A peer-reviewed open-access journal
NeoBiota
Advancing research on alien species and biological invasions

NeoBiota 103: 187–214 (2025)
DOI: 10.3897/neobiota.103.159848

Research Article

National implementation of the European Union policy framework for monitoring introduced non-indigenous species in marine and brackish waters: a Belgian case study based on an updated species inventory

Thomas J. Verleye[1], Thomas R. H. Kerkhove[2], Gert Van Hoey[3], Hans Pirlet[1], Francis Kerckhof[2], Ann-Katrien Lescrauwaet[1], Leen Vandepitte[1], Jan Mees[1]

1 Flanders Marine Institute (VLIZ), InnovOcean campus, Jacobsenstraat 1, 8400 Ostend, Belgium
2 Marine Ecology and Management (MARECO), Royal Belgian Institute of Natural Sciences (RBINS), 3de en 23ste Linieregimentsplein, 8400 Ostend, Belgium
3 Flanders Research Institute for Agriculture, Fisheries and Food (ILVO), InnovOcean campus, Jacobsenstraat 1, 8400 Ostend, Belgium
Corresponding author: Thomas J. Verleye (thomas.verleye@vliz.be)

Abstract

Based on a thorough literature review and expert consultation, this study provides an inventory of all introduced non-indigenous species (iNIS) reported for Belgian marine and brackish waters. The data indicate a strong increase in iNIS in the study area from the 1990s onward, averaging 2.2 newly detected species per year, with a cumulative total of 108 iNIS between 1800 and 2024. The majority of these iNIS have the Northwestern Pacific or Northwestern Atlantic as their native region and are primarily introduced in Western Europe via shipping or aquaculture. In addition to compiling the inventory, the context in which the iNIS are detected is examined, distinguishing between official monitoring programs, project-based data collection efforts, and citizen science initiatives. Our findings indicate that while the EU aims to promote coordination between its Marine Strategy Framework Directive (MSFD) and Water Framework Directive (WFD), a misalignment occurs in the practical implementation of iNIS monitoring at the Belgian level. For example, a coherent and integrated monitoring framework across marine, brackish, and freshwater systems is still lacking. Furthermore, despite the EU's ambition to ensure comprehensive iNIS monitoring, no legal framework currently mandates targeted monitoring in coastal ports, despite their well-documented role as hotspots for new marine introductions. After all, iNIS monitoring is only mandatory under the MSFD, which in essence applies only seaward from the coastal baseline and therefore does not cover waters within these ports. In addition, while the EU's IAS Regulation has recently incorporated a few marine species on the Union list, its monitoring requirements remain primarily focused on terrestrial and freshwater species. As a result, observations published by citizens with significant expertise in the field represent the primary source of marine iNIS data in coastal port areas in recent decades in Belgium. The fragmentary nature of iNIS data complicates the efficient flow of information to international or European iNIS reference databases that support policy and decision-making. Yet, even species officially reported by Member States under MSFD Descriptor 2 are not always included in these reference databases. Nonetheless, accurate data on iNIS presence and distribution are essential for effectively targeting and managing iNIS.

Key words: Citizen science, introduced non-indigenous species, inventory, marine, Marine Strategy Framework Directive, monitoring, policy, ports

Academic editor: Belinda Gallardo
Received: 22 May 2025
Accepted: 11 September 2025
Published: 30 October 2025

Citation: Verleye TJ, Kerkhove TRH, Van Hoey G, Pirlet H, Kerckhof F, Lescrauwaet A-K, Vandepitte L, Mees J (2025) National implementation of the European Union policy framework for monitoring introduced non-indigenous species in marine and brackish waters: a Belgian case study based on an updated species inventory. NeoBiota 103: 187–214. https://doi.org/10.3897/neobiota.103.159848

Introduction

Introduced non-indigenous species (iNIS) are organisms that do not naturally occur in a geographically defined region and whose presence results from human activities that enabled them to overcome fundamental biogeographical barriers, either intentionally or unintentionally (Carlton 2001). The non-standardized use of the term "NIS" (or "NNS": non-native species), which in some contexts is applied more broadly to also include natural range expanders (including those shifting due to climate change), however, creates interpretational inconsistencies (e.g., Pederson et al. 2011; Hettinger 2012; Soto et al. 2024). In the present study, the focus is explicitly on human-mediated introductions only, in line with the European Union (EU) Marine Strategy Framework Directive 2008/56/EC (MSFD). For this reason, the term "iNIS" was adopted to clearly indicate that the scope of this study excludes natural range expanders. While many iNIS pose little risk to their new environment, others may cause impacts ranging from negligible to severe, including predation, introduction of parasites or diseases, competition for resources, or habitat modification (IUCN 2020). When such effects adversely affect biodiversity and ecosystem services, the species are classified as invasive alien species (IAS) under Regulation (EU) No 1143/2014. IAS thus represents a subset of iNIS (see also IAS Regulation Art. 2.2a). The severity of biological invasions depends on the ecological and biological traits of the invader, interactions with native species, and prevailing environmental conditions (Katsanevakis et al. 2023). Beyond disrupting ecosystems, IAS can also negatively affect human health, the economy, and food security (Katsanevakis et al. 2014; Mazza et al. 2014; Ojaveer et al. 2015; Tsirintanis et al. 2022; IPBES 2023; Turbelin et al. 2024).

Due to their potential far-reaching environmental and socio-economic impacts and the associated costs related to eradication and management, iNIS and IAS have gained increased attention in global and European regulations and policy initiatives in recent decades, such as the United Nations Convention on Biological Diversity – Kunming-Montreal Global Biodiversity Framework (CBD-COP15); the MSFD; the IAS Regulation; the EU Biodiversity Strategy for 2030; and the International Maritime Organization (IMO) Ballast Water Management Convention (BWMC). Despite the growing policy attention, data point toward a strong increase in the introduction rate of new marine and brackish iNIS during recent decades due to accelerated globalization and the increasing trend in intercontinental trade through various pathways, such as shipping, aquaculture, and canals (Hulme et al. 2008; Katsanevakis et al. 2013; Ojaveer et al. 2018). Therefore, most policy frameworks focus on prevention and mitigation of new introductions due to anthropogenic activities.

One of the key elements for a targeted and effective policy approach, including the evaluation of preventive policy measures, is the reliance on publicly available, accurate, and up-to-date information (Tsiamis et al. 2019; Katsanevakis et al. 2023). Several databases have been developed that may serve this purpose, for example, the World Register of Introduced Marine Species (WRiMS), focusing on brackish and marine iNIS (Costello et al. 2021, 2025); AquaNIS, which covers aquatic NIS and species of uncertain origin (AquaNIS 2025); and the European Alien Species Information Network (EASIN), specifically developed to support EU iNIS management policy (Katsanevakis et al. 2015). It should be noted that the local, national, and regional application of global or EU biodiversity data systems for developing effective iNIS policies is dependent on their coverage within specific regions (i.e., integration of area-specific data into these systems). This coverage, in turn, is influenced by the presence or absence of dedicated monitoring programs (Lehtiniemi et al. 2015; Katsanevakis et al. 2023), the availability of taxonomic expertise, and regional biases in sampling and data collection efforts (Troudet et al. 2017; McClain et al. 2024).

This study aims to conduct a comprehensive assessment of iNIS in the Belgian part of the North Sea and adjacent estuaries to create a complete inventory of current records of iNIS within these ecosystems. Building upon the work of Verleye et al. (2024), this updated species inventory includes data on the year of introduction, the native regions, the current distribution within Belgium, and the primary introduction vectors. The context of the data collection (iNIS observations) is also analyzed, distinguishing between official monitoring programs, project-based data collection efforts, and citizen science initiatives. The latter are defined here as independent individuals who are not affiliated with a scientific institution but possess extensive expertise in specific taxonomic groups. Furthermore, the study evaluates the efficiency of the Belgian marine iNIS monitoring programs as part of the implementation of EU policies (MSFD, Water Framework Directive (WFD), IAS Regulation). Additionally, the study examines the flow of information toward reference databases such as EASIN, AquaNIS, and WRiMS. By first completing WRiMS (which can then serve to feed other databases), this study will improve the accuracy and completeness of these reference databases, ensuring that the data reflect local marine and brackish iNIS in Belgium.

Methods

iNIS inventory of Belgian marine and brackish waters

Geographical scope and species inventory

This study builds upon the inventory of iNIS in Belgian marine and brackish water systems of Verleye et al. (2024) as a primary reference, covering the Belgian part of the North Sea, the marine intertidal zone, coastal port areas, estuaries, mudflats, salt marshes, and brackish inland waters. For inland waters, only habitats with some seawater influence (mesohaline or polyhaline) were taken into account (Fig. 1). Only iNIS first observed after 1800 were included in the inventory, as earlier occurrences could not be reliably confirmed. At the iNIS level, key information was collected related to the introduction vectors, the native regions, the year of first observation, and the level of species establishment (Suppl. material 1).

The data for the inventory were sourced via the VLIZ Alien Species Consortium, a community of 32 experts from 17 institutes across four countries. This national species inventory, based on the taxonomy of the World Register of Marine Species (WoRMS; WoRMS Editorial Board 2025) – which is a key contributor to the Global Biodiversity Information Facility (GBIF) Backbone Taxonomy – builds upon previous reviews (Kerckhof et al. 2007; Vandepitte et al. 2012; Verleye et al. 2020) and was further enhanced by data from monitoring initiatives under the MSFD and the WFD, as well as citizen science initiatives and project-based data collection efforts.

Starting from this initial inventory, expert consultations were conducted to capture diverse taxonomic expertise and ensure a robust dataset. Online biodiversity information systems such as GBIF and waarnemingen.be (Observation.org 2025) – a citizen science platform in Belgium managed by the NGOs Natuurpunt and

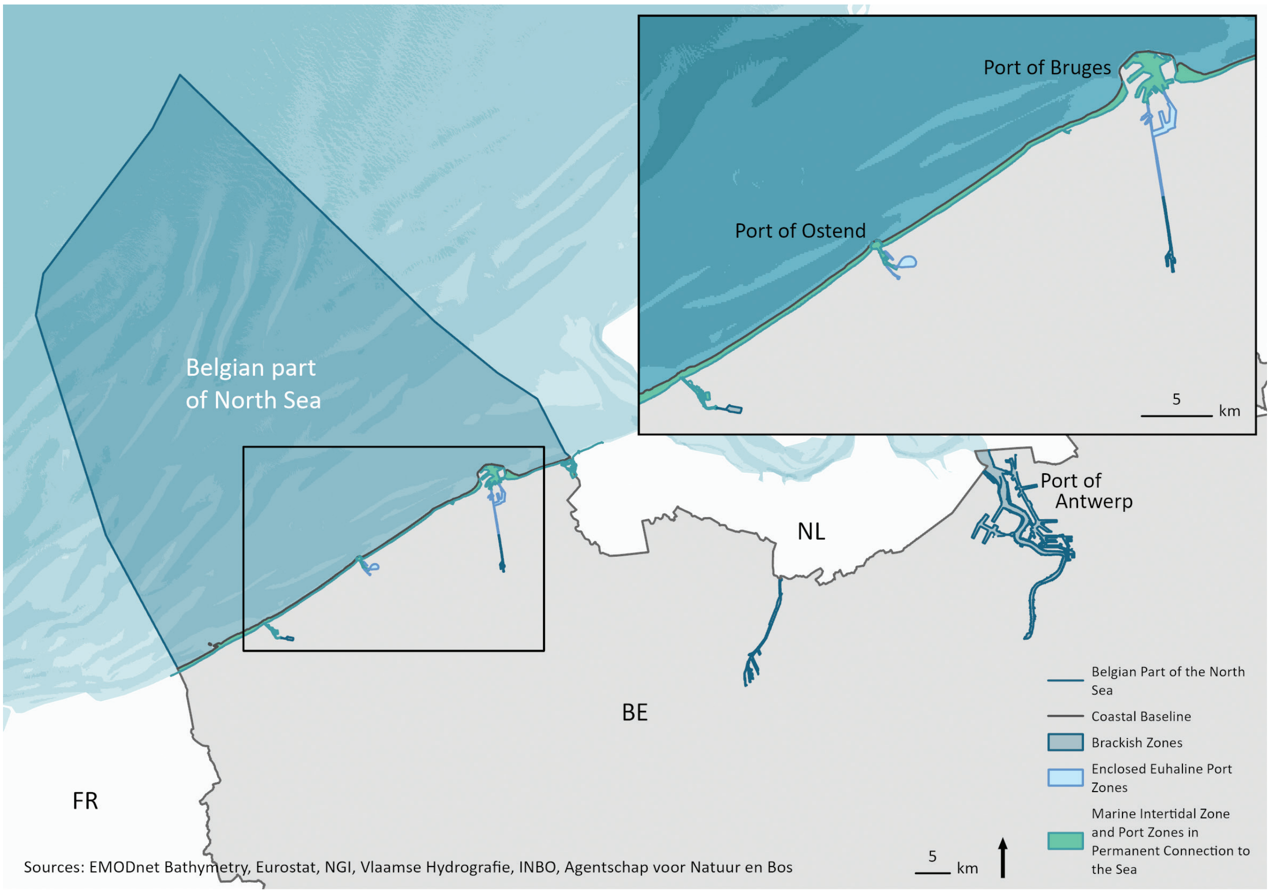

Figure 1. Study area showing the demarcation of the Belgian part of the North Sea (including the exclusive economic zone and territorial waters), the position of the coastal baseline (i.e., low-water line), the marine intertidal zone, the zones of the ports in permanent connection with the sea, the enclosed euhaline (>30 psu) port zones, and the brackish (polyhaline, mesohaline) water zones.

Natagora – provided supplementary local distribution data on species already retained in the inventory. Next, this Belgian iNIS inventory for marine and brackish waters was compared with WRiMS data to identify any discrepancies in iNIS listings for the Exclusive Economic Zone (EEZ) and other relevant territories in Belgium. These differences were subsequently analyzed in detail to align and optimize both inventories (Suppl. material 2). This included, among other things, the removal of false positives (endemic species, species not yet observed in Belgium) as well as the addition of new species in WRiMS. Remaining differences between the final inventory and the WRiMS data at the Belgian level are due to differing approaches in both lists. For example, WRiMS includes some freshwater species that tolerate brackish water environments. However, if these species are only observed in freshwater systems in Belgium, they fall outside the geographical scope of the present study. Additionally, a single observation of marine or brackish iNIS from decades ago without recent records could be included in WRiMS but is not necessarily retained in the current inventory (Suppl. material 2).

Taxonomic bias

Taxonomically biased records present a well-documented limitation of conventional monitoring approaches (Troudet et al. 2017; McClain et al. 2024). By combining the diverse individual expertise within the VLIZ Alien Species Consortium, efforts were made to minimize this bias. However, bias persists for species that are difficult to detect, historically underrepresented in marine sciences, part of species complexes (cryptic species), or lacking effective monitoring techniques. In this context, information on the pelagic environment, including phytoplankton and zooplankton, was limited until recently, meaning these species are likely underrepresented in the current inventory (see also Lescrauwaet et al. 2015).

Year of first observation

Except in cases of intentional introduction, the exact introduction date is generally unknown. However, the date of the first recorded observation is available. Therefore, this study uses "year of first observation" rather than "year of introduction." Similarly, if sessile organisms appear to be several years old at the time of first observation, the observation date was recorded instead of estimating an earlier introduction date based on their age.

Native distribution ranges

Each species was assigned to its likely native region. A distinction was made between the following regions: NE-NW-SE-SW Atlantic (ATL), NE-NW-SE-SW Pacific (PAC), Indian Ocean (IND), Mediterranean Sea (MED), Pontocaspian region (POCA), and cosmopolitan (sub)tropical species (COS). For this study, the attribution was based on a screening of the scientific literature supplemented by peer-reviewed expert evaluation (one or two experts per species). However, in some cases, the natural biogeographic range of a species spans two or more regions, while for a few species, uncertainty remains regarding their exact native distribution. If there was uncertainty between a few regions, all were assigned to the respective iNIS. If the native distribution range was unknown, it was categorized as "unknown." However, in cases where there was a strong suspicion regarding a specific native region that has not yet been confirmed, both the suspected region and the classification "unknown" were assigned. When a species was attributed to multiple native regions, each was given equal weight, ensuring that the total contribution of the areas per species summed to one.

Introduction pathways and vectors

Each iNIS was categorized according to the primary human-induced pathway(s) and vector(s) through which it was introduced to Western Europe, defined here as the Greater North Sea area and the Bay of Biscay, encompassing Belgium and its neighboring countries: the Netherlands, France, Germany, and the United Kingdom. A pathway refers to a process (i.e., broader means) through which a species is introduced to a new environment (e.g., shipping), while the vector refers to the actual dispersal mechanism or physical medium that facilitates the movement of the species along the pathway (e.g., hull fouling or ballast water) (Genovesi and Shine 2004; Pyšek et al. 2011; Harrower et al. 2017). In this study, the categorization was based on a screening of the scientific literature supplemented by peer-reviewed expert evaluation (one or two experts per species) and followed the pathway categorization of the CBD (Harrower et al. 2017), as summarized in Table 1. However, in many cases, definitive evidence regarding the primary introduction pathway or vector was

Table 1. Overview of the relevant CBD pathway/vector (sub)categories as described in Harrower et al. (2017).

Relevant CBD pathway categories	Subcategories	Code
Release in nature	Erosion control/dune stabilization	RN-EC
	Fishery in the wild	RN-F
	Landscape / flora / fauna "improvement" in the wild	RN-L
Escape from confinement	Aquaculture / mariculture	EC-AQ
	Live food and live bait	EC-LB
Transport – Contaminant	Contaminants on animals (excluding parasites and species transported by host and vector)	TC-CA
	Parasites on animals (including species transported by host and vector)	TC-PA
	Contaminants on plants (excluding parasites and species transported by host and vector)	TC-CP
Transport – Stowaway	Container/bulk	TS-CB
	Hitchhikers on ship/boat (excluding ballast water and hull fouling)	TS-HH
	Ship/boat ballast water	TS-BW
	Ship/boat hull fouling	TS-HF
Corridors	Interconnected waterways/basins/seas	C-IW

lacking. In such situations, multiple "potential" CBD-(sub)categories of pathways/vectors were attributed to the concerned species. Furthermore, certain species were introduced multiple times, independently and via different pathways or vectors. Lastly, some species were introduced through a combination of (sub)categories. For example, the construction of canals (C-IW in Table 1) facilitated the spread of species by allowing them to be transported by ships (TS-HH, TS-BW, TS-HF) through these newly connected water systems, or parasites (TC-PA) and fouling organisms (TC-CA) were introduced alongside species imported for aquaculture (EC-AQ). When multiple subcategories were assigned to a species, they were weighted equally (see also European Environment Agency 2024) so that their total always equaled one. Additionally, non-target species that accidentally hitchhiked to new regions alongside targeted aquaculture species – without being dependent on these species in the context of parasitism, pathogens, symbiosis, or fouling – were assigned to the subcategory "Escape from confinement – Aquaculture/mariculture" (EC-AQ). These species were not categorized under the subcategories Food contaminant (including live food), Contaminant on animals (excluding parasites and species transported by host and vector), or Parasites on animals (including species transported by host and vector).

Assessing policy frameworks for effective iNIS monitoring and early detection

The key EU regulatory frameworks for detecting, monitoring, and managing iNIS – both generally and from a marine perspective – were analyzed, including their objectives, targets, implementation, and challenges in addressing marine iNIS. Further, based on the iNIS inventory, an analysis was conducted to determine how often the first detection of iNIS species actually occurred within the context of official monitoring programs, thereby assessing the adequacy of these programs for detecting new iNIS (Suppl. material 3). This analysis was only conducted for species introduced after 2011, i.e., the baseline year of the first reporting cycle on Good Environmental Status under MSFD Descriptor 2 (Belgian State 2018a). Four main detection contexts were distinguished: MSFD monitoring, WFD monitoring, project-based data collection, and citizen science observations. Furthermore, the extent to which the brackish and marine iNIS observed in Belgium were already recorded in international and European iNIS reference data repositories was examined.

Results

iNIS in Belgian marine and brackish waters

As of 2024, 108 iNIS have been confirmed in the Belgian part of the North Sea and adjacent estuaries (Suppl. material 1). Five iNIS were already reported in Belgium as early as the 19th century. The number of new iNIS records exhibited a steady increase throughout most of the 20th century (until 1990), with no more than five new iNIS observations per decade. By 1990, a total of 33 iNIS had been recorded in the study area. However, for the period 1991–2000, a sudden surge in the number of new iNIS records can be observed, with 25 new iNIS detections within a decade. This sharp increase is followed by the addition of 14 new iNIS between 2001 and 2010 and another 25 between 2011 and 2020. In the period from 2021 to 2024, an additional 10 new iNIS were identified (Fig. 2). The increasing trend in the number of iNIS over the study period was confirmed by a Poisson regression ($\beta = 0.186$, SE = 0.028, $p < 0.001$), corresponding to an average increase of ~20% per decade. A piecewise Poisson regression further indicated a significant structural break in the upward trend after 1990, with the number of new iNIS records being on average more than six times higher after 1990 compared to previous decades ($\beta = 1.846$, SE = 0.425, $p < 0.001$). Unlike species recorded before 1990, of which 85% are now considered widely established in the study area, only 50% of the species introduced after 1990 have become widely established. Of the remaining 50%, 27% currently exhibit a localized presence within a highly specific (isolated) area, 8% are characterized by very low abundances but are still considered established, and for the remaining 15% it is unclear whether they have successfully established.

At the taxonomic group level, arthropods represent the largest proportion of identified iNIS, accounting for 35% of the total. This diverse group includes crabs, copepods, amphipods, isopods, sea spiders, barnacles, and shrimp. Arthropods are followed by mollusks (14%), worms (annelids, flatworms, nematodes, and nemerteans) (11%), and algae and seaweeds (11%). Other groups include cnidarians (6%), bryozoans (6%), ascidians (6%), fish (5%), vascular plants (2%), non-algal unicellular eukaryotes (1%), rotifers (1%), ctenophores (1%), and sponges (1%) (Fig. 2; Suppl. material 1).

Native distribution ranges of iNIS

The native regions of the iNIS in the study area are highly diverse, and for 13% of the species, the native distribution range is considered “unknown.” The main native regions are the Northwestern Pacific and Northwestern Atlantic, accounting for 31% (weighted score of 33.8 species) and 27% (28.7 species) of the iNIS in the study area, respectively. In total, the Pacific region as a whole is the native area of 44% (47.2 species) of the identified iNIS, and the Atlantic region accounts for 30% (32.4 species). The Pontocaspian region is the home range of 5% of the iNIS (5.5 species), the Mediterranean of 3% (3.5 species), and the Indian Ocean of 2% (1.8 species) (Fig. 3; Suppl. material 1).

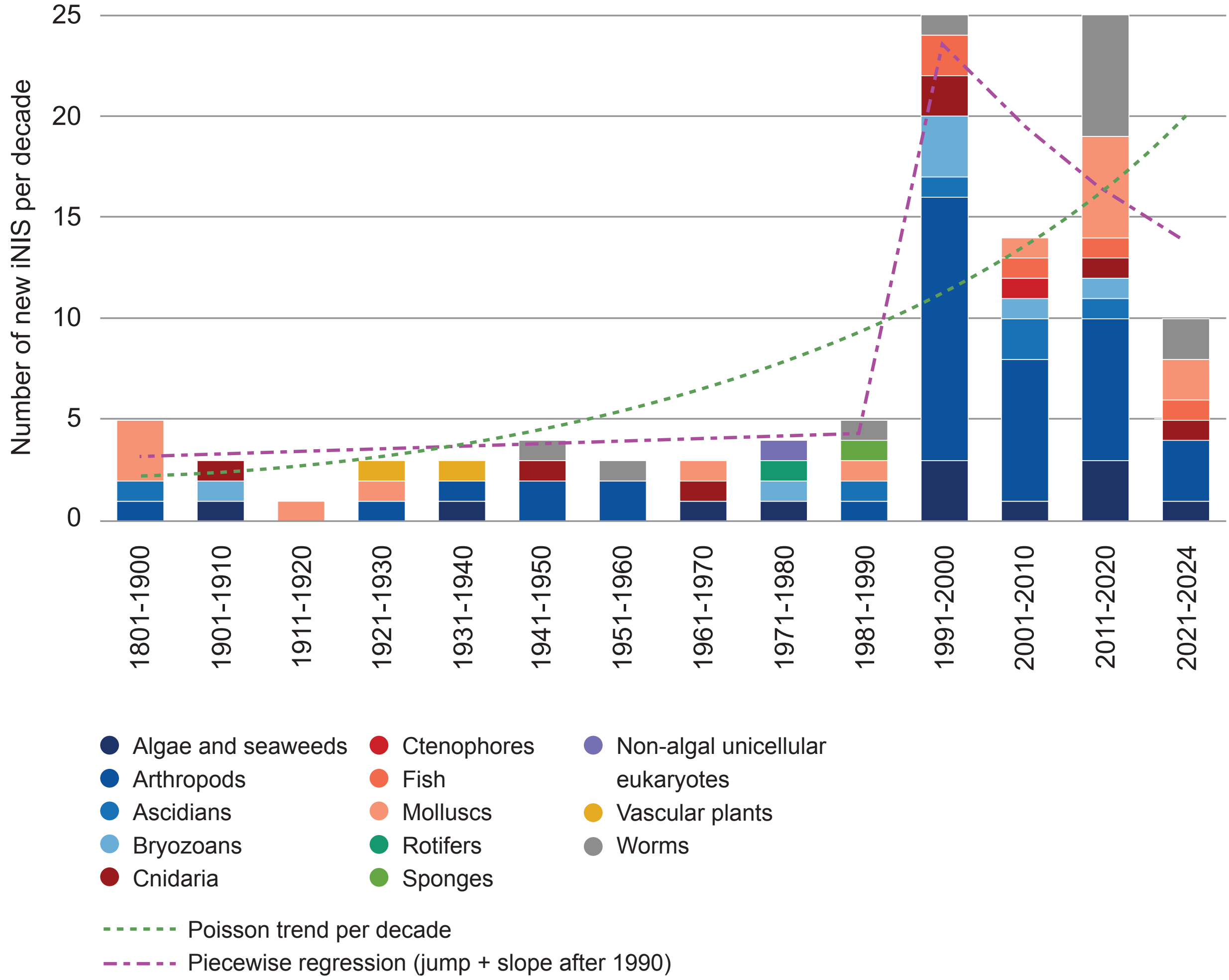

Figure 2. Number of newly observed iNIS in the study area per decade (with species introduced between 1801 and 1900 grouped together), categorized by species groups. The group "algae and seaweeds" includes eukaryotic algae, both unicellular and multicellular forms, including diatoms, green algae, brown algae, and red algae. The collective term "worms" encompasses organisms from several different phyla, including Annelida (segmented worms), Platyhelminthes (flatworms), Nematoda (roundworms or nematodes), and Nemertea (ribbon worms).

Main introduction pathways and vectors

When examining the primary introduction pathways toward Western Europe for iNIS occurring in the study area, shipping – including the vectors "ballast water transport" and "hull fouling" – and aquaculture are by far the predominant transport pathways (Fig. 4; Suppl. material 1). Due to the frequent uncertainty regarding the actual pathway and/or vector responsible for a given species introduction, multiple potential introduction modes are often considered. For instance, ballast water transport is linked to 59 iNIS, hull fouling to 54 iNIS, and aquaculture to 49 iNIS. After weighting (cf. methodology), ballast water transport is considered responsible for the introduction of 32% of all iNIS (34.6 species), hull fouling for 26% (27.9 species), and aquaculture for 22% (23.7 species). The different species groups can clearly be associated with distinct types of transport pathways. For example, algae and seaweeds are mainly introduced through aquaculture, whereas arthropods are primarily associated with transport via shipping (ballast water transport, hull fouling). These differences in pathway distribution were statistically significant ($\chi^2(9) = 27.61$, $p = 0.0011$). In the case of mollusks, both shipping (ballast water transport) and aquaculture play a significant role (Fig. 4; Suppl. material 1).

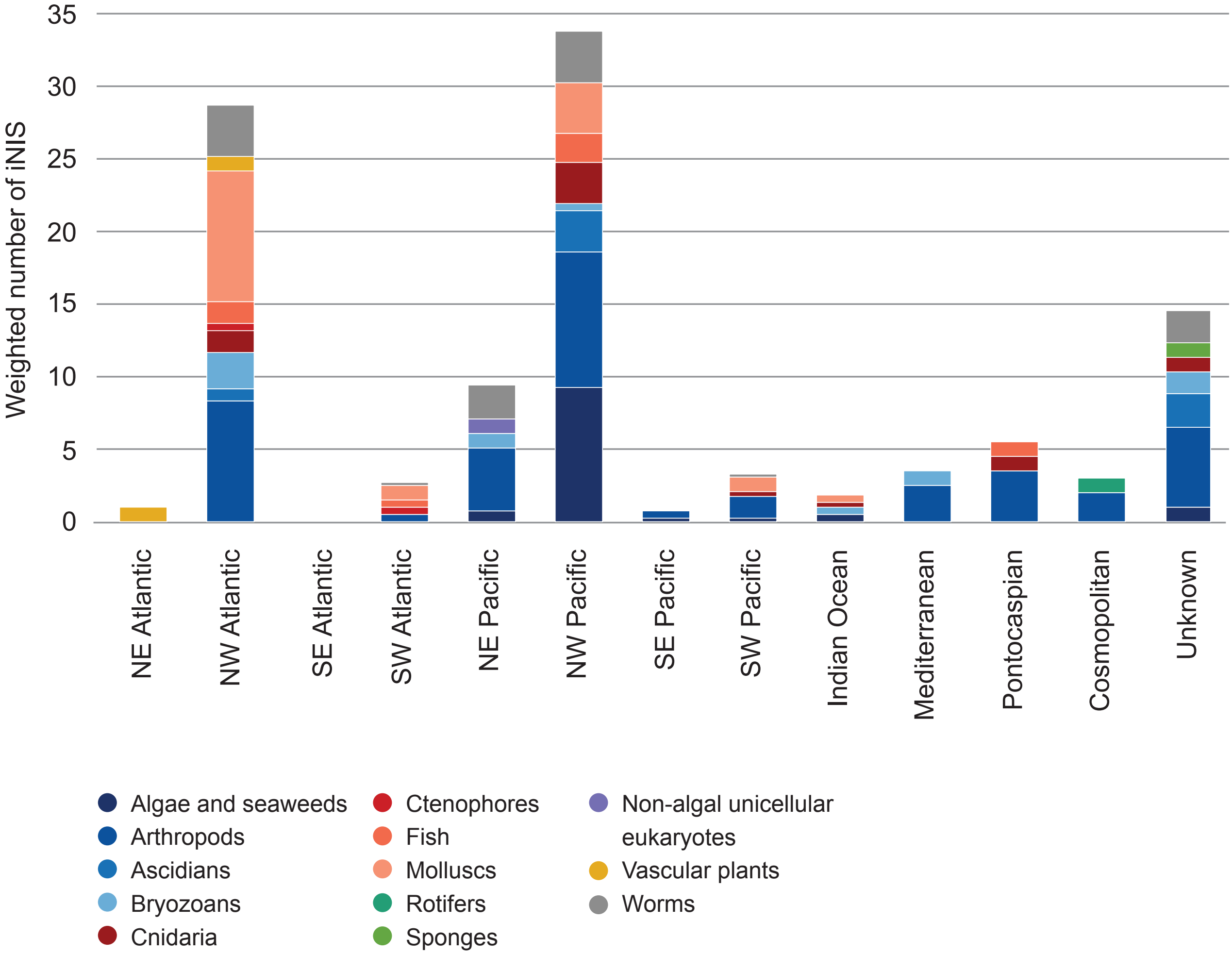

Figure 3. Weighted number of iNIS in Belgian marine and brackish waters for each native region, with species groups shown as color-coded bars.

Geographic patterns in first detection in Western Europe

Of the 108 identified iNIS in the study area, 103 originate from outside Europe. For 83 species, the first detection on European territory occurred in Western Europe. For 12 of the 108 iNIS (11%), it is likely that they reached Western Europe via Belgium. For two other species (2%), it remains unclear whether they were first observed in Belgium or the Netherlands. For the remaining 87% of marine and brackish iNIS found in Belgium, first observations were made in one of the neighboring countries: 31% (33 species) were first recorded in the Netherlands, 23% (25 species) in the United Kingdom, 19% (20 species) in France, 12% (13 species) in Germany, 2% (two species) in the broader North Sea region (unspecified), and for 1% (one species), uncertainty remains regarding the exact location of its first introduction in Western Europe (Suppl. material 1).

iNIS observation context and reporting coverage of newly detected species

In order to assess the adequacy of the Belgian monitoring programs for iNIS detection, the context in which new iNIS were first observed was examined. Of the 35 iNIS first recorded in the study area after 2011, nine iNIS were observed in the

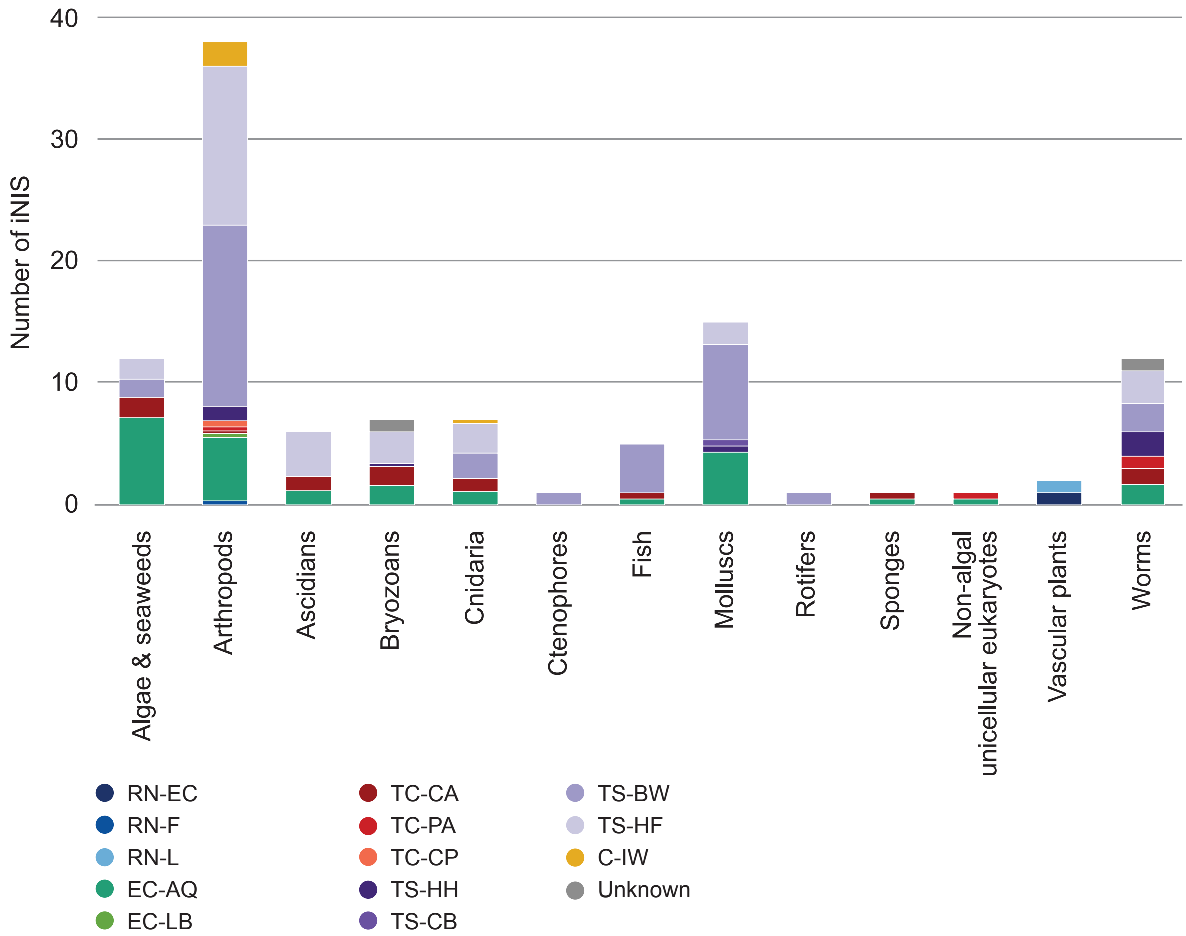

Figure 4. Number of iNIS per species group in Belgian marine and brackish waters, broken down by (potential) CBD pathway/vector subcategories (see Table 1) of primary introductions in Western Europe, using the weighting approach described in the methodology.

context of formal monitoring programs (MSFD, WFD), six were detected within the framework of a research project, and 20 were found through citizen science initiatives (Suppl. material 3).

To assess the completeness of the Belgian marine iNIS reporting on MSFD Descriptor 2, only marine iNIS detected between 2011 and 2021 were considered, as this timeframe corresponds to the MSFD reporting periods covered thus far. Within this subset, only 10 out of 20 newly introduced marine iNIS in the study area appear to have been included in the official national MSFD reports (Fig. 5).

Discussion

Anthropogenic drivers of increasing iNIS

The recorded increase in the number of iNIS between 1800 and 2024, and particularly the sharp acceleration since the 1990s, reflects a dynamic and intensifying pattern of species introductions in the study area. This trend is consistent with broader global patterns (e.g., Seebens et al. 2017) and, in particular, aligns with findings from the Netherlands, which show a sharp increase from 1990 onward (Gittenberger et al. 2017), and from the French Northern Seas, where the number of iNIS has risen significantly since 2000 (Massé et al. 2023). Similar trends are also observed in the Mediterranean Sea (Zenetos et al. 2012). Aside from potential

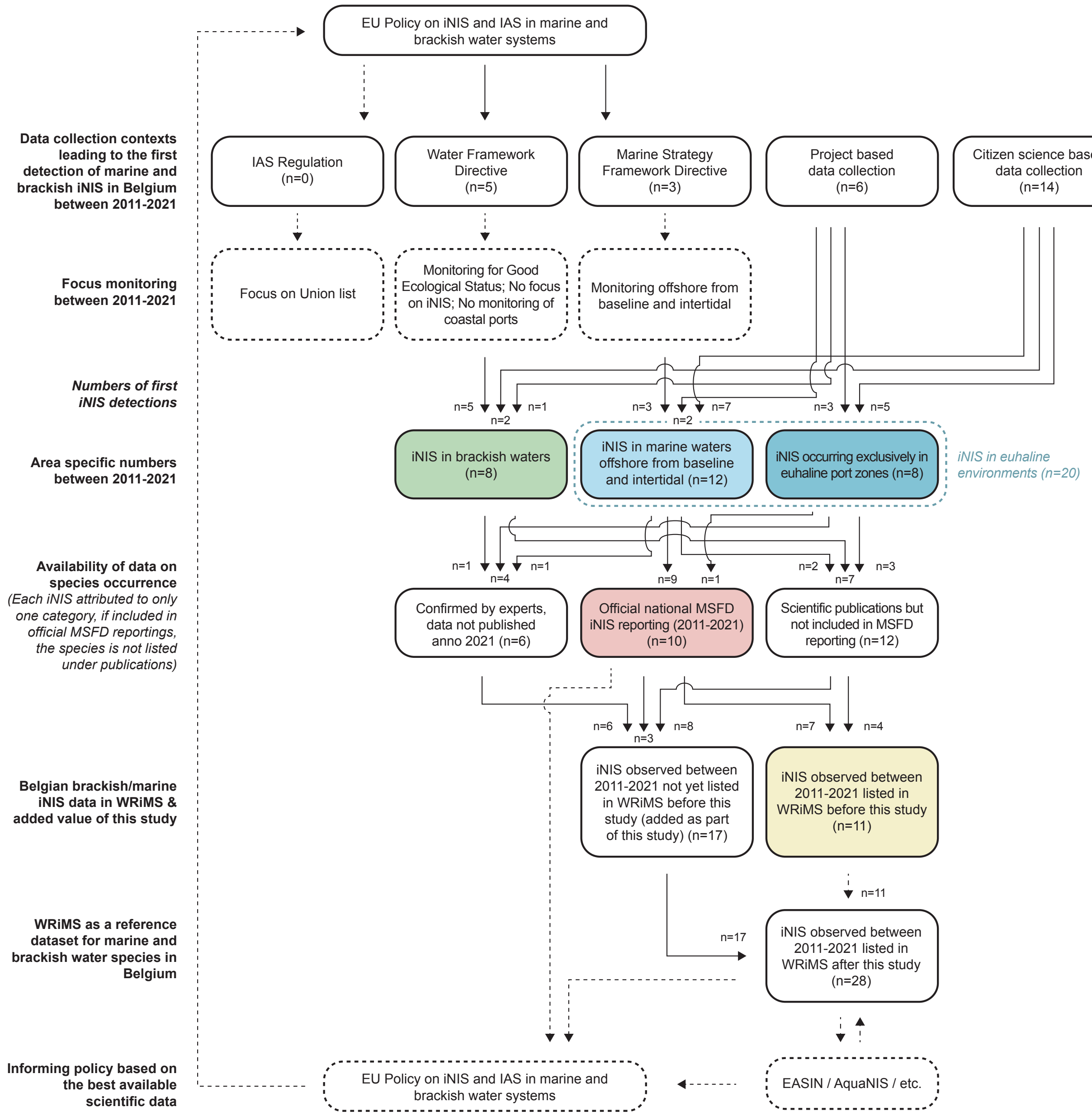

Figure 5. Flowchart illustrating the monitoring and data collection contexts leading to the first detection of iNIS in Belgian marine and brackish waters (estuaries) in the period 2011–2021 (n = 28). The diagram highlights the significant role of citizen science for marine iNIS detections. It also visualizes the challenges in data flow from diverse sources to overarching iNIS data repositories, which underpin EU policy. Furthermore, it underscores the importance of this study in compiling a comprehensive species inventory for marine and brackish waters, which feeds into WRiMS, establishing it as the primary future data source for Belgian records.

effects of monitoring biases (see further), this increasing trend is likely driven by accelerated globalization and the growing volume of intercontinental trade, which facilitates species introductions through multiple pathways, including shipping, aquaculture, and canals (Hulme et al. 2008; Katsanevakis et al. 2013; Ojaveer et al. 2018). The fact that the vast majority (95%) of iNIS recorded in the study area have their native distribution outside Europe underscores the role of globalized economic activities as key drivers of marine and brackish species introductions.

The geographical pattern of first detections, with most species initially observed in neighboring Western European countries, suggests a regional stepping-stone effect, where species establish in nearby coastal systems before expanding their range into Belgian waters. Only a small proportion of species (11%) are likely to have reached Western Europe via Belgium directly (i.e., primary introduction). For these species, shipping appears to be the most important pathway. The intercontinental nature of shipping – particularly in the port of Antwerp – has significantly increased since 1990, with maritime trade volumes to and from Asia increasing sevenfold over the past three decades, while cargo transport with the Americas and Africa has doubled (Merckx Jean-Pierre, personal communication). These vessels frequently visit multiple Northeastern Atlantic and North Sea ports, facilitating both the primary introduction and secondary spread of iNIS. Regarding ballast water transport, the IMO BWMC (which entered into force on 8 September 2017) aims to prevent the introduction of species from one region to another by establishing global standards and procedures for the management and control of ships' ballast water and sediments. But given that only on 8 September 2024 did all ships have to be in compliance with the D-2 standard for ballast water management, it is not yet possible to assess the effectiveness of this measure for Belgium.

Additionally, economic activities such as aquaculture can also contribute to the introduction of new iNIS via deliberate introductions of species for cultivation ("aquaculture") or accidentally, as certain species may be transported alongside imported shellfish ("contaminants", "parasites"). The dates of first introduction indicate that aquaculture serves as a primary pathway for new introductions in neighboring countries such as France and the Netherlands. From there, these species subsequently spread to Belgium through secondary routes (see also Kerckhof 2014; Kerckhof et al. 2012), whereas to date, direct primary introductions via aquaculture in Belgium remain limited.

Linking native distribution regions and introduction pathways

The predominant introduction pathways not only show associations with specific species groups (Fig. 4; Suppl. material 1) but also reflect the nature of human-mediated connections between the native regions and Western Europe. Clear associations can be identified between these native distribution regions and the modes of transport involved in species introductions (Table 2). For instance, five out of six iNIS (83%) originating from the Pontocaspian region were introduced as a result of the construction of canals connecting the Black Sea basin to Western European waterways (e.g., Bij de Vaate et al. 2002). For species originating from the Northwestern and Southwestern Atlantic, shipping (ballast water, hull fouling) was the predominant pathway for introduction, reflecting the strong maritime connectivity between these continents (MarineTraffic 2025). This pattern differs from that observed in the Northwestern Pacific, where aquaculture was the most significant mode of transport, with numerous species being introduced – both intentionally and unintentionally – as a result of the introduction of Japanese oyster spat *Magallana gigas* (e.g., Buizer 1989; Critchley et al. 1990; Eno et al. 1997; Verlaque 2001; Dankers et al. 2004; Gosliner and Behrens 2006).

Observational biases and future perspectives

Beyond changes in the intensity and nature of economic activities, the likelihood of detecting new species has also increased due to improved monitoring practices. Since the 1990s, biological monitoring in Belgian waters has expanded and

Table 2. Matrix showing the relative percentage of iNIS originating from specific regions in relation to their (potential) primary introduction vectors. Row totals may exceed 100% because species can have multiple potential vectors.

Native region	RN-EC	RN-F	RN-L	EC-AQ	EC-LB	TC-CA	TC-PA	TC-CP	TS-CB	TS-HH	TS-BW	TS-HF	C-IW	Unknown
NE ATL	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
NW ATL	0%	3%	3%	29%	0%	14%	0%	3%	0%	11%	63%	40%	0%	6%
SE ATL	–	–	–	–	–	–	–	–	–	–	–	–	–	–
SW ATL	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	80%	20%	0%	0%
NE PAC	0%	0%	0%	57%	0%	36%	7%	0%	0%	0%	57%	79%	0%	0%
NW PAC	0%	0%	0%	69%	0%	29%	2%	0%	0%	2%	43%	50%	0%	0%
SE PAC	0%	0%	0%	50%	0%	0%	0%	0%	0%	0%	50%	50%	0%	0%
SW PAC	0%	0%	0%	33%	0%	0%	0%	0%	17%	0%	83%	67%	0%	0%
IND	0%	0%	0%	50%	0%	25%	0%	0%	0%	0%	50%	25%	0%	0%
MED	0%	0%	0%	25%	0%	0%	25%	0%	0%	0%	50%	50%	50%	0%
POCA	0%	0%	0%	0%	17%	0%	0%	0%	0%	0%	100%	50%	83%	0%
COS	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	67%	67%	0%	0%
Unknown	0%	0%	0%	50%	0%	39%	0%	0%	0%	6%	33%	72%	0%	0%

improved significantly (Verleye et al. 2024), although it is not specifically focused on iNIS. Enhanced and more frequent analyses of biological samples have increased the chances of detecting new iNIS. However, this mainly results in earlier detection of new introductions, but not necessarily in more detections in the long term. Citizen scientists, on the other hand, have been actively searching for new iNIS in the coastal region since the 1970s.

Despite the expanded and improved biological monitoring, observational biases remain. Compared to benthic habitats (Breine et al. 2018), research on pelagic habitats in the Belgian part of the North Sea is still in its early stages (Van Ginderdeuren et al. 2014). As a result, pelagic data are limited, likely leading to an underrepresentation of phytoplankton and zooplankton species in the current inventory. Recent efforts have started to address this gap, with increased monitoring of the pelagic environment, primarily in the context of MSFD Descriptor 1 (biodiversity) (Belgian State 2020; Lagaisse et al. 2024; VLIZ 2025). However, these efforts may also provide new opportunities for the systematic detection of pelagic iNIS.

To further reduce taxonomic and habitat-related biases, molecular tools such as (environmental) DNA-based methods, including metabarcoding and quantitative polymerase chain reaction (qPCR), are being explored as potential tools to complement traditional observation methods for the detection of aquatic iNIS (Fonseca et al. 2023; Hablützel et al. 2023). While these approaches show promise, their applicability and reliability for comprehensive monitoring still require further evaluation (Kopp et al. 2023). If further refined, these approaches could potentially contribute to early detection, the identification of cryptic species, and expanded taxonomic coverage.

Challenges concerning marine iNIS in EU regulation and national policy

Building on the Belgian iNIS inventory for marine and brackish water systems, the capacity of current monitoring approaches to detect new iNIS in Belgium was assessed. However, prior to this assessment, it is crucial to first examine the key EU regulatory frameworks that govern the detection, monitoring, and management of iNIS and IAS, both in general and from a marine perspective.

To this day, Regulation (EU) No 1143/2014 (IAS Regulation) on the prevention and management of the introduction and spread of IAS primarily targets terrestrial and freshwater species. The regularly updated list of IAS of Union concern (Union list) prioritizes the approach to certain species, selected by the European Commission in consultation with the EU Member States (Commission Implementing Regulation (EU) 2016/1141, amended by Implementing Regulations (EU) 2017/1263, 2019/1262, 2022/1203, and 2025/1422). However, the criteria for inclusion on the Union list (Article 4.3a–e), all of which must be met, make it difficult to include marine species, resulting in only five strictly marine species listed to date, of which only one currently occurs in Belgian waters. Specifically, the adverse impacts on biodiversity, human health, and the economy (Article 4.3c) are often not straightforward to demonstrate for marine species. Furthermore, successful eradication of marine IAS in open systems, such as the sea and the ocean, becomes virtually impossible if the critical window for a rapid response following the initial introduction is missed (Katsanevakis et al. 2023). Moreover, cost-benefit analyses entail considerable uncertainty when it comes to assessing the effectiveness of coordinated Union-level action in preventing the introduction, establishment, or spread of a species, or in mitigating the adverse effects of marine IAS (Articles 4.3d–e). Due to the limited practical and cost-effective means to eradicate or manage IAS in the marine environment without harming local ecosystems, preventing the introduction of IAS is currently considered the only feasible management option for the marine environment (OSPAR 2023). This approach is attempted, among other efforts, by the IMO BWMC, the IMO 2023 Ships' Biofouling Guidelines (resolution MEPC.378(80)), the International Council for the Exploration of the Sea (ICES) Code of Practice on the Introduction and Transfer of Marine Organisms (1994, revised in 2005) (ICES 2005), and Regulation (EC) No 708/2007 concerning the use of alien and locally absent species in aquaculture.

For marine iNIS in particular, the Working Group on Introductions and Transfers of Marine Organisms (WGITMO) was established within ICES in 1970. WGITMO maintains annual records of new introductions in the ICES area and provides management advice on request. However, a legally binding framework for the monitoring and reporting of newly introduced marine species only emerged with the entry into force of the MSFD, the primary EU policy instrument for this purpose. It aims to ensure that iNIS remain at levels that do not adversely alter ecosystems, i.e., the Good Environmental Status (GES) for Descriptor 2. The Commission Decision (EU) 2017/848 introduced criteria and methodological standards to streamline monitoring and track the progression toward GES. The primary criterion D2C1 requires reporting the number of new iNIS records into the wild for each six-year assessment period, aiming to minimize (and ideally reduce to zero) such introductions, while the OSPAR "NIS Common Indicator" (NIS3) was developed in alignment with the MSFD to enable Contracting Parties that are EU Member States to use its results for MSFD reporting (OSPAR 2018). Within this context, Belgium has decided to focus only on monitoring newly introduced macrofauna and macroflora (>1 mm) that could lead to significant changes to the ecosystem, excluding species with taxonomic uncertainty or negligible effects from permanent introduction (Kerkhove and Kerckhof 2024).

Secondary MSFD criteria D2C2 and D2C3 focus, respectively, on the abundances and spatial distribution of iNIS (with emphasis on IAS, i.e., those on the Union list or species relevant for D2C3) and the species groups and habitats that are adversely altered by iNIS, with particular attention to IAS. However, assessing the degree of competition or potential negative ecosystem effects associated with a particular iNIS is challenging to measure unambiguously, which complicates reporting on and achieving D2C3. To gain better scientific insights into (local) ecosystem interactions, significant investments should be made, preferably at the regional sea level (see also OSPAR 2018). The challenge of setting targets that are ambitious, measurable, and realistic is not unique to the MSFD but also occurs in other policy frameworks, such as the EU Biodiversity Strategy 2030, which includes a commitment to reduce the number of Red List species threatened by IAS by 50% by 2030. This approach is complicated and hardly measurable for the marine environment, given that it deals with multiple challenges and uncertainties, including: (1) the frequent lack of a comprehensive overview of all IAS in a specific region or Member State due to the absence of targeted monitoring programs (e.g., Lehtiniemi et al. 2015), (2) concerns raised in the literature about overreliance on the IUCN Red List in conservation policies, highlighting its incompleteness, partial outdatedness, and potential misuse in priority setting (e.g., Palacio et al. 2023), and (3) the generally poor knowledge base on often complex species interactions, which presents a critical limiting factor in assessing this target (OSPAR 2018; Ojaveer et al. 2024).

In addition to monitoring obligations for EU Member States, the MSFD requires the development of a program of measures, which is subject to a six-year revision cycle. The program should address each of the MSFD descriptors, while individual measures should aim to ensure that environmental targets are met and GES is achieved or maintained (initial target year: 2020). A listing of the Belgian MSFD measures contributing to the achievement of GES for Descriptor 2 is provided in Table 3 (Belgian State 2022). Some measures were designed within other legal frameworks, such as the IMO-related obligations, and are thus reused within the context of the MSFD. However, many measures lack sufficient concreteness, and, although developed by the federal authority responsible for environmental policy at sea, their implementation may exceed this authority's competence, as measures related to the stricter implementation of the IMO BWMC fall under the competence of the federal authority for mobility and transport. Further, a recent European Commission evaluation (COM (2025) 3; SWD (2025) 1) rated the adequacy of Belgium's program of measures for Descriptor 2 as "moderate". While progress was noted in addressing iNIS introductions via shipping, gaps remain concerning aquaculture and offshore wind farms, both identified as potential future pathways given their provisional spatial allocations in the draft marine spatial plan (MSP) for 2026–2034 (subject to final approval; see also Federal Government 2025).

Constraints of current monitoring approaches for detecting new iNIS in marine and brackish waters

To assess the effectiveness of national measures (Table 3) and to measure progress toward GES according to the criteria listed for Descriptor 2 in Commission Decision (EU) 2017/848, five official monitoring programs were selected or established in the framework of the MSFD by the Belgian federal authorities responsible for environmental policy at sea (Belgian State 2020) (Table 4). However, three of these monitoring

Table 3. Overview of the Belgian MSFD measures contributing to the achievement of GES for Descriptor 2 of the MSFD (Belgian State 2022).

Year of implementation	Measures
Since 2016 (first MSFD cycle)	Environmental impact assessment and appropriate assessment (with attention to fouling).
	Permit condition (e.g., wind farms): maximum restriction on the introduction of hard substrates.
	Permit condition: monitoring during construction and operation – fouling macrobenthos.
	Prohibition on the intentional (unless permitted) and unintentional introduction of alien organisms through ballast water, regulated by the Marine Environment Act of December 11, 2022.
	Anti-fouling measures (2011 IMO Guidelines for the control of biofouling on ships).
Since 2022 (second MSFD cycle)	Development of a classification system for alien species (categorized by threat level).
	Enforcement of IMO 2023 Ships' Biofouling Guidelines: cleaning of ship hulls before entering Belgian waters.
	Stricter adherence to and implementation of the Ballast Water Convention, with increased attention to ballast water exchange monitoring.

Table 4. Overview of the formal national MSFD monitoring programs on iNIS in the Belgian territory (Belgian State 2020).

Monitoring program	Activity	Implementing institution
ANSBE-P6-Benthos-1-soft-sediment	Monitoring of soft-sediment benthos to assess environmental impacts of dredge disposal and sand extraction zones in the Belgian part of the North Sea.	Institute for Agricultural, Fisheries, and Food Research – ILVO
ANSBE-P7-Benthos-2-epi-fish	Monitoring of epibenthos and demersal fish for environmental impact assessments of dredge disposal and sand extraction zones in the Belgian part of the North Sea.	Institute for Agricultural, Fisheries, and Food Research – ILVO
ANSBE-P8-Benthos-3-windfarm	Monitoring of macrobenthos and sediment within offshore wind farm areas.	Ghent University – UGent
ANSBE-P9-Benthos-4-hard-substrate	Monitoring of spatial environmental data through remote sensing and sedimentological and biological data based on field verification via direct physical sampling at selected locations considered representative of broader areas.	Royal Belgian Institute of Natural Sciences – RBINS
ANSBE-P10-NIS	Monitoring of iNIS on hard substrates, including groynes, buoys, wind turbines, monitoring poles, and other artificial offshore structures such as artificial reefs and islands, once available.	Royal Belgian Institute of Natural Sciences – RBINS

programs are essentially executed within the obligations of their environmental license (i.e., for sand extraction, dumping sites, and offshore wind farms) and do not specifically focus on iNIS. Neither does the fourth program, in which the general state of natural hard substrates is monitored. Only the fifth monitoring program focuses specifically on iNIS, but only for artificial hard substrates such as groynes, navigation buoys, offshore wind turbines, and other artificial structures. The current monitoring approach for Descriptor 2, in which dedicated monitoring activities for iNIS are thus limited, reflects a pragmatic strategy within a context of constrained budgets.

Between 2011 and 2021, eight new marine iNIS were reported by Belgium for the first MSFD benchmarking period, 2011–2016 (Belgian State 2018a), and two new species were reported between 2016 and 2021 (Kerkhove and Kerckhof 2024). It is important to emphasize that only three out of the 10 iNIS were effectively detected through one of the five officially recognized iNIS monitoring programs under the MSFD. For six iNIS, initial observations were made by citizen scientists, while one species was first reported on a project-based basis (Suppl. material 3).

However, between 2011 and 2021, in total 28 new iNIS have been identified in Belgian marine and brackish waters according to our inventory, of which 20 were found in euhaline environments (>30 psu) and eight in brackish waters (poly- and mesohaline environments) (Fig. 5). This significantly exceeds the number of species (10) reported by Belgium under the MSFD during the same period. This can predominantly be attributed to the spatial implementation limits of the MSFD, which, according to the directive, only applies to waters, the seabed, and subsoil on the seaward side of the coastal baseline (i.e., the low-water line along the coast; cf. United Nations Convention on the Law of the Sea (UNCLOS) Art. 5). This means that the marine intertidal zone, coastal ports, estuaries, and inland brackish waters are by definition not addressed through the MSFD but through the WFD. However, as the WFD does not concern iNIS specifically (Cardoso and Fee 2008; Vandekerkhove et al. 2013; Filipe et al. 2019; Boon et al. 2020), Belgium decided to also include iNIS observed in the intertidal and open port zones (i.e., port areas in permanent open connection to the sea) in its MSFD reporting (Belgian State 2018a; Kerkhove and Kerckhof 2024). This decision was taken in response to EU-level policy encouraging Member States to ensure coordination and alignment across directives through existing institutional structures. As a result, our data indicate that, for species occurring in offshore, intertidal, and open port zone habitats, the two Belgian MSFD assessments seem to provide moderate coverage for new iNIS observed between 2011 and 2021, with 10 out of the 16 observed iNIS within the scope of our inventory being reported under the MSFD (Suppl. material 3).

However, coastal ports – commonly regarded as hotspots for new introductions (Donelan et al. 2022; Verleye et al. 2024) – are not systematically included in the MSFD monitoring programs to date as they classify as "internal waters" (i.e., landward from the baseline). As a result, former MSFD reportings primarily rely on alternative data collection sources for open port zones, such as citizen science, which often reports findings with delays or lacks official reporting (see further). In addition, euhaline enclosed port zones are not considered at all in Belgian MSFD reporting. Consequently, between 2011 and 2021, only one of the eight marine iNIS that are confined exclusively to port areas has been reported under the MSFD (Fig. 5; Suppl. material 3). Although monitoring in coastal ports should ideally fall under the WFD, for which iNIS monitoring is not required, coastal ports are currently not embedded into the WFD monitoring network in Belgium.

This approach entails risks regarding the early detection of new iNIS and, consequently, their potential early control. Between 2011 and 2024, 12 new marine iNIS have been identified whose distributions are exclusively restricted to ports, of which eight species are limited to enclosed euhaline port areas. Of these 12 species, nine were observed by citizen scientists, while three were identified through targeted project-based data collection (Suppl. material 3). Although these observations represent an important source of information, they also have some drawbacks compared to a systematic, government-led monitoring program. For instance, in the context of citizen science, there is often a significant delay between the first observation of a species and the publication of the data, or no publication at all, which may prevent the relevant authorities from taking prompt action in response to a new introduction. Additionally, targeted project-based sampling may also pose challenges in terms of data availability. For example, in preparation for the international implementation of the IMO BWMC, OSPAR/HELCOM developed a standardized port-survey protocol for iNIS detection, forming the basis for granting ballast water management exemptions under Regulation A-4 (G7 Guidelines; Resolution MEPC.289(71)) (HELCOM/OSPAR 2015). As the costs had to be borne privately (by ports or ship owners), this monitoring was ultimately carried out in only one Belgian port (e.g., Gittenberger et al. 2018), and as potential economic concerns existed, the data were not made publicly available. As a result, potentially valuable local biodiversity data do not feed into species repositories or official public reports, and as such, they are not brought to the attention of policy-makers. In response to these issues and limitations, the federal authority recently decided to expand the monitoring activities under the MSFD (ANSBE-P10) to include artificial hard substrates in selected port areas that remain in permanent open connection with the sea, even though such areas formally fall outside its jurisdiction (Kerkhove and Kerckhof 2024). However, this expansion does not provide comprehensive spatial coverage of the area. Further, enclosed euhaline port areas remain excluded from any continuous or systematic biodiversity monitoring program, nor are they reported under the MSFD.

For brackish water iNIS detections after 2011, five out of the nine observed species within the scope of our inventory were observed in the context of the WFD biodiversity monitoring programs in inland Belgian brackish water environments. Although these efforts do not specifically target iNIS, they are reported when encountered. Additionally, if fish listed on the Union list (IAS Regulation) are detected, targeted sampling is conducted in high-risk areas to monitor these populations (Verreycken Hugo (INBO), personal communication). For the remaining four brackish iNIS, three were initially observed by citizen scientists and one on a project basis (Fig. 5; Suppl. material 3).

The above underscores the significance of citizen science observations for the initial detection of new iNIS in Belgian marine and brackish water systems, aligning with findings of, e.g., Thiel et al. (2014), Mannino and Balistreri (2018), and Pocock et al. (2019), who highlight the growing share of observation data collected by citizen scientists. While acknowledging the important contribution of citizen science, this also reinforces the need to establish dedicated monitoring programs for iNIS and to improve coordination between national implementation efforts under the MSFD and WFD. Although the EU encourages alignment through coordinated implementation across directives, the differing approaches to the binding nature of iNIS monitoring under the MSFD and WFD continue to pose challenges at the national level. After all, the legal spatial application boundaries between the two frameworks are somewhat artificial, as species do not adhere to these boundaries in their distribution as long as environmental conditions remain favorable. Addressing this limitation requires the development of a comprehensive and systematic monitoring approach for port areas, including enclosed euhaline waters.

Integrating and optimizing the local and regional iNIS data flow

In addition to the direct challenges associated with monitoring marine iNIS, it is crucial that available data, including local data from different regions, are consolidated, quality controlled, and made accessible through integrated data systems. Fragmented and/or incomplete data complicate the realistic assessment of new species introductions and consequently hinder comprehensive policymaking by preventing a well-founded evaluation of the effectiveness of management measures. For example, of the 28 iNIS first observed in Belgian marine and brackish waters between 2011 and 2021, only 11 were already recorded in the World Register of Introduced Marine Species (WRiMS) as present in Belgium prior to this study (Fig. 5). As such, this study added 17 iNIS to WRiMS for the period considered (Suppl. materials 2, 3). In comparison, 16 of the 28 species had already been attributed to Belgium in EASIN, and 14 in AquaNIS. Many observations are published in scientific journals or entered into a range of (local) biodiversity databases, such as the citizen science-driven waarnemingen.be (Observation.org 2025), but these data are not automatically integrated into iNIS reference databases, which is crucial for supporting iNIS policy at the EU and EU Member State level. Moreover, even official national reports under the MSFD do not automatically lead to inclusion of the reported iNIS in these repositories. Of the 10 marine iNIS officially reported by Belgium under the MSFD between 2011 and 2021, seven were listed in WRiMS and eight in both EASIN and AquaNIS prior to this study (Suppl. material 3).

The fragmentary nature of iNIS data highlights the importance of developing comprehensive iNIS inventories through extensive literature and database screening, in collaboration with experts from diverse taxonomic fields. The Belgian inventory, for example, was subsequently used to update WRiMS, enhancing its role as a reference database for marine and brackish water species in Belgium. The optimization of WRiMS, which is Darwin Core (DwC) compatible, ensures that the global species list and associated species information for marine and brackish waters – including the Belgian list – can flow into systems such as EASIN, although the optimization of this data flow is still an ongoing process.

Conclusion

The rapid increase in the number of newly reported iNIS in Belgian marine and brackish waters – averaging 2.2 species per year since 1991 – underscores the urgent need for effective management through regulatory measures and control. Given the limitations of current approaches in controlling further spread of established marine iNIS, preventive measures addressing the primary introduction pathways remain the most viable strategy for the management of marine iNIS. However, the evaluation of the effectiveness of these measures requires a robust and standardized monitoring strategy. For the Belgian case, this study highlights a misalignment in the practical implementation of marine iNIS monitoring across the MSFD and WFD domains. Although the European Commission encourages Member States to align and coordinate implementation between the two directives, only the MSFD legally obliges Member States to monitor iNIS. As a result, no systematic and coherent framework exists at the Belgian level for the early detection and management of marine iNIS in euhaline water systems of coastal ports (i.e., landward from the coastal baseline), even though these areas act as hotspots for introductions. This challenge is further compounded by the lack of targeted monitoring obligations for marine species under the IAS Regulation, as the focus remains predominantly on terrestrial and freshwater species, with marine species often failing to meet the inclusion criteria for the Union list. Consequently, species identification in these areas largely depends on citizen science initiatives and project-based data collection, with results from these sometimes not being publicly available. Therefore, the establishment of a comprehensive, harmonized monitoring program that includes marine iNIS monitoring landward from the coastal baseline (in euhaline internal waters) is strongly recommended to enhance and accelerate early detection of new iNIS. Furthermore, particular attention is needed to ensure that observation data flow efficiently to iNIS reference data repositories, as the present study demonstrates that reporting species within the framework of official monitoring programs (such as the MSFD) or citizen science platforms (waarnemingen.be) does not currently guarantee the inclusion of a species in these reference databases. Ensuring this efficient data flow improves data accessibility and is essential for informed decision-making for the sustainable management of iNIS and marine ecosystems in general.

Acknowledgments

The authors acknowledge the following members of the VLIZ Alien Species Consortium for their contributions to species data validation and analysis: Azémar Frédéric, Backeljau Thierry, Belpaire Claude, Boets Pieter, De Blauwe Hans, De Clerck Olivier, De Grave Sammy, de Voogd Nicole, Delbare Daan, d'Udekem d'Acoz Cédric, Dumoulin Emmanuel, Faasse Marco, Flandroit Antoine, Gittenberger Arjan, Hillewaert Hans, Jonckheere Ingrid, Provoost Sam, Rumes Bob, Sabbe Koen, Soors Jan, Speybroeck Jeroen, Tackx Micky, Van den Neucker Tom, van der Loos Luna, van Haaren Ton, Van Landuyt Wouter, van Moorsel Godfried, Vansteenbrugge Lies, Verreycken Hugo, and Volckaert Filip. This paper was published in an open access format thanks to the support of the VLIZ Open Access budget.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

No use of AI was reported.

Funding

The authors have no funding to report.

Author contributions

Conceptualization: TJV. Formal analysis: TRHK, TJV. Investigation: TRHK, TJV. Methodology: TRHK, TJV. Supervision: TJV. Validation: TRHK, TJV, GVH. Visualization: TJV. Writing – original draft: TRHK, TJV. Writing – review and editing: AKL, GVH, TJV, JM, TRHK, HP, FK, LV.

Author ORCIDs

Thomas J. Verleye https://orcid.org/0000-0003-0724-9311
Thomas R. H. Kerkhove https://orcid.org/0000-0003-0996-4570
Gert Van Hoey https://orcid.org/0000-0003-2055-5292
Hans Pirlet https://orcid.org/0000-0001-8897-7235
Francis Kerckhof https://orcid.org/0000-0001-8879-6442
Ann-Katrien Lescrauwaet https://orcid.org/0000-0001-5285-4348
Leen Vandepitte https://orcid.org/0000-0002-8160-7941
Jan Mees https://orcid.org/0000-0001-5709-3816

Data availability

The data underpinning the analysis reported in this paper are deposited in the Marine Data Archive of VLIZ at https://doi.org/10.14284/758.

References

AquaNIS (2025) Information system on Aquatic Non-Indigenous and Cryptogenic Species. World Wide Web electronic publication. https://aquanisresearch.com [Accessed 2025-03-17]

Belgian State (2018a) Actualisatie van de initiële beoordeling voor de Belgische mariene wateren. Kaderrichtlijn Mariene Strategie – Art 8, lid 1a & 1b. BMM/Federale Overheidsdienst Volksgezondheid, Veiligheid van de Voedselketen en Leefmilieu (Brussel): 1–243. https://odnature.naturalsciences.be/msfd_media/documents/KRMS_Art8_2018.pdf

Belgian State (2018b) Actualisatie van de omschrijving van goede milieutoestand & vaststelling van milieudoelen voor de Belgische mariene wateren. Kaderrichtlijn Mariene Strategie – Art 9 & 10: België 2018–2024. BMM/Federale Overheidsdienst Volksgezondheid, Veiligheid van de Voedselketen en Leefmilieu (Brussel): 1–30. https://odnature.naturalsciences.be/msfd/documents/14/KRMS_Art9-10_2018_review.pdf

Belgian State (2020) Actualisatie van het monitoringsprogramma voor de Belgische mariene wateren: Kaderrichtlijn Mariene Strategie – Art. 11. BMM/Federale Overheidsdienst Volksgezondheid, Veiligheid van de Voedselketen en Leefmilieu (Brussel): 1–65. https://odnature.naturalsciences.be/msfd_media/documents/BE_MSFD_Monitoring_Art11_2020_nl.pdf

Belgian State (2022) Maatregelenprogramma voor de Belgische mariene wateren. Natura 2000 en Kaderrichtlijn Mariene Strategie - Art 13. Federale Overheidsdienst Volksgezondheid, Veiligheid van de Voedselketen en Leefmilieu (Brussel): 1–111. https://www.health.belgium.be/sites/default/files/uploads/fields/fpshealth_theme_file/maatregelenprogramma_2de_cyclus_2022.pdf

Bij de Vaate A, Jazdzewski K, Ketelaars HAM, Gollasch S, van der Velde G (2002) Geographical patterns in range extension of Ponto-Caspian macroinvertebrate species in Europe. Canadian Journal of Fisheries and Aquatic Sciences 59(7): 1159–1174. https://doi.org/10.1139/f02-098

Boon PJ, Clarke SA, Copp GH (2020) Alien species and the EU Water Framework Directive: A comparative assessment of European approaches. Biological Invasions 22(4): 1497–1512. https://doi.org/10.1007/s10530-020-02201-z

Breine N, De Backer A, Hostens K, Van Colen C, Moens T, Van Hoey G (2018) Diversity and biological trait analysis of soft-bottom macrobenthic communities in the Belgian part of the North Sea. PeerJ Preprints 6: e26685v1. https://doi.org/10.7287/peerj.preprints.26685v1

Buizer B (1989) De zakpijp *Aplidium glabrum* en de sponzen *Haliclona rosea*, *Prosuberites epiphytum* en *Hymeniacidon perlevis* succesvol in de Oosterschelde. Het Zeepaard 49(6): 156–159. https://www.vliz.be/en/imis?module=ref&refid=197745

Cardoso AC, Fee G (2008) Incorporating invasive alien species into ecological assessment in the context of the Water Framework Directive. Aquatic Invasions 3(4): 361–366. https://doi.org/10.3391/ai.2008.3.4.1

Carlton JT (2001) Introduced Species in U.S. Coastal Waters: Environmental Impacts and Management Priorities. Pew Oceans Commission, Arlington, Virginia. https://www.pewtrusts.org/-/media/legacy/uploadedfiles/wwwpewtrustsorg/reports/protecting_ocean_life/envoceansspeciespdf.pdf

Costello MJ, Dekeyzer S, Galil B, Hutchings P, Katsanevakis S, Pagad S, Robinson T, Turon X, Vandepitte L, Vanhoorne B, Verfaille K, Willan R, Rius M (2021) Introducing the World Register of Introduced Marine Species (WRiMS). Management of Biological Invasions: International Journal of Applied Research on Biological Invasions 12(4): 792–811. https://doi.org/10.3391/mbi.2021.12.4.02

Costello MJ, Ahyong S, Bieler R, Boudouresque C, Desiderato A, Downey R, Galil BS, Gollasch S, Hutchings P, Kamburska L, Katsanevakis S, Kupriyanova E, Lejeusne C, Ma KCK, Marchini A, Occhipinti A, Pagad S, Pino L, Poore GCB, Rewicz T, Rius M, Robinson TB, Sobczyk R, Stępień A, Turon X, Valls Domedel G, Verleye T, Vieira LM, Willan RC, Zhan A (2025) World Register of Introduced Marine Species (WRiMS). https://doi.org/10.14284/347 [Accessed 2025-03-21]

Critchley AT, Farnham WF, Yoshida T, Norton TA (1990) A bibliography of the invasive alga *Sargassum muticum* (Yendo) Fensholt (Fucales; Sargassaceae). Botanica Marina 33(6): 551–562. https://doi.org/10.1515/botm.1990.33.6.551

Dankers NMJA, Dijkman EM, De Jong ML, de Kort G, Meijboom A (2004) De verspreiding en uitbreiding van de Japanse Oester in de Waddenzee. Alterra-Rapport, 909. Alterra (Wageningen): 1–51. https://www.vliz.be/en/imis?module=ref&refid=108740

Donelan SC, Miller AW, Muirhead JR, Ruiz GM (2022) Marine species introduction via reproduction and its response to ship transit routes. Frontiers in Ecology and the Environment 20(10): 581–588. https://doi.org/10.1002/fee.2551

Eno NC, Clark RA, Sanderson WG [Eds] (1997) Non-native marine species in British waters: a review and directory. Joint Nature Conservation Committee (Peterborough): 1–152. https://www.vliz.be/nl/imis?module=ref&refid=24400

European Environment Agency (2024) Marine non-indigenous species in Europe's seas. https://www.eea.europa.eu/en/analysis/indicators/marine-non-indigenous-species-in?activeAccordion=546a7c35-9188-4d23-94ee-005d97c26f2b [Accessed 2024-12-17]

Federal Government (2025) Federal coalition agreement 31 January 2025. Brussels, 1–198. https://www.belgium.be/sites/default/files/resources/publication/files/Regeerakkoord-Bart_De_Wever_nl.pdf

Filipe AF, Feio MJ, Garcia-Raventós A, Ramião JP, Pace G, Martins FM, Magalhães MF (2019) The European Water Framework Directive facing current challenges: Recommendations for a more efficient biological assessment of inland surface waters. Inland Waters 9(1): 95–103. https://doi.org/10.1080/20442041.2018.1494973

Fonseca VG, Davison PI, Creach V, Stone D, Bass D, Tidbury HJ (2023) The application of eDNA for monitoring aquatic non-indigenous species: Practical and policy considerations. Diversity 15(5): 631. https://doi.org/10.3390/d15050631

Genovesi P, Shine C (2004) European strategy on invasive alien species: Convention on the Conservation of European Wildlife and Habitats (Bern Convention). Nature and environment, No. 137. Council of Europe Publishing. https://www.cbd.int/doc/external/cop-09/bern-01-en.pdf

Gittenberger A, Rensing M, Wesdorp KH (2017) Uitheemse mariene soorten in Nederland. GiMaRIS Rapport, 19. GiMaRIS (Leiden), 1–39.

Gittenberger A, Rensing M, Wesdorp KH, D'Hont A (2018) Monitoring non-native species in the port of Antwerp in 2017 conform the joint HELCOM/OSPAR port survey protocol. Commissioned by Antwerp Port Authority. GiMaRIS Rapport, 2018_01. GiMaRIS (Sassenheim). 1–46.

Gosliner TM, Behrens DW (2006) Anatomy of an invasion: Systematics and distribution of the introduced opisthobranch snail, *Haminoea japonica* Pilsbry, 1895 (Gastropoda: Opisthobranchia: Haminoeidae). Proceedings of the California Academy of Sciences 57(37): 1003–1010. https://www.vliz.be/en/imis?module=ref&refid=395088

Hablützel P, Martínez PA, Bilsen A, Christodoulou M, Delacauw S, Deneudt K, Khodami S, Lagaisse R, Heynderickx H, Obst M, Sapkota R, Sundberg P, Uhlir C, Stæhr PAU, Winding A (2023) DNA-based monitoring of Non-Indigenous Species. GEANS – Genetic tools for Ecosystem health Assessment in the North Sea region. Flanders Marine Institute, Ostend, 1–42. https://doi.org/10.13140/RG.2.2.23641.53606

Harrower CA, Scalera R, Pagad S, Schönrogge K, Roy HE (2017) Guidance for interpretation of CBD categories on introduction pathways. Technical note prepared by IUCN for the European Commission. https://www.cbd.int/doc/c/9d85/3bc5/d640f059d03acd717602cd76/sbstta-22-inf-09-en.pdf

HELCOM/OSPAR (2015) Joint Harmonised Procedure for the Contracting Parties of OSPAR and HELCOM on the granting of exemptions under International Convention for the Control and Management of Ships' Ballast Water and Sediments, Regulation A-4. Adopted as OSPAR Agreement 2013-09 and by HELCOM Ministerial Meeting Copenhagen 3 October 2013. Amended by HELCOM HOD 48-2015 (June) and OSPAR Agreement 2015-01 and HELCOM HOD 59-2020 and OSPAR Agreement 2020-01. OSPAR Commission, London, 1–49. https://www.ospar.org/documents?v=44007

Hettinger N (2012) Conceptualizing and Evaluating Non-Native Species. Nature Education Knowledge 3(10): 7. https://www.nature.com/scitable/knowledge/library/conceptualizing-and-evaluating-non-native-species-80060037/

Hulme PE, Bacher S, Kenis M, Klotz S, Kühn I, Minchin D, Nentwig W, Olenin S, Panov V, Pergl J, Pyšek P, Roques A, Sol D, Solarz W, Vilà M (2008) Grasping at the routes of biological invasions: A framework for integrating pathways into policy. Journal of Applied Ecology 45(2): 403–414. https://doi.org/10.1111/j.1365-2664.2007.01442.x

ICES (2005) ICES Code of Practice on the Introductions and Transfers of Marine Organisms 2005, 1–30. https://doi.org/10.17895/ices.pub.7536

IPBES (2023) Summary for Policymakers of the Thematic Assessment Report on Invasive Alien Species and their Control of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. In: Roy HE, Pauchard A, Stoett P, Renard Truong T, Bacher S, Galil BS, Hulme PE, Ikeda T, Sankaran KV, McGeoch MA, Meyerson LA, Nuñez MA, Ordonez A, Rahlao SJ, Schwindt E, Seebens H, Sheppard AW, Vandvik V (Eds) IPBES secretariat (Bonn, Germany). https://doi.org/10.5281/zenodo.7430692

IUCN (2020) IUCN EICAT Categories and Criteria. The Environmental Impact Classification for Alien Taxa First edition. IUCN (Gland, Switzerland and Cambridge, UK), 1–22. https://doi.org/10.2305/IUCN.CH.2020.05.en

Katsanevakis S, Zenetos A, Belchior C, Cardoso AC (2013) Invading European Seas: Assessing pathways of introduction of marine aliens. Ocean and Coastal Management 76: 64–74. https://doi.org/10.1016/j.ocecoaman.2013.02.024

Katsanevakis S, Wallentinus I, Zenetos A, Leppäkoski E, Cinar ME, Öztürk B, Grabowski M, Golani D, Cardoso AC (2014) Impacts of marine invasive alien species on ecosystem services and biodiversity: A pan-European review. Aquatic Invasions 9(4): 391–423. https://doi.org/10.3391/ai.2014.9.4.01

Katsanevakis S, Deriu I, D'Amico F, Nunes AL, Pelaez Sanchez S, Crocetta F, Arianoutsou M, Bazos I, Christopoulou A, Curto G, Delipetrou P, Kokkoris Y, Panov VE, Rabitsch W, Roques A, Scalera R, Shirley SM, Tricarico E, Vannini A, Zenetos A, Zervou S, Zikos A, Cardoso AC (2015) European Alien Species Information Network (EASIN): Supporting European policies and scientific research. Management of Biological Invasions: International Journal of Applied Research on Biological Invasions 6(2): 147–157. https://doi.org/10.3391/mbi.2015.6.2.05

Katsanevakis S, Olenin S, Puntila-Dodd R, Rilov G, Stæhr PAU, Teixeira H, Tsirintanis K, Birchenough SNR, Jakobsen HH, Knudsen SW, Lanzén A, Mazaris AD, Piraino S, Tidbury HJ (2023) Marine invasive alien species in Europe: 9 years after the IAS Regulation. Frontiers in Marine Science 10: 1271755. https://doi.org/10.3389/fmars.2023.1271755

Kerckhof F (2014) Een populatie van de Aziatische tapijtschelp *Ruditapes philippinarum* (Adams & Reeve, 1850) in de Zeebrugse haven. De Strandvlo 34(2): 57–61. https://www.vliz.be/nl/imis?module=ref&refid=240737

Kerckhof F, Haelters J, Gollasch S (2007) Alien species in the marine and brackish ecosystem: The situation in Belgian waters. Aquatic Invasions 2(3): 243–257. https://doi.org/10.3391/ai.2007.2.3.9

Kerckhof F, Verbeke D, Bauwens F (2012) Nieuws uit de Baai van Heist: de roodwieren Caulacanthus ustulatus (Mertens ex Turner) Kützing, 1843 en Gracilaria vermiculophylla (Ohmi) Papenfuss 1967 nieuw voor de Belgische kust en een merkwaardig habitat van intertidale mossels. De Strandvlo 32(1): 19–23. https://www.vliz.be/en/imis?module=ref&refid=215164

Kerkhove T, Kerckhof F (2024) Non-indigenous species introduced by human activities. Indicator report. In: Belgian State (2025) Mariene Strategie Deel 1 voor de Belgische mariene wateren. Staat van Belgische mariene wateren, goede milieutoestand en milieudoelen. Kaderrichtlijn Mariene Strategie - Artikel 8, 9 en 10. Federale Overheidsdienst Volksgezondheid, Veiligheid van de Voedselketen en Leefmilieu & Instituut voor Natuurwetenschappen, Brussel, België. https://odnature.naturalsciences.be/msfd_media/documents/D2-ANS-BE-NIS-2024-Non-indigenous_species_introduced_by_human_activities.pdf

Kopp D, Faillettaz R, Le Joncour A, Simon J, Morandeau F, Le Bourdonnec P, Bouché L, Méhault S (2023) Assessing without harvesting: Pros and cons of environmental DNA sampling and image analysis for marine biodiversity evaluation. Marine Environmental Research 188: 106004. https://doi.org/10.1016/j.marenvres.2023.106004

Lagaisse R, Amadei Martinez L, Decrop W, Deneudt K, Muyle J, Mortelmans J, Flanders Marine Institute (VLIZ) (2024) LifeWatch observatory data: phytoplankton annotated image library by FlowCam imaging for the Belgian part of the North Sea. Marine Data Archive. https://doi.org/10.14284/680

Lehtiniemi M, Ojaveer H, David M, Galil B, Gollasch S, McKenzie C, Minchin D, Occhipinti-Ambrogi A, Olenin S, Pederson J (2015) Dose of truth – Monitoring marine non-indigenous species to serve legislative requirements. Marine Policy 54: 26–35. https://doi.org/10.1016/j.marpol.2014.12.015

Lescrauwaet A-K, Vandepitte L, Fockedey N, De Pooter D, Verleye T, Mees J (2015) Invasive Alien Species in Belgian marine waters: An information platform and checklist for science and policy support. Management of Biological Invasions : International Journal of Applied Research on Biological Invasions 6(2): 209–213. https://doi.org/10.3391/mbi.2015.6.2.11

Mannino AM, Balistreri P (2018) Citizen science: A successful tool for monitoring invasive alien species (IAS) in Marine Protected Areas. The case study of the Egadi Islands MPA (Tyrrhenian Sea, Italy). Biodiversity (Nepean) 19(1–2): 42–48. https://doi.org/10.1080/14888386.2018.1468280

MarineTraffic (2025). Global Ship Tracking Intelligence | AIS Marine Traffic. https://www.marinetraffic.com [Accessed 2025-05-20]

Massé C, Viard F, Humbert S, Antajan E, Auby I, Bachelet G, Bernard G, Bouchet VMP, Burel T, Dauvin J-C, Delegrange A, Derrien-Courtel S, Droual G, Gouillieux B, Goulletquer P, Guérin L, Janson A-L, Jourde J, Labrune C, Lavesque N, Leclerc J-C, Le Duff M, Le Garrec V, Noë IP, Nowaczyk A, Pergent-Martini C, Pezy J-P, Raoux A, Raybaud V, Ruitton S, Sauriau P-G, Spilmont N, Thibaut D, Vincent D, Curd A (2023) An Overview of Marine Non-Indigenous Species Found in Three Contrasting Biogeographic Metropolitan French Regions: Insights on Distribution, Origins and Pathways of Introduction. Diversity 15(2): 161. https://doi.org/10.3390/d15020161

Mazza G, Tricarico E, Genovesi P, Gherardi F (2014) Biological invaders are threats to human health: An overview. Ethology Ecology and Evolution 26(2–3): 112–129. https://doi.org/10.1080/03949370.2013.863225

McClain C, Webb T, Heim N, Knope M, Monarrez P, Payne J (2024) Size bias in the documentation of marine biodiversity. Oikos. https://doi.org/10.1111/oik.10828

Observation.org (2025) Stichting Observation International and local partners. https://observation.org [Accessed 2025-03-25]

Ojaveer H, Galil BS, Campbell ML, Carlton JT, Canning-Clode J, Cook EJ, Davidson AD, Hewitt CL, Jelmert A, Marchini A, McKenzie CH, Minchin D, Occhipinti-Ambrogi A, Olenin S, Ruiz G (2015) Classification of non-indigenous species based on their impacts: Considerations for application in marine management. PLoS Biology 13(4): e1002130. https://doi.org/10.1371/journal.pbio.1002130

Ojaveer H, Galil BS, Carlton JT, Alleway H, Goulletquer P, Lehtiniemi M, Marchini A, Miller W, Occhipinti-Ambrogi A, Peharda M, Ruiz GM, Williams SL, Zaiko A (2018) Historical baselines in marine bioinvasions: Implications for policy and management. PLoS One 13(8): e0202383. https://doi.org/10.1371/journal.pone.0202383

Ojaveer H, Galil B, Seebens H (2024) The commitment of the EU Biodiversity Strategy for 2030 is unfeasible for marine threatened species affected by invasive alien species. Marine Policy 173: 106582. https://doi.org/10.1016/j.marpol.2024.106582

OSPAR (2018) OSPAR CEMP Guidelines Common Indicator: Changes to non-indigenous species communities (NIS3) (OSPAR Agreement 2018-04). OSPAR Commission (London): 1–20. https://www.ospar.org/documents?v=38992

OSPAR (2023) Quality Status Report 2023. Non-Indigenous Species Thematic Assessment. OSPAR Commission (London). https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr-2023/thematic-assessments/nis/ [Accessed 2025-01-20]

Palacio RD, Abarca M, Armenteras D, Balza U, Dollar LJ, Froese GZL, Galligan BP, Giordano AJ, Gula J, Jacobson AP, Jędrzejewski W, Khorozyan I, Mastretta-Yanes A, Moreno JS, Mudumba T, Nana ED, Naveda-Rodríguez A, Negret PJ, Ortuño Crespo G, Serrano FC, Serrano-Villavicencio JE, Sundar KSG, Thomas E, Villar DA, Hughes AC (2023) The global influence of the IUCN Red List can hinder species conservation efforts. Authorea. https://doi.org/10.22541/au.169945445.50394320/v1

Pederson J, Mieszkowska N, Carlton JT, Gollasch S, Jelmert A, Minchin D, Occhipinti-Ambrogi A, Wallentinus I (2011) Climate change and non-native species in the North Atlantic. In: Reid PC, Valdés L (Eds) ICES Status Report on Climate Change in the North Atlantic. ICES Cooperative Research Report 310: 174–190. https://doi.org/10.17895/ices.pub.5404

Pocock MJO, Roy HE, August T, Kuria A, Barasa F, Bett J, Githiru M, Kairo J, Kimani J, Kinuthia W, Kissui B, Madindou I, Mbogo K, Mirembe J, Mugo P, Muniale FM, Njoroge P, Njuguna EG, Olendo MI, Opige M, Otieno TO, Ng'weno CC, Pallangyo E, Thenya T, Wanjiru A, Trevelyan R (2019) Developing the global potential of citizen science: Assessing opportunities that benefit people, society and the environment in East Africa. Journal of Applied Ecology 56(2): 274–281. https://doi.org/10.1111/1365-2664.13279

Pyšek P, Jarošík V, Pergl J (2011) Alien Plants Introduced by Different Pathways Differ in Invasion Success: Unintentional Introductions as a Threat to Natural Areas. PLoS One 6(9): e24890. https://doi.org/10.1371/journal.pone.0024890

Seebens H, Blackburn TM, Dyer EE, Genovesi P, Hulme PE, Jeschke JM, Pagad S, Pyšek P, Winter M, Arianoutsou M, Bacher S, Blasius B, Brundu G, Capinha C, Celesti-Grapow L, Dawson W, Dullinger S, Fuentes N, Jäger H, Kartesz J, Kenis M, Kreft H, Kühn I, Lenzner B, Liebhold A, Mosena A, Moser D, Nishino M, Pearman D, Pergl J, Rabitsch W, Rojas-Sandoval J, Roques A, Rorke S, Rossinelli S, Roy HE, Scalera R, Schindler S, Štajerová K, Tokarska-Guzik B, van Kleunen M, Walker K, Weigelt P, Yamanaka T, Essl F (2017) No saturation in the accumulation of alien species worldwide. Nature Communications 8(1): 14435. https://doi.org/10.1038/ncomms14435

Soto I, Balzani P, Carneiro L, Cuthbert RN, Macêdo R, Tarkan AS, Ahmed DA, Bang A, Bacela-Spychalska K, Bailey SA, Baudry T, Ballesteros-Mejia L, Bortolus A, Briski E, Britton JR, Buřič M, Camacho-Cervantes M, Cano-Barbacil C, Copilaş-Ciocianu D, Coughlan NE, Courtois P, Csabai Z, Dalu T, De Santis V, Dickey JWE, Dimarco RD, Falk-Andersson J, Fernandez RD, Florencio M, Franco ACS, García-Berthou E, Giannetto D, Glavendekic MM, Grabowski M, Heringer G, Herrera I, Huang W, Kamelamela KL, Kirichenko NI, Kouba A, Kourantidou M, Kurtul I, Laufer G, Lipták B, Liu C, López-López E, Lozano V, Mammola S, Marchini A, Meshkova V, Milardi M, Musolin DL, Nuñez MA, Oficialdegui FJ, Patoka J, Pattison Z, Pincheira-Donoso D, Piria M, Probert AF, Rasmussen JJ, Renault D, Ribeiro F, Rilov G, Robinson TB, Sanchez AE, Schwindt E, South J, Stoett P, Verreycken H, Vilizzi L, Wang YJ, Watari Y, Wehi PM, Weiperth A, Wiberg-Larsen P, Yapıcı S, Yoğurtçuoğlu B, Zenni RD, Galil BS, Dick JTA, Russell JC, Ricciardi A, Simberloff D, Bradshaw CJA, Haubrock PJ (2024) Taming the terminological tempest in invasion science. Biological Reviews of the Cambridge Philosophical Society 99(4): 1357–1390. https://doi.org/10.1111/brv.13071

Thiel M, Penna-Díaz MA, Luna-Jorquera G, Sala S, Sellanes J, Stotz W (2014) Citizen scientists and marine research: Volunteer participants, their contributions and projection for the future. Oceanography and Marine Biology - an Annual Review 52: 257–314. https://doi.org/10.1201/b17143-6

Troudet J, Grandcolas P, Blin A, Vignes-Lebbe R, Legendre F (2017) Taxonomic bias in biodiversity data and societal preferences. Scientific Reports 7(1): 9132. https://doi.org/10.1038/s41598-017-09084-6

Tsiamis K, Palialexis A, Stefanova K, Ničević Gladan Ž, Skejić S, Despalatović M, Cvitković I, Dragičević B, Dulčić J, Vidjak O, Bojanić N, Žuljević A, Aplikioti M, Argyrou M, Josephides M, Michailidis N, Jakobsen HH, Staehr PA, Ojaveer H, Lehtiniemi M, Massé C, Zenetos A, Castriota L, Livii S, Mazziotti C, Schembri PJ, Evans J, Bartolo AG, Kabuta SH, Smolders S, Knegtering E, Gittenberger A, Gruszka P, Kraśniewski W, Bartilotti C, Tuaty-Guerra M, Canning-Clode J, Costa AC, Parente MI, Botelho AZ, Micael J, Miodonski JV, Carreira GP, Lopes V, Chainho P, Barberá C, Naddafi R, Florin AB, Barry P, Stebbing PD, Cardoso AC (2019) Non-indigenous species refined national baseline inventories: A synthesis in the context of the European Union's Marine Strategy Framework Directive. Marine Pollution Bulletin 145: 429–435. https://doi.org/10.1016/j.marpolbul.2019.06.012

Tsirintanis K, Azzurro E, Crocetta F, Dimiza M, Froglia C, Gerovasileiou V, Langeneck J, Mancinelli G, Rosso A, Stern N, Triantaphyllou M, Tsiamis K, Turon X, Verlaque M, Zenetos A, Katsanevakis S (2022) Bioinvasion impacts on biodiversity, ecosystem services, and human health in the Mediterranean Sea. Aquatic Invasions 17(3): 308–352. https://doi.org/10.3391/ai.2022.17.3.01

Turbelin AJ, Hudgins EJ, Catford JA, Cuthbert RN, Diagne C, Kourantidou M, Roiz D, Courchamp F (2024) Biological invasions as burdens to primary economic sectors. Global Environmental Change 87: 102858. https://doi.org/10.1016/j.gloenvcha.2024.102858

Van Ginderdeuren K, Van Hoey G, Vincx M, Hostens K (2014) The mesozooplankton community of the Belgian shelf (North Sea). Journal of Sea Research 85: 48–58. https://doi.org/10.1016/j.seares.2013.10.003

Vandekerkhove J, Cardoso AC, Boon PJ (2013) Is there a need for a more explicit accounting of invasive alien species under the Water Framework Directive? Management of Biological Invasions : International Journal of Applied Research on Biological Invasions 4(1): 25–36. https://doi.org/10.3391/mbi.2013.4.1.04

Vandepitte L, De Pooter D, Lescrauwaet A-K, Fockedey N, Mees J (2012) Niet-inheemse soorten van het Belgisch deel van de Noordzee en aanpalende estuaria. VLIZ Special Publication, 59. Vlaams Instituut voor de Zee (VLIZ) (Oostende): 1–371. https://www.vliz.be/en/imis?module=ref&refid=217736

Verlaque M (2001) Checklist of the macroalgae of Thau Lagoon (Hérault, France), a hotspot of marine species introduction in Europe. Oceanologica Acta 24(1): 29–49. https://doi.org/10.1016/S0399-1784(00)01127-0

Verleye T, De Raedemaecker F, Vandepitte L, Fockedey N, Lescrauwaet AK, De Pooter D, Mees J (2020) Niet-inheemse soorten in het Belgisch deel van de Noordzee en aanpalende estuaria anno 2020. VLIZ Special Publication, 86. Vlaams Instituut voor de Zee (VLIZ) (Oostende): 1–623. https://www.vliz.be/en/imis?module=ref&refid=331869

Verleye TJ, De Raedemaecker F, Vandepitte L, Fockedey N, Lescrauwaet AK, Mees J (2024) Geïntroduceerde niet-inheemse soorten in het Belgisch deel van de Noordzee en aanpalende estuaria anno

2024. VLIZ Special Publication, 93. Vlaams Instituut voor de Zee (VLIZ) (Oostende): 1–826. https://doi.org/10.48470/96

VLIZ (2025) LifeWatch observatory data: zooplankton observations in the Belgian Part of the North Sea. Flanders Marine Institute (VLIZ) (Ostend). https://doi.org/10.14284/711

WoRMS Editorial Board (2025) World Register of Marine Species. https://doi.org/10.14284/170 [Accessed 2025-02-26]

Zenetos A, Gofas S, Morri C, Rosso A, Violanti D, García Raso JE, Çinar ME, Almogi-Labin A, Ates AS, Azzurro E, Ballesteros E, Bianchi CN, Bilecenoglu M, Gambi MC, Giangrande A, Gravili C, Hyams-Kaphzan O, Karachle PK, Katsanevakis S, Lipej L, Mastrototaro F, Mineur F, Pancucci-Papadopoulou MA, Ramos Esplá A, Salas C, San Martín G, Sfriso A, Streftaris N, Verlaque M (2012) Alien species in the Mediterranean Sea by 2012. A contribution to the application of European Union's Marine Strategy Framework Directive (MSFD). Part 2. Introduction trends and pathways. Mediterranean Marine Science 13(2): 328–352. https://doi.org/10.12681/mms.327

Supplementary material 1

Overview of the iNIS in marine and brackish waters in Belgium, including the year of first observation in Belgium, the status of establishment in Belgium, the year of first observation in Europe and in Western Europe, the native region(s), and the primary introduction pathways and vectors responsible for introductions in Western Europe

Authors: Thomas J. Verleye, Thomas R. H. Kerkhove, Gert Van Hoey, Hans Pirlet, Francis Kerckhof, Ann-Katrien Lescrauwaet, Leen Vandepitte, Jan Mees

Data type: xlsx

Explanation note: Abbreviations used to indicate introduction pathways and vectors are explained in Table 1.

Link: https://doi.org/10.3897/neobiota.103.159848.suppl1

Supplementary material 2

Overview of the iNIS in marine and brackish waters in Belgium, as recorded in WRiMS and Verleye et al. (2024) prior to the present study, with an explanation of the actions taken to optimize (in terms of completeness) and align both inventories

Authors: Thomas J. Verleye, Thomas R. H. Kerkhove, Gert Van Hoey, Hans Pirlet, Francis Kerckhof, Ann-Katrien Lescrauwaet, Leen Vandepitte, Jan Mees

Data type: xlsx

Link: https://doi.org/10.3897/neobiota.103.159848.suppl2

Supplementary material 3

Inventory of marine and brackish iNIS first observed in Belgium after the initial MSFD benchmarking period (2011), including the data collection context and publication level of the first observation for each species, their habitat type, observed distribution, and level of establishment in Belgium

Authors: Thomas J. Verleye, Thomas R. H. Kerkhove, Gert Van Hoey, Hans Pirlet, Francis Kerckhof, Ann-Katrien Lescrauwaet, Leen Vandepitte, Jan Mees

Data type: xlsx

Explanation note: The table also indicates whether the species occur within the legal implementation area of the MSFD, whether they were included in formal Belgian MSFD reportings (Belgian State 2018a; Kerkhove and Kerckhof 2024), and whether the species' occurrences in Belgium were documented in reference databases prior to this study.

Link: https://doi.org/10.3897/neobiota.103.159848.suppl3