham et al., 2019). After following the many steps councils must follow before implementing a plan with enforceable rules, i.e., showing that the benefits of a plan will outweigh its costs, and that formal consultation takes place with those that may be affected by the new rules, the plan became operative in 2017, applying to all vessels and consisting of three rules: (i) to hold a Fiordland Clean Vessel Pass; (ii) to meet the three following standards: to have hull biofouling of "no more than a slime layer and goose barnacles" (including niche areas), to have all marine gear and equipment on the vessel visibly clean treated and dry, and that any on-board residual seawater has been treated or is visibly clean and treated; and (iii) to keep records of actions to meet the required standards and provide those records upon request (Cunningham et al., 2019).

3. **Australia**

Australia is heavily affected by NIS. Perhaps this explains it as a forerunner in regulating marine bioinvasions, with the Voluntary ballast water guidelines for vessels entering Australian ports from overseas (1990). Along with the US Nonindigenous Aquatic Nuisance Prevention and Control Act, it contributed to the IMO Ballast water guidelines, published in 1991 (Ojaveer et al., 2018).

In terms of recommendations to manage marine biofouling, Australia and New Zealand have a common document: the Australian and New Zealand Antifouling and IWC Guidelines, published in 2015, and drafted since 2011 (Tamburri et al., 2021). It provides guidance on the "best-practice approaches for the application, maintenance, removal and disposal of anti-fouling coatings and the management of biofouling and invasive aquatic species on vessels and movable structures in Australia and New Zealand" (Department of The Environment and New Zealand Ministry for Primary Industries, 2013). According to its government website, the document targets decision-makers. An updated version is expected to be released in 2024. Additional guidance is also provided for some activities, such as offshore oil and gas production, commercial fishing vessels, and the aquaculture industry.

Vessel operators shall also comply with the Australian Biofouling Management Requirements set out within the scope of managing unacceptable levels of biosecurity risk from the Biosecurity Act 2015 (see Division 5), when operating under biosecurity control within Australian territorial seas. That means submitting a pre-arrival report to show compliance with one of the following management practices: (i) implementation of an effective biofouling management plan and record book; (ii) cleaning all biofouling within 30 days prior to arriving in Australian territory; or (iii) an alternative biofouling management method pre-approved by the Department of Agriculture, Fisheries and Forestry (2023). This should also be observed in case of mandatory or voluntary territorial or state management legislation, e.g., in its Northern Territory, Queensland, and Western Australia.

The timeline below highlights the main national normative strategies in the countries that publish the most about bioinvasion via biofouling, as well as at a regional and global level (see Figure 4). To sum up, legislation on marine bioinvasion is becoming more and more aware of the threats represented by biofouling. Concerns of the international community regarding the protection of marine environment began in the 1970s, with the conferences that culminated in the signing of UNCLOS, in 1982. More general and non-obligatory normative provisions prevailed at the time. Furthermore, the notion that ballast water from ships would be the main vector for the introduction of non-native non-indigenous species into the marine environment dominated science for many years. Only after the 2011 IMO Biofouling Guidelines, predictions surpassed the level of taking measures (using expressions such as “take action” and “regulate”) into a more rigorous approach, with more precise obligations around bioinvasion via biofouling, specially via national initiatives. Standards that apply risk assessment appear in this context of growing concern about biofouling and the taking of mandatory measures, alongside predictions such as analysis of pathways, monitoring, and setting up management measures, with the aim of achieving greater predictability and security. Accordingly, country-level strategies incorporate risk assessment either to guide decision-makers while defining general standards that may be established by the norms or as part of the recommendations and obligations that must be observed by specific stakeholders. New Zealand is an example of the first, whereas the Biosecurity Plan for the Shetland Islands (Collin and Shucksmith, 2022) implements the latter.

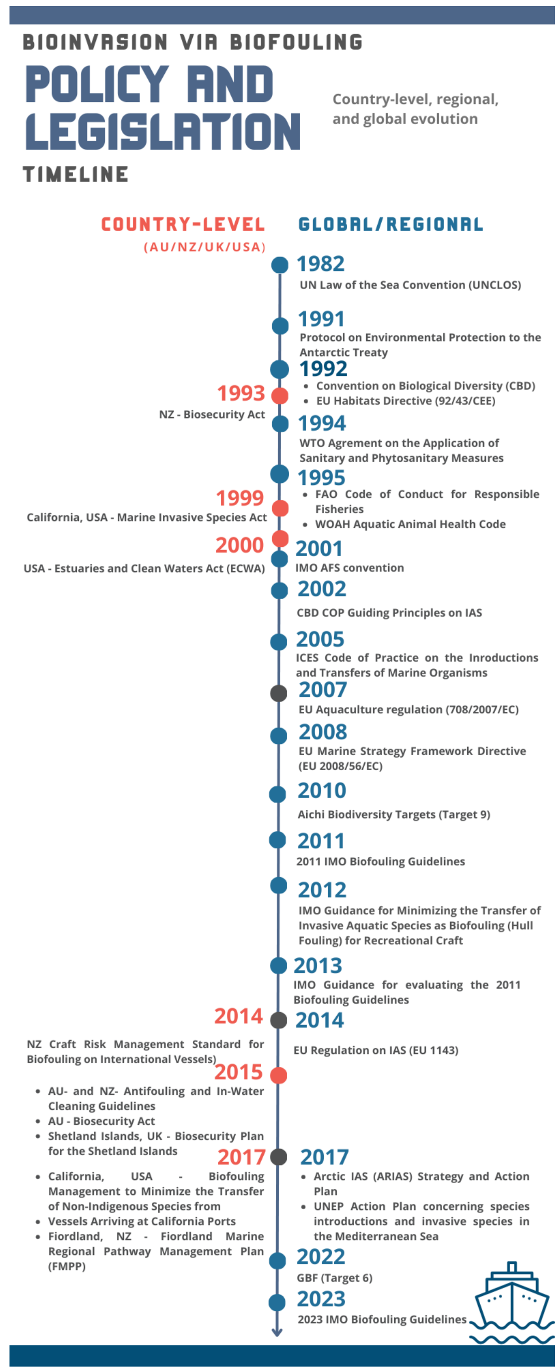


**Figure 4.** Country-level, regional, and global policy and legislation evolution toward the incorporation of risk analysis to manage marine bioinvasion via biofouling

## Challenges and future directions

Marine bioinvasion risk assessment can find NIS with the greatest potential to negatively impact a region. This type of analysis guides decision-making on measures to prevent, control, and manage such NIS, reducing the financial and environmental costs associated with their presence. However, in view of the growing number of cases and studies on the subject, standardizing the methodologies to quantify the extent of NIS effects and evaluating their potential risks have become a necessary step (Srėbalienė et al., 2019). Adopting a methodology or approach to assess risk as part of a public policy to manage bioinvasion via biofouling could be a mean to guide states and entrepreneurs in this direction. Nevertheless, the collected data show international and national legislation that expressly mention scarce risk assessments. Although commitments on biofouling management are increasingly bold, including the establishment of targets such as the aforementioned GBF, countries are still in their infancy when it comes to adopting mandatory measures on the subject. Moreover, marine bioinvasion risk analysis shows some difficulties that must be considered, such as lack of data, spatial and temporal variability, complexity of ecosystems, and incorrect use of data. There is often a lack of data to accurately assess the invasive potential and ecological, economic, and social impacts of NIS, as well as incorrect assessments of the importance of each parameter in analyses. In this context, the use of smart tools and big data can help analyze the large datasets needed for a more robust risk analysis. In addition to helping to find patterns and relationships that would be difficult to find via traditional approaches.

Nevertheless, climate change and biological invasions have been extensively discussed in conservation strategies (Giakoumi et al., 2016; Guidetti and Danovaro, 2018; Mačić et al., 2018). However, the synergistic effect between these processes has been neglected. According to several authors (Seebens et al., 2021); Roy et al., 2017; Capinha et al., 2015), the pattern of marine species distribution lies under significant threat due to climate change-induced shifts in survival and species maintenance boundaries, either leading to expansion or contraction and anthropogenic dispersal. For example, extreme natural events, such as floods, tsunamis, and strong winds, can disperse NIS and provide them with openings for colonization in previously unoccupied regions. Thus, NIS could gain advantages from climate change. As a result, it is crucial to revise and incorporate potential climate change effects into risk assessments, as suggested by Roy et al. in 2017.

## Data availability statement

All data are available from the corresponding author upon reasonable request.

## Supplementary material

Supplementary material availabe at: https://zenodo.org/records/15605118

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F. C. B. A.: Conceptualization; Formal Analysis; Investigation; Writing – original draft; Writing – review & editing.

D. B.: Supervision; Conceptualization; Writing – review & editing.

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## Conflits of interest

The authors declare no conflicts of interest.

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