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Marine Non-Indigenous Species Dynamics in Time and Space within the Coastal Waters of the Republic of Ireland

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Abstract: Documenting temporal and spatial occurrence trends of Non-Indigenous Species (NIS) is essential to understand vectors and pathways of introduction, and for horizon scanning for future introductions. This study provides an overview of marine NIS found in the Republic of Ireland up to 2020. Taxonomic groups, species origin, and location of first reporting (counties) were compiled and analysed focusing on the last three decades. While the unambiguous characterisation of introduction events is challenging, analysis of 110 species corroborated the global weight of evidence that shipping activities to/from ports and marinas are the most likely vectors and pathways in Ireland. A comparable review study for the Netherlands revealed that most NIS were first introduced to mainland Europe and subsequently would take on average >15 years to reach Ireland. In the last two decades there has been an increase in NIS-focused surveys in Ireland. Incorporating data from these surveys in centralized national repositories such as the National Biodiversity Data Centre, will strongly aid the evaluation of potential NIS management responses. Furthermore, the availability of robust baseline data as well as predictions of future invaders and their associated vectors and pathways will facilitate the effective application of emerging monitoring technologies such as DNA-based approaches.

Keywords: marine invasive species; monitoring effort; origins; temporal trends; *Asterocarpa humilis*; *Lomentaria hakodatensis*; *Smittoidea prolifica*; NIS detection; the Republic of Ireland

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1. Introduction

The spread of Non-Indigenous Species (NIS) is an increasing global phenomenon [1–3]. Invasive Alien Species (IAS) is a sub-group of NIS that can have significant detrimental effects on biodiversity, ecosystem services, and economies [4,5]. In response to this, several studies have been conducted in recent years to gather baseline data on NIS and IAS in Irish marine and terrestrial environments. Fast detection of marine NIS is critical to understanding the mechanisms of introduction, patterns of establishment and spread, and the potential impacts of NIS, including the socio-economic losses arising from displacement or substitution of native species in food webs and habitats [6–9].

In Europe, the EU Regulation 1143/2014 [10] deals with Invasive Alien Species (IAS) in all ecosystems, while the Marine Strategy Framework Directive (MSFD) (2008/56/EC) [11] specifically aims to reduce the risks of NIS within European seas and oceans [12]. Zenetos et al. [13] performed a baseline study regarding NIS in marine waters at European and subregional levels. This study reported that 874 NIS have been introduced to European

marine waters up to 2020, of which the vast majority are invertebrates (59%). For the Celtic Seas, including Ireland and the Western English Channel waters of France, 107 NIS including parasites and pathogens are reported. Following this study on a European level, countries such as Spain, France, the Netherlands and Denmark have published reviews on marine NIS in their waters, often including unpublished records of additional NIS, and evaluating and analysing their origins, pathways, and establishment in more detail [14–17]. To complement these studies, which are focused on trends in marine NIS in Europe up to 2020, this paper presents a review and analysis of all NIS that have been recorded in brackish and marine coastal waters of the Republic of Ireland up to 2020. Our review focuses on macrofauna and macroflora, originating from outside the NE Atlantic, which were first recorded in the last three decades. Analyses were conducted on taxonomic groups, species origins, and counties in which these NIS were first detected. Temporal trends are discussed with particular attention to any potential explanatory bias and/or data gaps. To differentiate between Irish and wider European trends, specific reference was made to an NIS baseline study recently published for the Netherlands, as that study includes the same analyses over the same time period, whereby monitoring efforts appeared to play a distinct role where it concerns the time and place that marine NIS are first detected [14]. The present study examines the practicality and effectiveness of using ongoing marine monitoring programs in the Republic of Ireland as a means of detecting NIS, while providing additional insights into potential ways of increasing the probability of detection. Novel technological advances are considered alongside a range of modern approaches promoting the development of NIS-inclusive surveillance and monitoring programmes.

2. Materials and Methods

2.1. Criteria and Definitions of NIS Included in This Study

The present study focused on NIS that were recorded up to the year 2020 in the marine waters of the Republic of Ireland with a salinity of >~5 ppt. Species were only included in the total NIS list if it was considered likely that their spread, from their region of origin to the coastal waters of the Republic of Ireland, was associated with anthropogenic activities.

More detailed trend analysis over time of the taxa, origins, and counties where species were first detected, were only performed with a selection of species, as not all NIS are equally well-recognised and monitored. The NIS included in these analyses are species of macroflora and macrofauna (>2 mm) with a known origin outside of NW Europe. Microorganisms (<2 mm), such as unicellular planktonic species, pathogens, such as bacteria and viruses, and endo-parasites, were excluded from detailed consideration due to the higher uncertainty of their origin and year of introduction. This is also because these species are more difficult to detect unless specifically targeted. Additionally, NIS that are native to NW European waters were excluded in the more detailed analyses, because of the possibility that they arrived by natural dispersal.

To illustrate trends in more recent years, we compared the recorded instances of NIS in the last three decades (i.e., 1991–2000, 2001–2010, and 2011–2020). An accumulation graph illustrating the NIS recorded over the years, divided by taxon, includes a wider selection of species' records. Figure 1 illustrates the coastal counties of Ireland. Considering that NIS-focused monitoring has not been equally intensive in all the coastal counties of Ireland (Figure 1), we discussed whether the counties of "first records" are also likely to be the sites of first introduction.

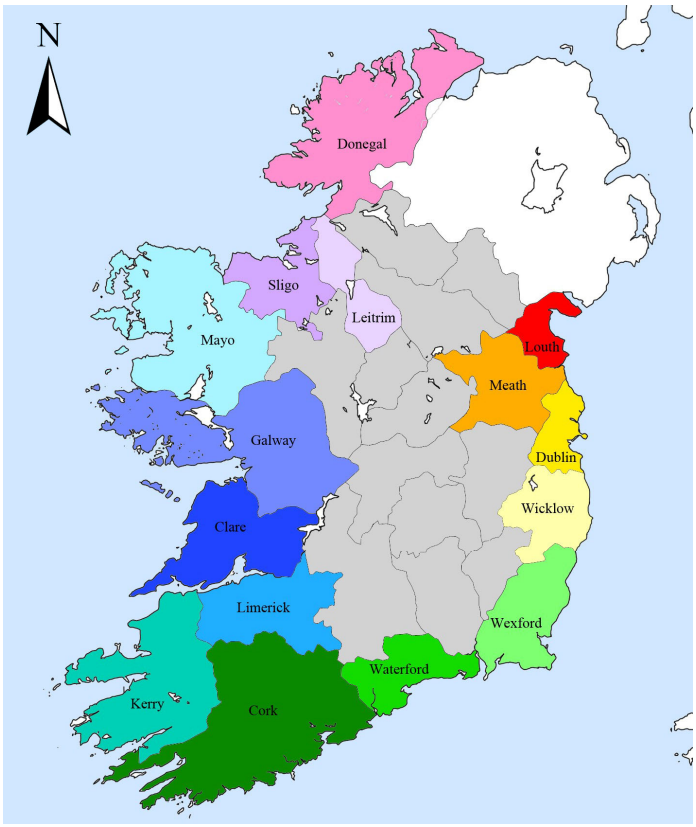

Figure 1. The counties of the Republic of Ireland where marine NIS may be first detected.

2.2. Data Collection

After thorough consultation of the current scientific literature, publicly available databases and international databases, we compiled a register of NIS reported for marine waters of the Republic of Ireland. All NIS on this register have at least one verified occurrence, including their citable source. Species names that were reported with a "cf" (confer, i.e., indicating that it probably belongs to the identified species) in the name, are considered unverified and were therefore, not included. All names of species were checked and aligned with the World Register of Species (www.marinespecies.org, accessed on 21 August 2023).

NIS specimens recorded from beached seaweeds, plastics, and other flotsam, like *Isognomon radiatus* (Anton, 1838) and *Ostrea equestris* Say, 1834 [18], are acknowledged but were excluded from this analysis, as was the case in overview lists for other EU countries such as the Netherlands [14]. This is because this review focuses on species that have survived transport and have established specimens in local habitats.

The sources of external information reviewed are appropriately cited. The bibliography includes published literature and online resources reporting the first records of NIS along the coasts of the Republic of Ireland.

To evaluate the relevance of ongoing monitoring programs to detect alien species, an assessment was made of the alien species recorded within the WFD (Water Framework Directive) and within the alien species focused surveys for BIM (Bord Iascaigh Mhara—Ireland's Seafood Development Agency) in areas with shellfish aquaculture and/or wild fisheries, and in marinas. Additionally, the database of the National Biodiversity Data Centre (NBDC) was explored for marine alien species records, acknowledging that species from these surveys for BIM will be added in the near future. Records from many of the other ongoing monitoring programs are already included in this database in accordance with the national goal that the NBDC (https://biodiversityireland.ie/, accessed on 21 August 2023) would act as a repository for all NIS data.

3. Results and Discussion

3.1. Non-Indigenous Species Dynamics in Time and Space in the Republic of Ireland

An overview of the 110 NIS that have been recorded in the marine waters of the Republic of Ireland with a salinity of >~5 ppt is provided in Table S1. This list includes species assumed to have spread outside their native region with human aid, excluding species that were only recorded on flotsam. Whether they arrived directly from their native region (primary introduction) or after an initial introduction elsewhere in NW Europe (by secondary distribution) is not discussed within the present article. Of these species, 28 concern macrofauna and macroflora, excluding parasites, with a known origin outside of NW Europe. These were first recorded in the Republic of Ireland in the most recent three decades (1990–2020) (Table S2). For eight of these species, the present article reports the first record within the Republic of Ireland (Table 1). This concerns (1) five seaweed species, viz. *Grateloupia turuturu* Yamada, 1941 (in 2015 in Cork); *Ulva australis* Areschoug, 1854 (in 2011 in County Wexford); *Ulva rhacodes* (Holmes) Papenfuss, 1960 (in 2011 in County Cork); *Undaria pinnatifida* (Harvey) Suringar, 1873 (in 2015 in County Kerry); and *Lomentaria hakodatensis* Yendo, 1920 (in 2015 in County Cork), (2) a sea-squirt, *Asterocarpa humilis* (Heller, 1878) (in 2019 in County Dublin), and (3) two bryozoans, viz. *Bugulina simplex* (Hincks, 1886) (in 2019 in County Wexford) and *Smittoidea prolifica* Osburn, 1952 (in 2017 in County Wexford). They were recorded during surveys focused on non-indigenous species, issued by BIM in shellfish production areas and marinas. The highest diversity of marine alien species within these surveys was found in the Dun Laoghaire marina, Dublin (e.g., Figure 2), a region also known from other studies as an alien species hotspot [18]. Figure 2 illustrates this by showing the underside of a buoy colonised by five non-indigenous species and one cryptogenic species (*Bugula neritina*). Four of the five non-indigenous species, i.e., the sea-squirts *Asterocarpa humilis* and *Didemnum vexillum* Kott, 2002, and the bryozoans *Tricellaria inopinata* d'Hondt and Occhipinti Ambrogi, 1985 and *Watersipora subatra* (Ortmann, 1890), were first recorded for the Republic of Ireland in or close by the marinas and port of Dublin between 2005 and 2019.

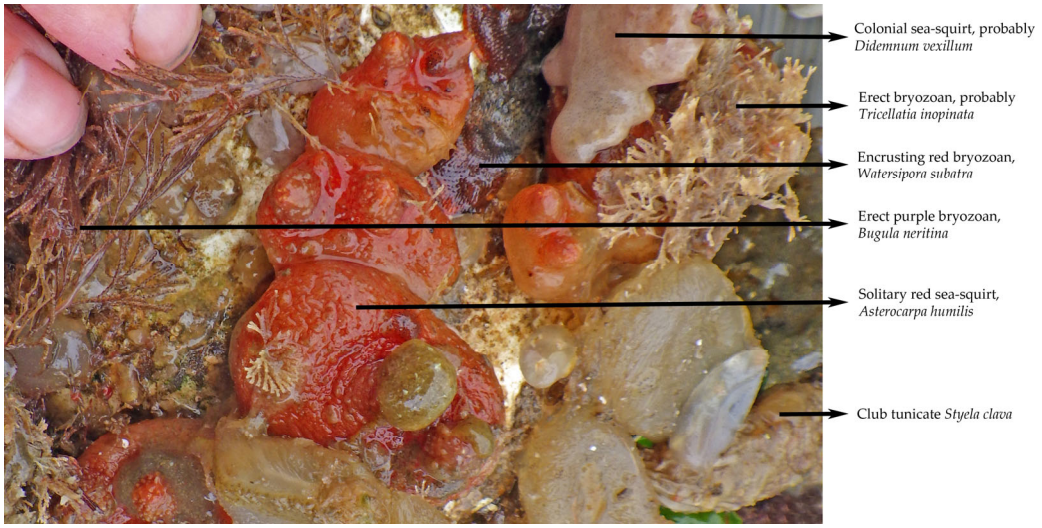

Figure 2. Fouling community on the underside of a buoy searched for alien species in 2019 in Dun Laoghaire marina, Dublin. The highest diversity of marine alien species in the Republic of Ireland, is generally found on floating objects in marinas. The colonial sea-squirt and the erect bryozoan identified as "probably" *Didemnum vexillum* and *Tricellaria inopinata,* cannot be identified from the photo, and as the individuals concerned may not have been studied in the lab, their identity remains uncertain. Based on material that was collected from this buoy, it may be concluded that these two alien species were present in addition to a much larger, not figured alien species, i.e., the kelp Wakame, *Undaria pinnatifida*. Photo by A. Gittenberger (GiMaRIS).

Table 1. First records of eight NIS in the Republic of Ireland, as reported in the present publication, indicating the year and locality where they were first recorded. * Species of which the presence in Ireland was already published on the basis of specimens found in Irish marinas in 2021 [19] but were not included in this review as they occurred post 2020. Further remarks are provided summarizing additional records of these species in alien species focused surveys for BIM. These records are at present being incorporated in the database of the NBDC (https://biodiversityireland.ie/, accessed on 21 August 2023).

Species	Year	Location	Remarks
ALGAE			
Grateloupia turuturu *	2015	Bantry Bay, Cork mussel rope culture	Recorded also in 2017, 2019 and 2020 in Wexford, Dublin, and Cork in mussel bottom culture, in a marina and mussel rope culture. Two records in NBDC (first in 2018) in Kerry and Cork.
Lomentaria hakodatensis	2015	Bantry Bay, Cork mussel rope culture	Recorded also in 2018, among mussel rope culture off Kenmare, Kerry.
Ulva australis	2011	Wexford bay, Wexford mussel bottom culture	Repeatedly recorded in the years after in Louth, Wexford, Cork, and Kerry.
Ulva rhacodes	2011	Youghal Bay, Cork mussel bottom culture	Was recorded only once
Undaria pinnatifida	2015	Tralee Bay, Kerry oyster bottom fishery	Also recorded in Lough Foyle, Donegal (in 2015) among oysters, and subsequently in 2016 and 2019 in marinas and areas with oyster and/or mussel aquaculture or wild fisheries, in counties Kerry, Dublin and Wexford.
ASCIDIACEA			
Asterocarpa humilis *	2019	Dún Laoghaire marina, Dublin	Various individuals were collected in the marina of Dún Laoghaire, where the species was also sighted in the following years.
BRYOZOA			
Bugulina simplex *	2019	Kilmore Quay marina, Wexford	In 2019, the species was also recorded in Dunmore East harbour, Waterford
Smittoidea prolifica	2017	Wexford bay, Wexford Mussel bottom culture	Recorded also in 2019 among mussels on the bottom in Kerry.

Records of *A. humilis*, *G. turuturu* and *B. simplex* in Ireland have already been published based on individuals collected from surveys of Irish marinas in 2021 [19]. However, as records of these three species from surveys conducted in 2019, 2015 and 2019, respectively, are being first published here, the authors [19] were unaware that they were already recorded in previous years. This 'publication time lag', from the point of discovery of new NIS to the time of publication of their records, can cause confusion in understanding temporal trends in NIS introduction. Acknowledging this, efforts are being made to co-ordinate and submit all NIS records, including the BIM surveys to the National Biodiversity Data Centre as a central repository for all the Irish data. This will improve specifically, the details of first record and data accessibility.

3.1.1. NIS Taxa Recorded over Time

It is clear that reports of NIS from the coastal waters of the Republic of Ireland have been steadily increasing over time (see Figures 3 and 4) and some general trends have emerged.

1. Algae (seaweeds) followed by Mollusca and Crustacea form the main taxa of NIS recorded in the coastal waters of the Republic of Ireland (Figure 3). When taking into account only marine alien species recorded as "new" in the last three decades, i.e., from 1990 to 2020, the Algae (seaweeds) are represented by most species, followed by the Ascidiacea and Bryozoa (Figure 4). It is unclear what may have caused the shift to the higher taxa to which newly recorded marine alien species belong. Alien bryozoan species were not recorded prior to the year 2000, but since then six new species were reported. A similar pattern was found in the Netherlands, where alien bryozoan species were not recorded before 1990, whereas nine new species were

found during 1990–2020 [14]. Varying monitoring efforts by Bryozoan specialists are likely to explain such a trend rather than a sudden increase in the introduction of such taxa.

An alternative explanation could be that hull fouling has become a more important introduction vector in recent decades, as Ascidiacea and Bryozoa mostly concern fouling species. Ballast water as a vector is generally considered less likely for these taxa as their pelagic life stages tend to be relatively short, i.e., hours to days [20,21], in comparison to many molluscan (especially bivalves) and crustacean species that can have pelagic life-stages of several weeks or more [22]. For molluscan and crustacean NIS ballast water is therefore also often considered as a logical introduction vector, a hypothesis that is supported by studies in which ballast water samples are searched for species [23]. The shift in new NIS taxa being recorded in Ireland, may partly be linked to stricter management of ballast water as a vector of NIS in recent decades, e.g., first by mandatory mid-ocean ballast water exchange and more recently by the implementation of the Ballast Water Convention, which is still in progress [24]. Where hull-fouling is concerned, the EC Biocidal Products Directive (98/8/EC) of 1998 may have actually increased the chances that NIS arrive within hull fouling communities in recent decades, as it restricts the use of TBT and other biocides in anti-fouling paints. Alternative nontoxic control measures against NIS being transported in fouling communities tend to be less effective [25].

2. The predominant higher taxa of NIS that were recorded as new to the Republic of Ireland have varied distinctly over the last three decades (Figure 4), with increasing numbers of alien Algae and Bryozoa being reported in the more recent decades. Meanwhile, the number of newly recorded alien molluscan species and crustaceans appears to be decreasing. Although most new records of macrofaunal NIS in the Republic of Ireland are molluscs and crustaceans (Figure 3), none of the species recorded in the most recent decade 2011–2020 (Figure 4) belong to these taxa.
3. Figure 3 shows a clear upward shift in first recordings of higher taxa from 1970 onwards. Prior to 1970 NIS records were of Algae, Crustacea and Cnidaria with a sudden increase in the recording of Ascidiacea, Annelida and Pisces NIS in the 1970s. Rather than indicating changes in vectors or frequencies of introductions, the increased reporting of higher taxa in the 1970s may also have arisen from the recruitment of new taxonomic expertise to the monitoring community. In the Netherlands no marked taxonomic transition can be discerned for this period [14]. Several NIS belonging to the taxa mentioned above were recorded much earlier in the 20th century there [14]. In other European countries, comparable shifts in recorded higher taxa may also have occurred. However, in recent analyses, for example, Denmark [15], France [16], and Spain [17], taxonomical groups of marine NIS newly recorded up to 2020 are not separated. Therefore, it remains unclear whether particular higher taxa may have been underscored occasionally in those countries as well. For Denmark, an analysis similar to that in the present study (Figure 3) was conducted, but species were grouped by functional groups rather than by higher taxonomic categories. Although functional group analyses can provide valuable insights into NIS introductions [13,15], when interpreting results, one should be aware that possibly not all taxa representing groups like the "benthic invertebrates" were equally well monitored over time. As in the present study for Ireland where it seems likely that this was the case, and we refrain from conducting further analyses on a functional group level.

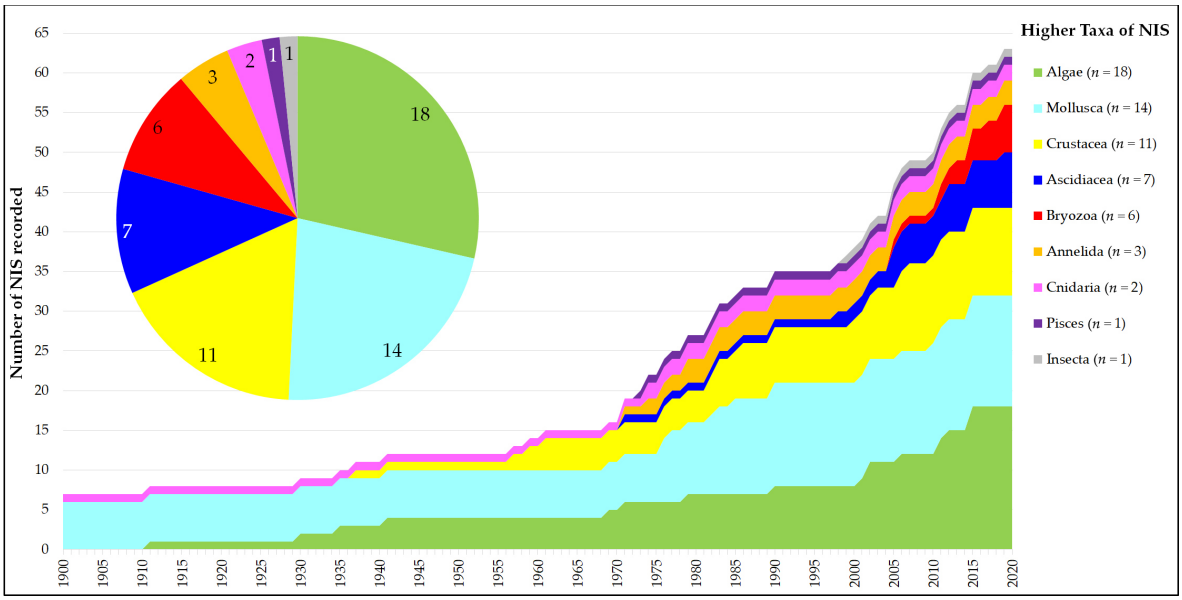

Figure 3. An accumulation graph illustrating the first records of NIS that were probably introduced with human aid in the coastal waters of the Republic of Ireland with a salinity of >~5 ppt, from 1900 up to 2020, divided by taxon (after Table S1). Only macroflora and macrofauna species are included with a known origin outside of NW Europe, excluding endo-parasites. Taxa are ordered by the number of NIS recorded in total since 1900 (see pie chart).

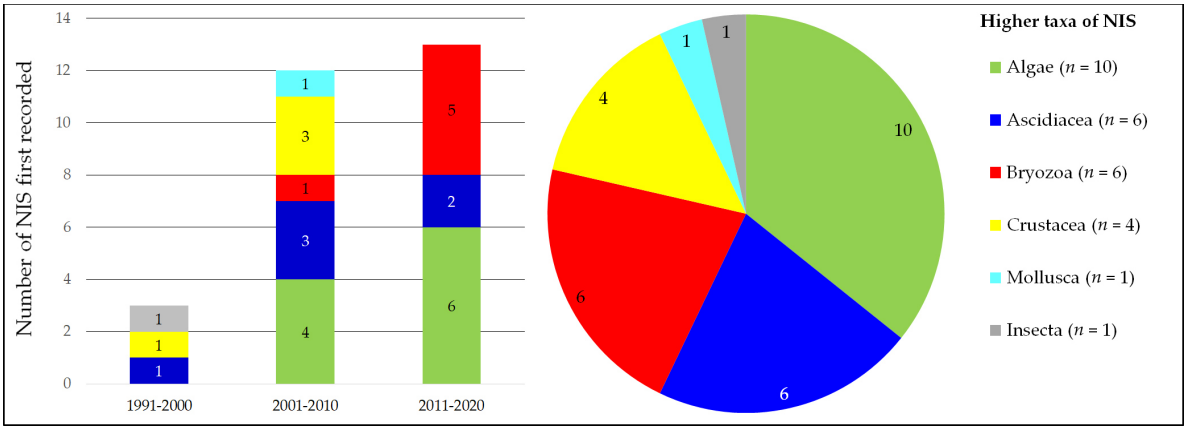

Figure 4. NIS taxa recorded for the first time 1991–2020 in the coastal waters of the Republic of Ireland (after Table S1). Only macroflora and macrofauna species are included with a known origin outside of NW Europe, excluding endo-parasites. Bar chart: NIS taxa first discovered in the decades 1991–2000, 2001–2010, and 2011–2020. Taxa are ordered by the number of NIS recorded in total in the period 1990–2020, as illustrated in the pie chart.

3.1.2. NIS Origins over Time

Over many decades, NIS arrived in the Republic of Ireland from different seas and oceans worldwide. Their origins vary over time (Figure 5). Based on this figure, several conclusions may be drawn.

1. Almost 75% of the marine NIS recorded as new for the Republic of Ireland over the last three decades originate from the Indo-Pacific region (blue shades in the pie-chart within Figure 5) and this is also the case in other Atlantic European countries like the Netherlands and France [14,16]. Historically many of these introductions are associated with the importation of the Pacific oyster *Magallana gigas* (Thunberg, 1793) to France and the Netherlands in the 1970s and 1980s [26]. However, while the live transport of *M. gigas* from Asia to European aquaculture sites has been proscribed

since the 1990s, the number of new NIS from the Pacific continues to be rise indicating that marine traffic is now the predominant vector [14].

2. From 2000 to 2020 the incidence of marine NIS originating from the Indo-Pacific has more than doubled compared to 1991–2000. The increase in new NIS recorded, three for 1991–2020 and twelve for 2000–2020, can at least in part be attributed to increased and more widespread monitoring.

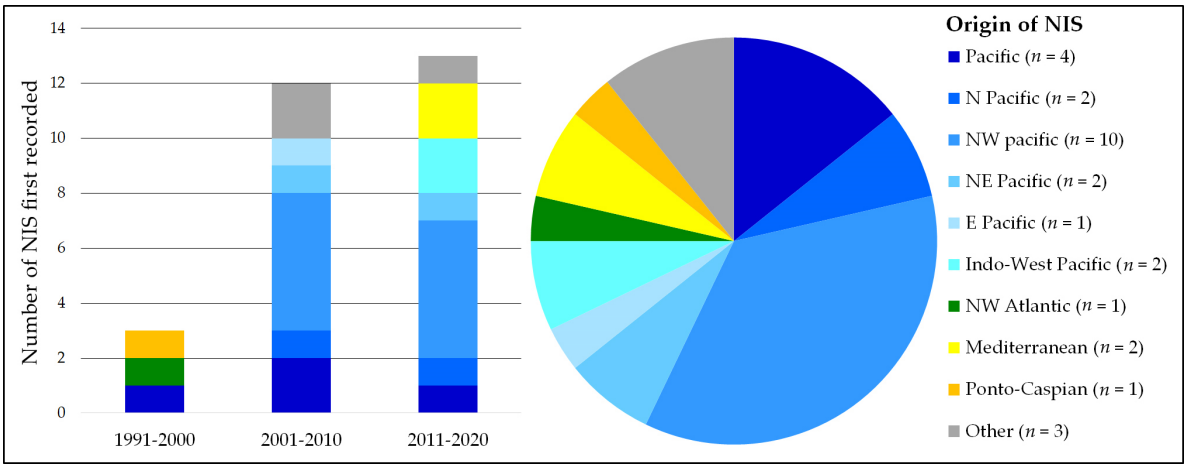

Figure 5. Origins of NIS recorded for the first time from 1991 to 2020 in the coastal waters of the Republic of Ireland (after Table S1). These graphs only include macroflora and macrofauna species with a known origin outside of NW Europe, excluding endo-parasites. Bar chart: Origins of NIS in the decades 1991–2000, 2001–2010, and 2011–2020. Pie chart: Origins of NIS first recorded in the period 1991 to 2020. NIS originating from the Pacific are all represented by shades of blue in the figures, while those from the Atlantic are represented by shades of green. Species assumed to be native to only a region within an ocean, e.g., the northeast Pacific, are included in that category only, and are therefore excluded in the count for the whole ocean, e.g., the darkest blue coloured "Pacific" category.

3.1.3. Counties Where NIS Were First Recorded

First records of NIS in the Republic of Ireland are widely, though unevenly, distributed in coastal counties and vary considerably over time. This is represented in Figures 6 and 7. From this several conclusions arise.

1. While the counties with the highest number of new NIS first recorded varies strongly over time, there appears to be a general trend that new NIS are mainly recorded at the east coast, i.e., in the counties Louth, Dublin, Wicklow, and Wexford, and on the south coast at Waterford, Cork, and Kerry. By contrast, very few new NIS have been recorded in the last three decades in the north and west coast counties of Donegal, Sligo, Mayo, Galway and Clare (Figures 1 and 6). This reflects the distribution of the major ports on the east and south coasts, i.e., in Dublin, Wexford, Waterford, and Cork, connecting Ireland with Great Britain and Europe.
2. There are outliers indicating less obvious vectors and pathways. For example, the crustacean *Chelicorophium curvispinum* was first detected in fresh water in the inland county Roscommon (county highlighted in grey for the decade 1991–2000 in Figure 7). The River Shannon in Roscommon is however navigable to the sea by recreational craft. This species was included in the analyses of this study as it is known to be able to also establish itself in brackish waters with a salinity of >~5 ppt.

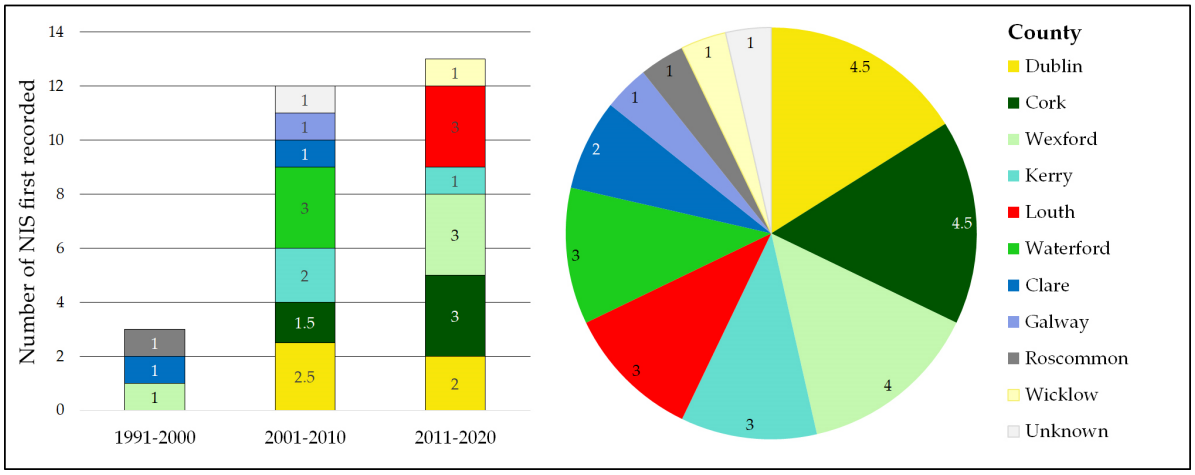

Figure 6. Counties in the Republic of Ireland (Figure 1) where NIS were first recorded from 1991 to 2020 in coastal waters (after Table S1). Within these graphs only macroflora and macrofauna species are considered with a known origin outside of NW Europe, excluding endo-parasites. Bar chart: Counties where NIS were recorded for the first time in the decades 1991–2000, 2001–2010, and 2011–2020. Pie chart: Counties where NIS were recorded for the first time in the period 1991 to 2020. Counties are ordered by the total number of NIS first recorded there. If a species was first recorded in two counties within the same year (without literature clearly indicating which county it was recorded in first), both counties are included in the graphs with a value of "0.5".

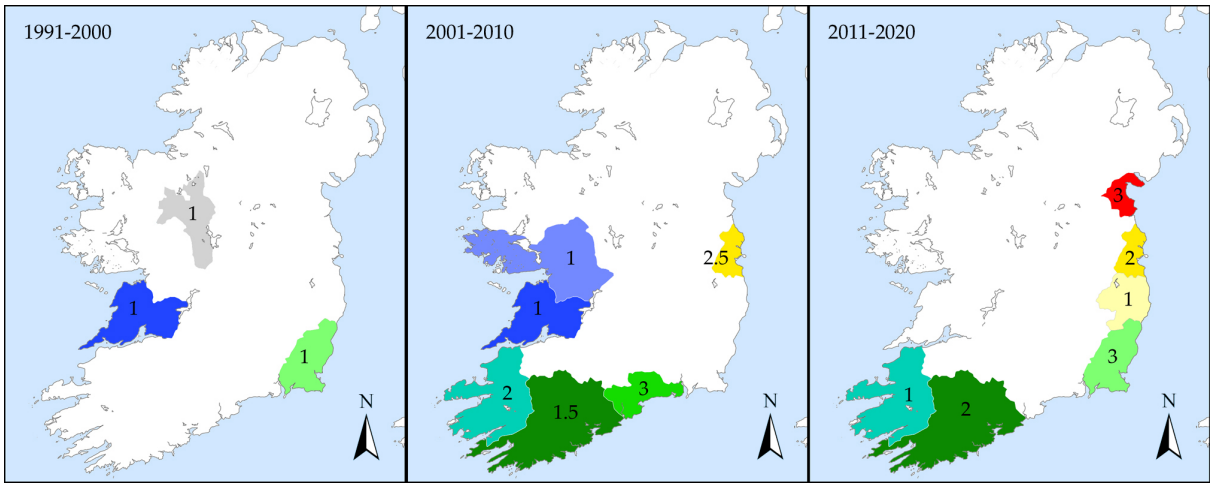

Figure 7. Spatio-temporal distribution of NIS first records in the Republic of Ireland (Figure 1) from 1991 to 2020 (after Table S2), highlighting counties where these NIS were first recorded in the decades 1991–2000, 2001–2010 and 2011–2020. If a species was first recorded in two counties within the same year (without literature clearly indicating in which county first), both counties are included with a value of "0.5".

3.1.4. Monitoring Effort

It is clear that, as in other EU countries, monitoring effort plays an important role in the detection of NIS introductions in the Republic of Ireland [14]. As already referred to, recent discoveries of new Bryozoan NIS are likely partly due to the recruitment of additional bryozoan expertise to the monitoring community. Also, the dramatic increase from three new NIS discovered from 1991–2000, to twelve from 2011–2020 likely results from increased NIS-focused monitoring effort since 2000 (e.g., [18,19,27–30]). Also, since 2010, Dutch import requirements for shellfish have necessitated additional and systematic NIS focused monitoring at Irish shellfish production sites and marinas by BIM thus enabling the development of further NIS management options for aquaculture.

None of the 28 NIS (macrofauna and flora with a known origin outside of NE Atlantic, parasites excluded), that were recorded as new to the Republic of Ireland in the last three decades, is present in the WFD macro-invertebrate database. This is not surprising as WFD monitoring is primarily of soft sediment habitats whereas the settlement requirement for most of the 28 recently recorded species is for hard substrate and surfaces such as occur at the aquaculture sites and marinas surveyed by BIM. The WFD database does include some NIS records, but only for species introduced more than 30 years ago.

In comparison, 19 of the 28 NIS have been repeatedly recorded within the NIS-focused surveys for BIM in areas with shellfish aquaculture or fisheries, and in marinas. In the National Invasive Species Database (https://maps.biodiversityireland.ie/, accessed on 21 August 2023) records of 20 of these 28 NIS can be found. Combining the data now present within this database with the records of the surveys conducted for BIM, records are available for 25 out of the 28 NIS recorded as new in the last three decades. As the BIM records are due to be included in the National Invasive Species Database (https://maps.biodiversityireland.ie/, accessed on 21 August 2023) in the near future, the resulting dataset is expected to give a reasonably complete inventory of marine NIS and provide a stronger baseline for stakeholders, managers, and the monitoring community.

3.1.5. Likely Pathways and Vectors

Likely pathways and vectors are sought based on NIS region of origin and the sites where they are first discovered in the receiving country. With varying monitoring efforts over the years, it is often difficult to resolve with certainty the initial vector or pathways for NIS introductions to the Republic of Ireland. Nonetheless, as the majority of new NIS are first documented on the east and south coasts where international ports and marinas are concentrated, indicating marine traffic as a main vector.

Vector and pathway identification should not proceed from unchecked assumptions. For example, while live transport of shellfish from Ireland to the Netherlands might present as a likely NIS vector to that country, this is not supported by the present analyses.

In total, 20 marine alien species with a known origin outside of NW Europe first recorded in the Republic of Ireland in 1990–2020 are also known from the coastal Netherlands (Table S2; [14]). A total of 18 of these were first recorded in The Netherlands. On average, NIS are recorded 15.7 years earlier there. Although differences in monitoring effort in both countries may partly explain this pattern, we assess that it indicates that most were established in coastal Europe including the Netherlands, long before arriving in Ireland. It follows that NIS species lists for the Netherlands and other European countries with Atlantic coasts are a primary resource for NIS horizon scanning in Ireland. Conversely, the marine alien species list of Ireland is not expected to be of much value to the Netherlands for predicting potential future invasions. This is supported by the documentation of 83 new marine NIS (excluding parasites), with a known origin outside of NW Europe in the Netherlands over the last three decades [14] compared to 28 marine NIS in the Republic of Ireland in the same period (Table S2). Even with a much smaller coast there appears to have been about twice as many successful establishments of marine NIS in the last thirty years in the Netherlands than in Ireland. Rotterdam is however the largest seaport in Europe.

Eighteen of the Pacific NIS recorded in Ireland between 1991 and 2020 (Figure 5), can to varying degrees be potentially associated with the production of the Pacific Oyster (*Magallana gigas*) at European sites, or with secondary spread from production sites. The arrival of *Magallana gigas* in Europe is widely attributed to imports to France and the Netherlands from the North West Pacific in the 1970s and 1980s [14]. Since then, it has become a mainstay of the Irish aquaculture industry with important production sites on all coasts. This underscores the need for systematic monitoring of NIS and associated potential vectors/pathways to better understand introduction and further spread of NIS in Ireland.

3.2. Innovative Methods and Developments for Improving NIS Detection and Surveillance

An increasing number of modern technologies and approaches are used in monitoring marine life, including optoacoustic, omics, satellites, remote sensors, and artificial intelligence [31,32]. In the context of unwanted and non-indigenous species, DNA-based approaches have shown great promise thanks to the possibility to detect species' presence using indirect methods such as environmental DNA (eDNA) [33,34]. This is particularly useful in marine environments, where areas to be surveyed can be large and inaccessible, and taxonomic resolution can be hampered either by indistinguishable early life stages or by lack of taxonomic expertise. As can be seen from this study, the number of NIS that are relevant for the Irish marine ecosystem are in the hundreds, thus rapid and cost-effective methods are needed to map their occurrence and distribution. Furthermore, eDNA offers the possibility to conduct regular surveillance efforts at introduction hotspots (e.g., ports and marinas) [35]. It is worth noting that eDNA is an indirect approach and data interpretation can be challenging if information on the target organism, its environment and eDNA's "behaviour" is patchy or unknown (e.g., [36]). Furthermore, sample acquisition as well as laboratory procedures can introduce biases and have limitations that must be assessed on a case-by-case basis [37,38]). Notwithstanding, research and development advances continue to reduce these current limitations such that eDNA approaches can be used as sentinel tools offering unprecedented opportunities to obtain initial insights on the potential presence and distribution of NIS in the marine environment. Such approaches can also be extremely cost-effective when combined with more traditional survey methods by covering larger areas and helping focus resources on the greatest area of need, i.e., highest risk areas. While presence of a NIS can only be ascertained by direct capture and characterisation (using morphologic and/or genetic data), integrated eDNA data can be obtained at faster and wider temporal and spatial scales (e.g., citizen science approach) (e.g., [39]), with emerging web-based tools aiding the fast screening of large eDNA-based datasets (e.g., [34]). The possibility to detect new introductions at their first entry is important for the identification and effective management of pathways and vectors, thus eDNA is likely to become a key component of future NIS surveillance programmes.

4. Conclusions

The present study revealed records of 110 marine NIS for the Republic of Ireland. Among these species, 28 are macrofauna and flora, excluding parasites, with a known origin outside of NW Europe, and first recorded between 1991 and 2020. For eight of these species this study reports the first record in the country, viz. the seaweeds *Grateloupia turuturu*, *Ulva australis*, *Ulva rhacodes*, *Undaria pinnatifida* and *Lomentaria hakodatensis*, the sea-squirt *Asterocarpa humilis*, and the bryozoans *Bugulina simplex* and *Smittoidea prolifica*. These species were reported from 2011–2020 when a series of NIS-focused surveys for BIM were conducted in areas with shellfish aquaculture and fisheries, and in marinas. Although these surveys and several other NIS surveys of marinas in 2001–2010 have played a major role in the detection of twelve new NIS in these two decades, only three new NIS were detected between 1991 and 2000. This may be attributed to varying monitoring efforts in the different decades. Inconsistent involvement over the years by specialized taxonomists may explain why bryozoans were not detected before 2000 yet six new bryozoan NIS were detected since then. Most marine NIS in Ireland originate from the Indo-Pacific, with relatively few from other regions such as the Mediterranean or West Atlantic waters. This remains difficult to explain because along the continental coast of Europe many more West Atlantic NIS have been detected in recent years. It is possible that these species will arrive in the Republic of Ireland in the years to come. In the Netherlands for example, on average, NIS are detected more than 15 years prior to the first records for Ireland. By contrast, only two NIS were detected first in the Republic of Ireland. This supports the hypothesis that most NIS in Ireland arrive by secondary range expansion, after their introduction elsewhere along the marine waters of continental Europe, which is to be expected given the geographic separation of the island of Ireland.

Taking into account that almost all marine NIS in Ireland are first recorded in counties bordering the east and south coasts, shipping is assumed to be the main introduction vector as most of the country's international ports and marinas linking to the UK and mainland Europe are located there. Far fewer NIS are first recorded in the northwest of Ireland, i.e., in counties like Donegal, Mayo and Galway, which do not have the same concentration of commercial ports.

Increased NIS-focused monitoring efforts in the last decade by BIM and other sources of records shared and stored collectively at the National Biodiversity Data Centre will create a more comprehensive database and provide more valuable insights into the pathways and vectors regarding marine NIS, than previously available. This study provides baseline data on trends of marine NIS in Ireland and will aid future monitoring efforts, which should be conducted routinely at an all-Ireland scale using standardised methods including direct and indirect approaches targeting wider taxonomic groups and prioritizing high impact species as well as introduction hotspots.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/d15091019/s1: Table S1: An overview of the NIS that have been recorded in the coastal waters of the Republic of Ireland (Excel file); Table S2: The 28 NIS macrofauna and macroflora with a known origin outside of the NE Atlantic, parasites excluded, that were recorded as new to the Republic of Ireland in the last three decades, indicating (1) first records for the Republic of Ireland, first reported in this publication, (2) monitoring programs with records of these species, (3) a comparison with first records of these NIS in the Netherlands.

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