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The haunting challenge of the trends and pathway assessments on newly introduced non-indigenous species in European seas

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ABSTRACT

The spread of aquatic non-indigenous species (NIS) is recognised as a major threat to the recipient regions ecosystems. The present study reviewed all NIS that have been introduced to the marine waters of the European Union (EU) until 2021, and their introduction pathways. Further, the study statistically analysed temporal trends

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in new NIS introductions and addressed uncertainties in relation to transporting pathways. Time-series analyses indicated that the observed trends in new NIS introductions have followed smoothly increasing trajectories for the entire study area, Mediterranean Sea, North-East Atlantic Ocean, and the Baltic Sea, whereas abrupt increase was detected for the Black Sea. It is noteworthy that the increasing trends started to slow down at the end of 2010s. Strongly increased research interest towards marine invasions since the early 2000s, and new environmental policies likely affected the observed trends. Future updates will be key to assessing whether this slowdown is truly a persisting trend or only an anomaly in the long term. The pathway assessment suffered from notable uncertainties, as the assigned confidence levels for pathways were low or unassigned for a large proportion of the introduced NIS in all study regions. Transport by shipping vectors was assigned as the most common pathway (51%) for new NIS introductions to EU seas, although there was very rarely direct evidence of this. The study highlights the need to overcome the pathway uncertainties, as robust information on introduction pathways is critical to manage new NIS introductions effectively.

1. Introduction

For several decades, non-indigenous species (NIS), including invasive alien species (IAS) have been recognised to pose major environmental, economic, and societal threats globally (Bax et al., 2003). The United Nations (UN) Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services has identified IAS as one of the five most threatening anthropogenic pressures endangering biodiversity worldwide alongside land- and sea-use change, climate change, pollution, and direct exploitation of species (IPBES, 2023).

Aquatic NIS encompass both freshwater and marine organisms and can be introduced through several pathways and vectors (Katsanevakis et al., 2013). While the pathways and vectors may vary across the introduced regions (e.g., in European regional seas, see Nunes et al., 2014), a general guidance document on NIS pathways has been provided by the International Union for Conservation of Nature (IUCN, 2017), which is based on the Convention on Biological Diversity (CBD) categorisation scheme of pathway types (UNEP, 2014). In short, introduction pathways refer to anthropogenic processes and activities that lead to the introduction of a species, whereas a transporting vector refers to a physical object or medium, such as a ship hull or ballast water, that is needed for the species to become introduced (Katsanevakis et al., 2013). The main pathway categories include deliberate releases into wilderness, aquaculture, shipping-related vectors, and man-made corridors. These pathways and vectors are broadly applicable to terrestrial, freshwater, and marine organisms, and have been further elaborated by Bailey et al. (2020) and Pergl et al. (2020) for aquatic introductions.

The ecological and socio-economic consequences of aquatic NIS introductions started to receive more attention towards the end of the 20th century, when severe adverse effects were observed, such as those caused by *Mnemiopsis leidyi* in the Black Sea, *Dreissena polymorpha* in the Great Lakes, and *Asterias amurensis* in Australia (Griffiths et al., 1991; Byrne et al., 1997; Knowler, 2005). These events and increased attention rapidly triggered policy developments across Europe. The European Union (EU) adopted the Water Framework Directive in 2000 to protect freshwaters and transitional waters, and it was followed in 2008 by the Marine Strategy Framework Directive (MSFD), which explicitly addresses marine NIS in Descriptor 2 (D2) (EC, 2000, 2008). Further EU policies, such as the EU Biodiversity Strategy (EC, 2011), as well as EU Regulation 708/2007 (EC, 2007) and EU Strategic Guidelines for the Sustainable Development of EU Aquaculture (EC, 2021) highlighted the importance of the issue, and the need to minimise risks of NIS introductions through aquaculture practices. Additionally, another EU policy, the IAS regulation, was introduced in 2014 to specifically address reporting, control, and eradication of NIS and IAS (EC, 2014). In short, the IAS regulation sets measures for Member States to prevent, eradicate, and control the spread of IAS with a specific emphasis on a list of alien species of Union concern, although the list includes more terrestrial and freshwater species than marine IAS. In parallel, the International Convention for the Control and Management of Ships' Ballast Water and Sediments (Ballast Water Management Convention, BWMC) was adopted in 2004 by the International Maritime Organization (IMO), representing a major global instrument aimed at reducing marine NIS introductions via ballast water discharges (IMO, 2004).

Following the MSFD, all EU Member States are required to report marine NIS introductions. A comprehensive baseline inventory of such introductions into EU marine waters by 2011 was compiled by Tsiamis et al. (2019), providing a foundational reference for monitoring efforts and future inventories. This work was subsequently updated to the year 2017 and followed by recommendations aimed at establishing scientifically robust threshold values for NIS in EU waters (Tsiamis et al., 2021).

Regional marine monitoring efforts conducted prior to EU-wide directives have historically focused on native species communities (Outinen et al., 2024). In contrast, less attention has been given to the detection of new NIS, as well as the assessment of the distribution, abundance, and impacts of established NIS (Tsiamis et al., 2021). The primary assessment criterion of D2 states that new NIS introductions should be minimised and eventually eliminated if possible (D2C1). Furthermore, secondary assessment criteria of D2 highlight assessments on the distribution and abundance of already established NIS (D2C2), as well as reporting native species communities or habitats adversely altered by NIS (D2C3) (EC, 2017). Several scientific collaborations on this topic have been conducted recently at a national, regional, pan-European and even global scale (Katsanevakis et al., 2013; Nunes et al., 2014; Tsiamis et al., 2019; Bailey et al., 2020; Băncilă et al., 2022; Zenetos et al., 2020, 2022a, 2022b; Galanidi et al., 2023; Massé et al., 2023). Some of the previously published NIS inventories and assessments have listed new NIS according to various assessment periods set by EU policies and regional recommendations, as well as discussed distribution, impacts, or pathways of transport of marine NIS (Korpinen et al., 2019; Zenetos et al., 2020, 2022b; Massé et al., 2023; Gittenberger et al., 2023a, 2023b). However, despite the continuity of these assessments, most inventories lack a consistent long-term time series analysis approach. As a result, they often fall short in capturing temporal trends in NIS detections, limiting the ability to assess changes in new NIS introductions and the effectiveness of management measures over extended periods. Furthermore, only two of the previously mentioned studies (Katsanevakis et al., 2013; Băncilă et al., 2022) have provided data on NIS introduction pathways including numerical estimates of the uncertainty or confidence levels associated with each pathway.

Facing these knowledge gaps, the present study listed all NIS recorded in the marine waters of the EU until the end of 2021, with the objective of statistically analysing temporal trends at a Pan-EU scale and regional sea level. Further, the study reports transporting pathways for all NIS with assigned levels of confidence for each pathway at Pan-EU and regional sea levels to get a unified dataset, identify the most prominent gaps, and improve future assessments.

2. Methods

2.1. Study area

The study area included the marine waters of the EU. The detailed geographical coverage is provided by the European Environment

Agency (EEA, 2024), including the four MSFD regional seas of the Baltic Sea, North-East Atlantic Ocean (NEA), Mediterranean Sea, and Black Sea. Pan-EU level was used as the primary scope of the continental assessment, but the same analyses were conducted using the four MSFD regions (Fig. 1). Importantly, the assessment does not cover the entire regional seas, which has clear implications on the assessment results. The assessment concerns only EU countries with the following exceptions and details. The Baltic Sea assessment included all NIS recorded in the sea area, excluding records from the marine waters of the Russian Federation. The Black Sea assessment included NIS recorded in the marine regions of Romania and Bulgaria. Regarding the Mediterranean Sea, the assessment covered all NIS records from Cyprus, Greece, Italy, Malta, Spain and France (Mediterranean areas), Slovenia, Croatia, Montenegro, and Albania. For the North-East Atlantic Ocean, a major factor in the assessments is the exclusion of the marine waters of the United Kingdom. Therefore, the assessment included NIS recorded from the Republic of Ireland, French waters associated with the Celtic Seas and Bay of Biscay, North Sea coastal waters of Sweden, Belgium, Denmark, Germany, Netherlands, and Norway, Atlantic Spain, mainland Portugal and Macaronesia, including the archipelagos of the Canary Islands, Madeira, and the Azores.

2.2. NIS records and introduction pathways

NIS recorded from the study area until the end of 2021 were included in the assessment. The dataset from a previous assessment (Zenetos et al., 2022b), including updated records until 2020, was used as a baseline, and national experts reviewed their respective marine areas with new information and potential changes in the status of listed NIS. The baseline dataset was compared to the European Alien Species Information Network (EASIN) and Information System on Aquatic Non-indigenous and Cryptogenic Species (AquaNIS) databases (AquaNIS, 2024; EASIN, 2024), and inconsistent NIS records were validated by national experts.

The species included in the analyses were listed according to the most recent advisory document for EU MSFD D2 (Tsiamis et al., 2021). All species that were considered non-indigenous to the entire study area (EU waters) were included, but species that were considered partly native (native to some part of the EU) were excluded from the Pan-EU level assessment. However, partly native species that were considered non-indigenous in another MSFD region were included in the regional sea analyses.

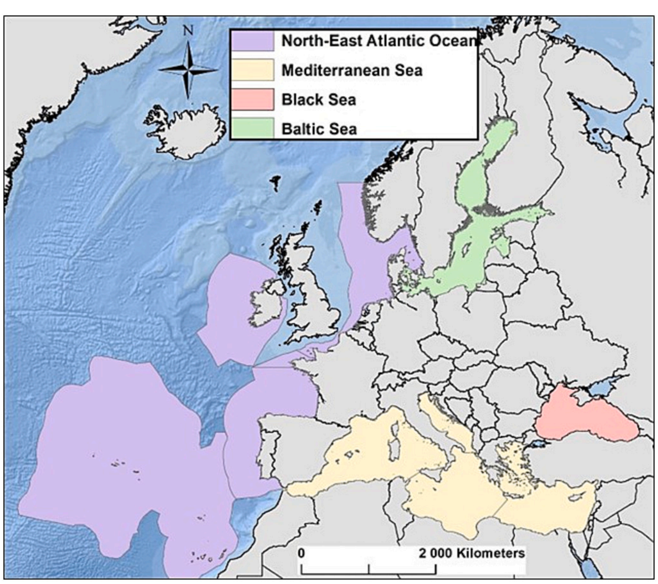

Fig. 1. Study area. The study area included only the EU waters of the described regional seas (EEA, 2024).

Due to a variety of uncertainties and remarks (Tsiamis et al., 2021), certain records were excluded from the analyses in the current study. First, oligohaline and freshwater species were included if these NIS were detected in coastal waters of any EU MSFD region, but true freshwater records (e.g., from the Kiel Canal or other distinct freshwater bodies) were excluded. Second, unicellular phytoplankton species (100 recorded species) were all excluded from the analyses, since several of these species are considered cosmopolitan, and it is often difficult to provide evidence whether their occurrence in an area has been due to natural or anthropogenic means (Gómez, 2019). Third, species records with uncertainties regarding their introduction status, commonly referred to as cryptogenic, range-expanding, or crypto-expanding species, were excluded from the analyses (122 cryptogenic and 38 range-expanding species). Cryptogenic species are species for which their native or non-native status is unknown in the study area (Carlton, 1996), whereas range-expanding species include species that expand their native range to adjacent sea areas via natural or indirect anthropogenic means (e.g., climate change) (Richardson et al., 2011). Fourth, questionable records (e.g., not officially validated by national experts or species with unresolved taxonomic status) and taxa only identified to genus level were excluded (31 and 16 taxa, respectively). Fifth, parasitic species (27 species) were excluded from the analyses due to the policy recommendation that they should be assessed and managed through the EU Aquatic Animal Health Directive and not the MSFD. Finally, the previous assessment approach (Zenetos et al., 2022b) excluded NIS that have been considered absent or extinct from the study area after the first record. However, these NIS have been included in the present analyses, since the assessment does not evaluate the establishment status of the introduced NIS.

2.3. Statistical trend analyses on newly introduced NIS

The study evaluated all newly introduced NIS at Pan-EU and regional spatial scales until 2021, but the examination of the results focused on six-year assessment periods according to the EU MSFD D2 guidance (Tsiamis et al., 2021) since 1970 (the first six-year assessment period set from 1970 to 1975), and the statistical time series analyses were conducted for a 50-year period from 1969 to 2018. Introduction years for all NIS were based on first detection dates; for uncertain records, publication years or decade averages were used (e.g., if reported as '1980s' then the decade average of 1985 was used as the introduction year).

Trends in newly introduced NIS were analysed using the method from Pélissié et al. (2024), which classifies ecological time series into trajectory classes. The approach assesses whether the time series is smooth (linear or quadratic) or abrupt, where the tested parameter decreases or increases quickly. Although both quadratic and linear trajectories are classified as smooth, a quadratic trajectory identifies whether the increase has accelerated or the decrease has decelerated towards the end of the time series, whereas a linear increase demonstrates a steady increase or decrease over time (Rigal et al., 2020). Abrupt shifts, in turn, aim to detect whether a sudden change over the course of the time series has caused a significant increase or decrease in the ecological dataset of interest (in this case, the number of newly introduced NIS) (Boulton and Lenton, 2019). The approach employs candidate trajectories ('no change', 'linear', 'quadratic', 'abrupt') for the dataset, and the best trajectory is selected using several measures. The measures include sample size-corrected Akaike Information Criterion (AICc), AICc weight, leave-one-out (LOO) cross-validation, and normalised root mean square error (NRMSE). AICc score identifies the most parsimonious model for the dataset, while the AICc weight expresses how much better the best model performs in comparison to the other models. LOO score indicates how robust the model is to the removal of individual data points, and the NRMSE score outlines the ratio between the variation not explained by the model and the overall variation – the lower the NRMSE score, the more the model explains the overall variation (Pélissié et al., 2024). Further, the applied methodology detects breakpoints for the abrupt model to identify years of significant shifts. The breakpoints were noted in the current study regardless of the best model fit to identify whether specific years indicated notable changes throughout the entire study period for each of the assessed regions. The analyses were made for new NIS introductions from 1969 to 2018 to reduce bias from reporting lags (Zenetos et al., 2019; OSPAR, 2023). Analyses were conducted using the R Shiny app (https://github.com/matpelissie/abrupt_shifts_ecological_timeseries_classification).

2.4. Pathways

All NIS records have been assigned introduction pathways by national experts following the IUCN (2017) and Pergl et al. (2020) terminology and guidance. The six main pathway categories used were release in nature (REL), escape from confinement (EC), transport contaminants (TC), transport stowaway (TS, divided into ship ballast, hull fouling, and other shipping vectors) (TS-ball, TS-hull, and TS-other), corridors (COR), and unaided (UNA). An 'unknown' category was included for NIS introductions without a documented pathway. The pathway categorisation regarding TS defines ballast water (TS-ball) and hull fouling (TS-hull) as distinct subcategories; hence, TS-other includes other TS subcategories associated with aquatic environments, such as angling and fishing equipment, hitchhikers on ship/boat excluding ballast water and hull fouling (e.g., sea chests), and other means of transport (e.g., offshore oil and gas platforms) (IUCN, 2017). In addition, unaided introductions refer to species dispersing from an adjacent region in which they are non-indigenous. NIS introduced via aquaculture activities can belong in REL or EC pathways, depending on whether the species has been freely released in the wild or held under confinement in the waterbodies of interest. In contrast, transport contaminants often include contaminants on aquaculture stocks and equipment (Pergl et al., 2020).

In cases where multiple pathways were documented to a single NIS, each pathway was assigned equal weighting to ensure balanced representation in the analysis. Therefore, the sum of pathways for each NIS always equals to one (e.g., two pathways are both given 0.5). Additionally, a confidence level (high, medium, or low) has been assigned for each NIS based on Pergl et al. (2020) matrix, reflecting the quality and reliability of the supporting evidence and information sources regarding the species' means of transport (Table 1). It is essential to note that not all introductions associated with a pathway were assigned a confidence level, primarily due to various region-specific uncertainties. Consequently, the confidence level for these introductions was labelled as NA (confidence level not assigned), indicating that a formal assessment of confidence was not conducted.

Table 1
Categorisation of the confidence levels for introduction pathways of NIS (simplified from Pergl et al., 2020).

Level of confidence	Description
High	- High source quality (peer-reviewed articles, other respected sources) - High evidence quality (direct evidence of a NIS arrival via a specific pathway)
Medium	- Intermediate source quality (grey literature from credible sources, expert consultation) - Intermediate evidence quality (Indirect evidence of the pathway, or direct evidence of the pathway from other regions)
Low	- Low source quality (grey literature from less known publications, unverified citizen observations) - Low evidence quality (Suspected pathway, no direct or indirect evidence)

3. Results

3.1. NIS introductions at the Pan-EU scale

By the end of 2021, a total of 891 NIS have been recorded across the entire study area, of which 726 were first documented since 1970 (raw research data included in Supplementary materials). The annual rate of new introductions was at its highest in 2016, reaching 31 NIS (Fig. 2). The trend in the beginning of the 21st century illustrates a markedly steeper increase in new introductions in comparison to the 1970s, 1980s and 1990s. This upward trajectory, however, ended towards the end of 2010s, causing a declining trend throughout the final years of the assessment, with the decrease particularly pronounced in 2020.

Statistical time series analyses for the entire study area showed that new NIS have arrived at an uneven rate throughout the time span of 1969–2018. The quadratic increase trajectory provided the best fit for the observed trend, and this upward trajectory was statistically significant (Fig. 3). In addition, the linear increase trajectory was nearly as suitable as the quadratic increase, and it was significantly different from zero. Although the abrupt increase was not the best fit for the data, 2008 was detected as a breakpoint associated with an abrupt increase in NIS introductions. The abrupt increase trajectory also detected 2010 as a breakpoint marking a significant decline in new introductions.

3.2. NIS introductions to the regional seas

Regional trends in new introductions largely mirror Pan-EU patterns, although some differences were detected (Fig. 4). The Mediterranean Sea and the North-East Atlantic Ocean have generally received much higher numbers of new NIS introductions (593 and 487 in total, respectively) compared to the semi-enclosed Baltic Sea and Black Sea (89 and 36 in total, respectively). Towards 2020, declining trends were observed in all regions except the Black Sea, where the number of new introductions began to decrease after 2012, and only a few new NIS introductions have been detected since.

The increase in new NIS introductions appeared linear for the Mediterranean Sea, where the number of new introductions has steadily increased throughout the assessment period (Appendix A, Fig. A.1). The quadratic increase model was not statistically significant for this region, while the abrupt increase model detected a single breakpoint in 2003, marking a significant increase in introductions. For the North-East Atlantic Ocean, the quadratic increase model provided the best fit to explain the statistically significant upward trend (Fig. A.2), although the linear increase trajectory was similarly significantly different from zero. The abrupt increase model identified two breakpoints, highlighting 1999 as a notable breakpoint when the rate of new introductions decreased, followed by an increase in 2008. Linear increase was detected as the best trajectory for the Baltic Sea introductions. The abrupt increase trajectory detected a single breakpoint for the Baltic Sea dataset with 2007 marking the year when the rate of new introductions notably increased (Fig. A.3). An abruptly increasing trend provided the best fit for the Black Sea (Fig. A.4), where the detected breakpoints occurred in 1996 and 1999, 1996 indicating a notable increase in the rate of new introductions, followed by a decrease in 1999.

3.3. Pathway assessment

The contribution of each introduction pathway up to 2021 varied between the Pan-EU and the regional sea datasets (Fig. 5). The Transport – Stowaway pathway, including the three distinct subcategories, dominated the proportional contribution on new NIS introductions in all study regions, accounting for 51% at the Pan-EU level, 46% to the Mediterranean Sea, 59% to the North-East Atlantic Ocean, 50% to the Baltic Sea, and 84% to the Black Sea. The Transport – Contaminant pathway contributed more substantially to introductions in the North-East Atlantic (16%) and Mediterranean Sea (12%) than in the Baltic

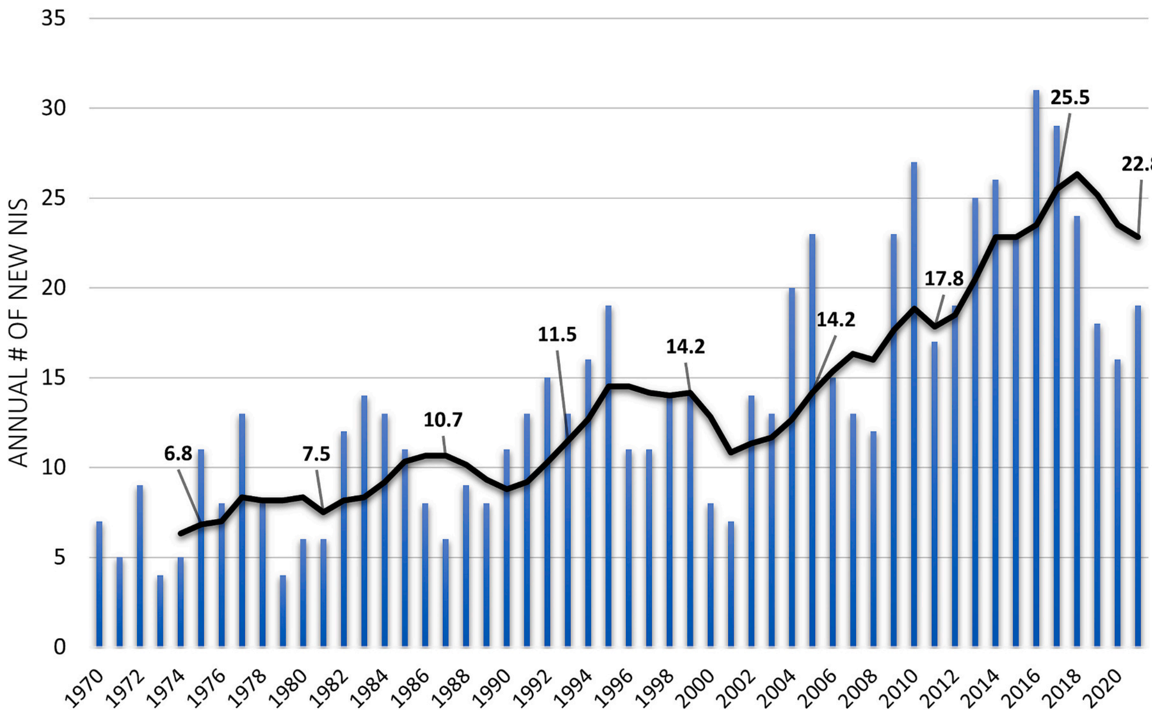

Fig. 2. The annual rate of new NIS introductions to EU seas from 1970 to 2021. The blue columns represent the annual rates of new NIS, and the black line represents moving annual averages for all six-year periods across the study years. The data labels within the moving average refer to the last year of each fixed six-year assessment period provided by Tsiamis et al. (2021) with the exception that the most recent data label (22.8) is an annual average from a period of 2016–2021 (the most recent six-year assessment period available for this study). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Sea (1%) and Black Sea (0%). The Escape from Confinement pathway was most prominent in the Baltic Sea (16%), followed by the North-East Atlantic (5%), Mediterranean Sea (3%), and Black Sea (1%). Unaided introductions made a strong contribution overall (20% at Pan-EU level), particularly in the Mediterranean Sea (28%), but much less in the Black Sea (12%), Baltic Sea (13%) and North-East Atlantic (4%). Unknown pathways accounted for 4–12% of introductions across the study regions, except for the Black Sea, where all introductions were assigned a known pathway.

Importantly, for 32–54% of NIS introductions across all known pathways at the Pan-EU level, the confidence level was either low or not assigned, except for the unaided pathway, for which 86% of introductions were assessed with a high or medium confidence level (Fig. 6, Table 2). More than 33% of the NIS introductions at Pan-EU level via Escape from Confinement, Release in Nature, Transport – Contaminant and Unaided pathways were assigned a high confidence level. In contrast, introductions via the Transport – Stowaway subcategories of ballast (TS-ball) and hull fouling (TS-hull) achieved high confidence levels for only 8% and 22% of the records, respectively.

Similarly, the assigned pathway confidence levels varied notably between the regional seas (Table 2, Fig. 7). As for the Pan-EU dataset, the unaided pathway received the highest proportion of high-confidence evaluations for introductions to the Mediterranean Sea, whereas the Transport–Stowaway subcategories of ballast water (TS-ball) and hull fouling (TS-hull) were associated with greater uncertainty. In the North-East Atlantic, TS-hull and TS-ball contributed substantially to NIS introductions. However, 37–47% of these records were either assigned a low confidence level or the confidence level was completely unassigned (NA). Remarkable uncertainties also characterised the pathways to the Baltic Sea. Only 41% of the introductions via Escape from Confinement and 7% via TS-hull were assigned high confidence levels, while none of the introductions through TS-ball had a high confidence level. In contrast, in the Black Sea there was greater certainty in assigning introductions to TS-ball and TS-hull, with respectively 36% and 50% of NIS assigned with high confidence. Meanwhile, only 22% of the Black Sea introductions attributed to unaided introductions had a high confidence level. The proportionally high uncertainties promoted closer scrutiny on only those NIS records with a high and medium confidence level for the pathway designation. The proportional contribution of the pathways changed remarkably when only NIS with high or high and medium confidence level pathway designations were displayed (Fig. 8). In particular, the UNA category represented most of the assigned pathways with a high confidence level, while TS-hull and TS-Ball pathways strongly declined.

4. Discussion

4.1. NIS introduction trends in the EU and its' regional seas

Even though several previous studies have evaluated NIS introductions to European Seas using various approaches (Korpinen et al., 2019), only Zenetos et al. (2022b) and Galanidi et al. (2023) provided a temporal analysis of new introductions over several decades. Building on earlier efforts (Tsiamis et al., 2019, 2021), these updates assembled extensive historical datasets on marine NIS introductions. However, because they followed the policy-recommended six-year assessment periods, their analyses and results were constrained by time-interval aggregations, limiting the capacity to evaluate continuous long-term trends across the entire time series.

The results of the current study demonstrated that increases in the rate of new NIS introductions have decelerated across Europe during the latter half of the 2010s. Similar signals were noted by Korpinen et al. (2019) and Zenetos et al. (2022b), who attributed the apparent slowdown to possible time lags in reporting or larger inter-annual variability. The fact that at least seven NIS – new to the North-East Atlantic Ocean – have been found in the Netherlands in 2022 and 2023 (Gittenberger, unpublished data; Vos et al., 2023; Knoop et al., 2024), supports these hypotheses. This elevates the total number of NIS in the North-East

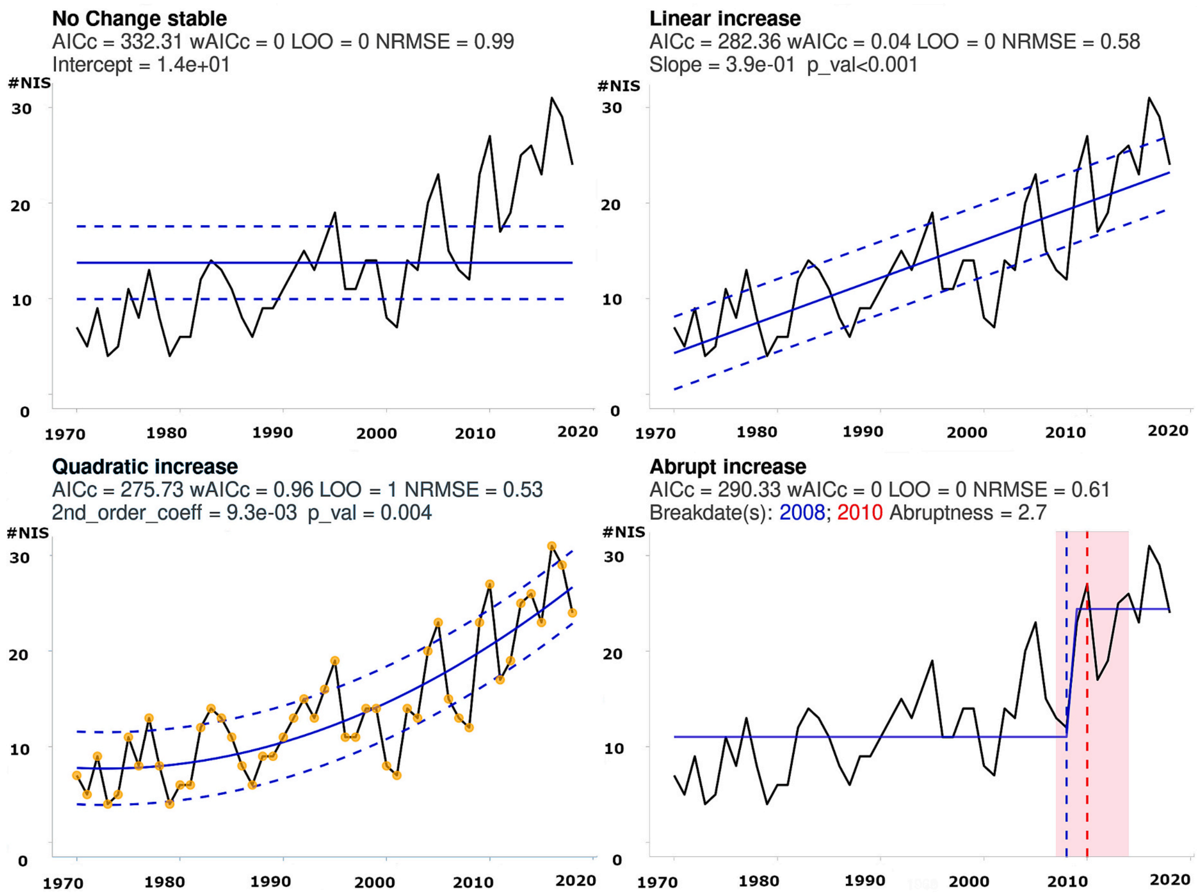

Fig. 3. The statistical time series analyses for the number of new NIS introductions per year at the Pan-EU level from 1969 to 2018. For the abrupt increase model, the blue-labelled year indicates an increasing breakpoint, whereas the red-labelled year indicates a decreasing breakpoint in the rate of new NIS introductions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Atlantic from eight (during 2018–2021) to fifteen in the next six-year assessment period (2018–2023). Considering additional reporting delays and potential new introductions in 2022 and 2023 in other countries, the decrease in new introductions likely represents an artefact resulting from reporting delays and not incorporating data from 2022 and 2023. Nevertheless, this example concerns only the North-East Atlantic, and it remains to be seen if the same occurs in other MSFD regions. While these explanations may hold true as datasets continue to be updated, it is equally plausible that introductions into European seas have genuinely decreased since the end of the last decade. Given that the data screening for this study was continued by the end of 2024, it would require a severe lag in reporting if tens of new NIS introductions ended up falling into the years of 2018–2021 in the future, suggesting that other drivers may explain the observed deceleration.

Zenetos et al. (2022b) proposed that the high rate of new introductions between 2000 and 2005 might reflect increased research effort. This hypothesis aligns with the breakpoints identified in the current study – 1996 in the Black Sea, 2003 in the Mediterranean Sea, 2007 in the Baltic Sea, and 2008 at the Pan-EU level and in the North-East Atlantic Ocean. It should be pointed out here that time series analysis at the Mediterranean Sea level and the eastern Mediterranean (including non-EU countries) has indicated an earlier time of abrupt increase in NIS introductions – during the mid-1990s (Galanidi and Zenetos, 2022). This may reflect introductions taking place in the eastern Mediterranean largely through the Suez Canal, with species taking several years to progress into EU waters. At the same time, the other three Mediterranean MSFD subregions (with far fewer differences between datasets) experienced significantly increasing breakpoints in new NIS introductions during 2000–2005 (Galanidi and Zenetos, 2022; UNEP, 2024), corroborating the findings of the current study. If increased scientific attention indeed explained these patterns, a slowdown after this ‘research peak’ should be expected at some point in time, since the majority of the information regarding new species arrivals from previous years was already gathered. Nevertheless, other potential reasons must be equally considered before making this conclusion. Changes in human activities associated with key pathways, such as shipping, aquaculture, and deliberate releases, may have influenced the introduction trends. In contrast, introductions via corridors or unaided dispersal are harder to assess because they are affected by indirect drivers such as climate change and NIS establishment into adjacent seas (Raitsos et al., 2010; Weterings et al., 2025). Global shipping volumes have more than quadrupled since 1970, and even the Covid-19 pandemic did not slow this trend down (UNCTAD, 2021). However, shipping volumes in the EU have remained relatively stable since 2008 (EC, 2024). Similarly, global aquaculture production increased fivefold between 1990 and 2010, whereas EU production has remained relatively stable since the 1990s (Tacon, 2020; Guillen et al., 2025).

Further, the assumption of growing research interest can be measured relatively easily by using the number of relevant research articles published over time. Although there are several platforms and keywords that can be used for literature searches, the research interest assumption was tested by using a simple search for “*Marine invasive species ‘OR’ Marine non-indigenous species ‘OR’ Marine non-native species*” in Web of Science (www.webofscience.com) online platform, and this was done separately for all years from 1975 to 2018 (1975 was the earliest year available) (Fig. 9). The number of published articles and

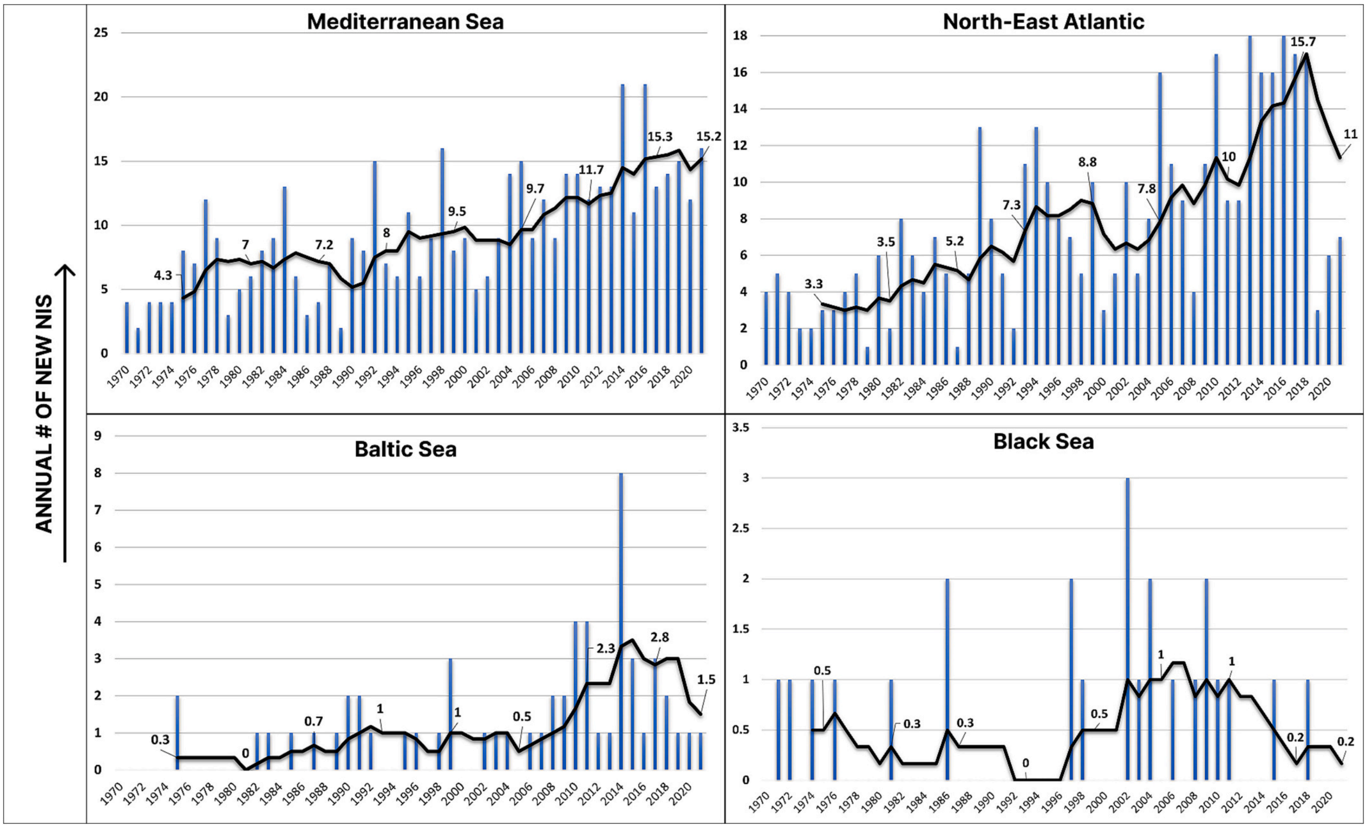

Fig. 4. The annual rate of new NIS introductions to European regional seas from 1970 to 2021. The blue columns represent the annual rates of new NIS, and the black line represents moving annual averages for all six-year periods across the study years. The data labels within the moving average refer to the last year of each fixed six-year assessment period provided by Tsiamis et al. (2021) with the exception that the most recent data labels are annual averages from a period of 2016–2021 (the most recent six-year assessment period available for this study). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

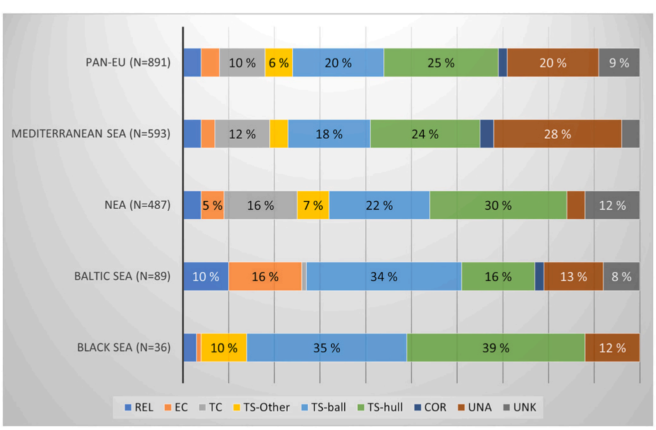

Fig. 5. Percentage contribution of introduction pathways into the EU and regional seas until 2021. REL – Release in Nature, EC – Escape from Confinement, TC – Transport Contaminant, TS – Transport Stowaway (divided into TS-ball, TS-other and TS-hull), COR – Corridor, UNA – Unaided, and UNK – Unknown. Data labels (% contribution) are provided only for the pathways that contributed ≥5% to the NIS introductions for each study region. NEA – North-East Atlantic Ocean.

documents increased remarkably in the early 2000s, and this increase only accelerated in the following years, suggesting that actual trends of new NIS to EU seas are difficult to assess because of this increased interest that has very likely affected the observed trends. Such a literature search or analysis could certainly be carried out in more detail (e.g., manually excluding non-relevant articles), but the results shown here inevitably reflect that research interest must have affected the number of newly detected NIS in Europe during this time. In addition, after conducting a time-series analysis to newly published articles with these keywords for 1975–2018 following the same methodology, quadratic trajectory was by far the best trajectory fit, as the number of articles started to increase notably in the early 2000s and accelerated ever since (Appendix B, Fig. B.1). Nevertheless, it is important to note that NIS introductions have not decreased in the long-term (e.g., in comparison to early 1900s), and marine areas are globally connected to one another via several human activities more than ever before, even though most of this anthropogenic connectivity appears to occur outside of Europe (as pointed in the previous paragraph).

A remaining unanswered question is – what caused this increased research interest? As mentioned in the introduction, there was not only a European-wide, but a global interest towards the impacts of marine NIS in the 1990s, after several introductions (Byrne et al., 1997; MacPhee, 2007) caused negative impacts. It is possible that the adverse effects of *M. leidyi*'s introduction into the Black Sea have accelerated the research interest in the area and the adjacent Mediterranean Sea, as shown by the current time series analyses with break dates of 1996 and 2003, respectively. The Baltic Sea and North-East Atlantic Ocean followed with break dates in 2007 and 2008, respectively, and at least in the Baltic Sea, this may be due to the arrival of the round goby (*Neogobius melanostomus*) and the fishhook water flea (*Cercopagis pengoi*) in the early 1990s, which, however, started spreading further in the Baltic years later (Ojaveer et al., 2015; Naumenko and Telesh, 2019; Rakauskas et al., 2020). Furthermore, *N. melanostomus* and *M. leidyi* first appeared in the North-East Atlantic Ocean in 2004 and 2005,

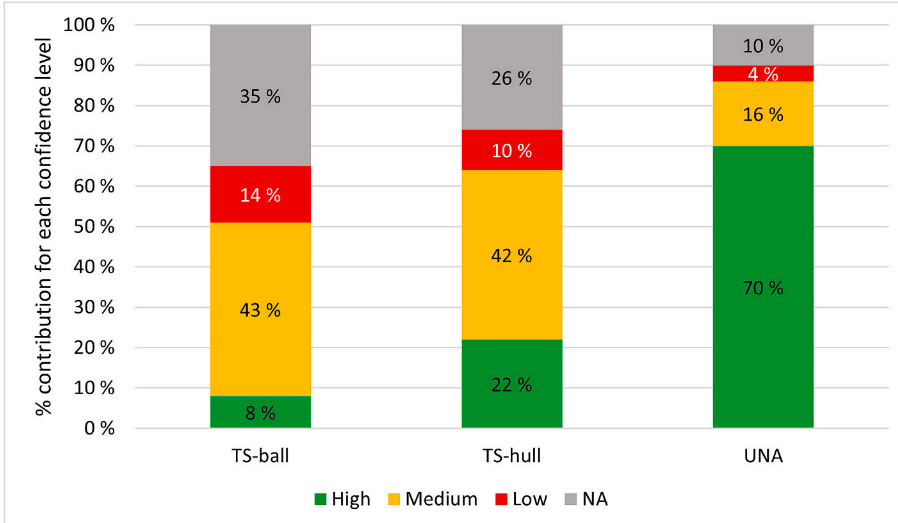

Fig. 6. Percentage contribution of each confidence level category regarding the three most prominent pathways at the Pan-EU level. TS-ball – Transport Stowaway, ballast water, TS-hull – Transport Stowaway, hull fouling, and UNA – Unaided. NA – confidence level for the introduction pathway was not assigned.

Table 2
Number of NIS (***n***) introduced to all study areas through each pathway until 2021, including the percentage for each confidence level assigned. The percentages of all introduced NIS and the associated pathway confidence levels (low, medium, high, NA) are presented in the table, whereas ***n*** refers to the total number of NIS assigned for each pathway. Note that most often ***n*** is not an integer as several pathways can be assigned for a NIS, thus one pathway per each introduction can represent only a fraction of all assigned pathways (see Methods). REL – Release in Nature, EC – Escape from Confinement, TC – Transport Contaminant, TS – Transport Stowaway (divided into TS-ballast, TS-other and TS-hull fouling), COR – Corridor, UNA – Unaided, and UNK – Unknown. NA – level of confidence for the pathway designation was not assigned.

Study area	Level of confidence	REL	EC	TC	TS-Other	TS-ball	TS-hull	COR	UNA	UNK
Pan-EU	High	42	34	35	26	8	22	28	70	0
	Medium	16	28	33	32	43	42	18	16	0
	Low	8	13	9	11	14	10	17	4	1
	NA	34	25	23	31	35	26	37	10	99
	n	**37.9**	**38.1**	**91.4**	**50.3**	**180.3**	**219.9**	**16.1**	**181.9**	**75**
Mediterranean Sea	High	32	15	23	5	4	12	25	75	0
	Medium	15	40	51	37	55	58	14	17	2
	Low	13	11	8	19	12	7	16	4	2
	NA	40	34	18	39	29	23	45	4	96
	Total	**23.6**	**18.9**	**69.7**	**22.7**	**105.7**	**141.4**	**17.7**	**170.2**	**23**
North-East Atlantic	High	30	49	40	43	15	31	0	0	0
	Medium	23	21	24	35	38	32	0	19	0
	Low	2	11	12	4	13	14	0	0	1
	NA	45	19	24	18	34	23	0	81	99
	Total	**16.8**	**26.5**	**75.3**	**35**	**108.3**	**146.8**	**0**	**20.7**	**57.5**
Baltic Sea	High	74	41	0	0	0	7	0	8	0
	Medium	10	37	100	0	43	40	25	51	0
	Low	12	8	0	100	21	18	25	16	18
	NA	4	14	0	0	36	35	50	25	82
	Total	**8.5**	**14.3**	**1**	**0.3**	**29.8**	**14.5**	**2**	**11.2**	**7.3**
Black Sea	High	100	100	0	0	36	50	0	22	0
	Medium	0	0	0	43	48	39	0	45	0
	Low	0	0	0	0	16	11	0	11	0
	NA	0	0	0	57	0	0	0	22	0
	Total	**1**	**0.5**	**0**	**3.5**	**12.5**	**14**	**0**	**4.5**	**0**

respectively, which may have increased research interest. Moreover, in 2009, it was discovered that the white colonial sea-squirts were found to be invading and smothering substrates not only in the North-East Atlantic, but also in New Zealand and North America, all concerning the same Northwestern Pacific species *Didemnum vexillum* (Stefaniak et al., 2009).

In addition, the increased research interest may have originated from the emergence of new environmental policies on NIS, which likely

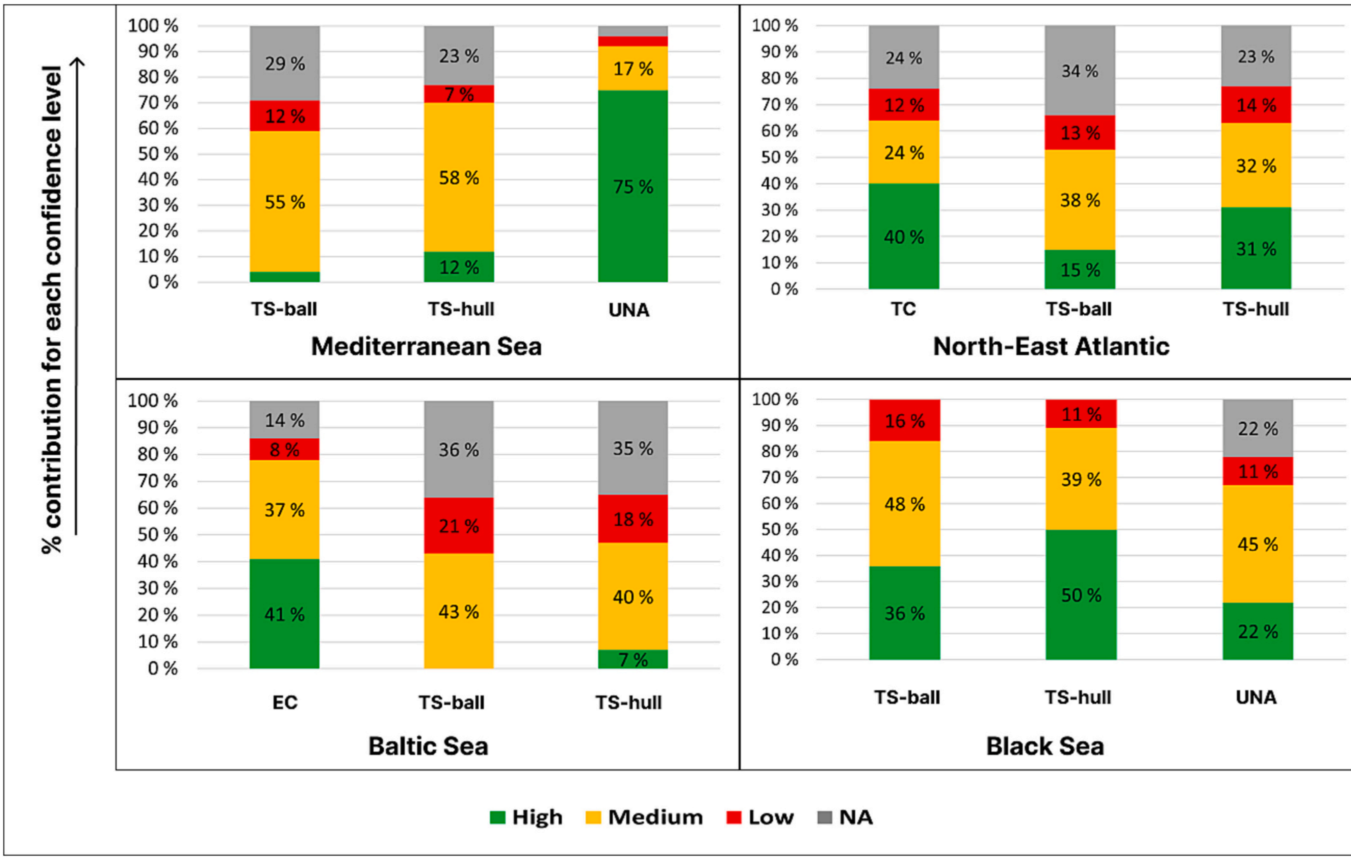

Fig. 7. Confidence levels for the most prominent NIS pathways into EU regional seas until 2021. TC – Transport Contaminant, TS-ball – Transport Stowaway ballast water, TS-hull – Transport Stowaway hull fouling, UNA – Unaided, and EC – Escape from Confinement. NA – level of confidence for the pathway designation was not assigned. Data labels (% contribution) are provided only for the confidence levels that contributed ≥5% for each of the presented pathway assessments.

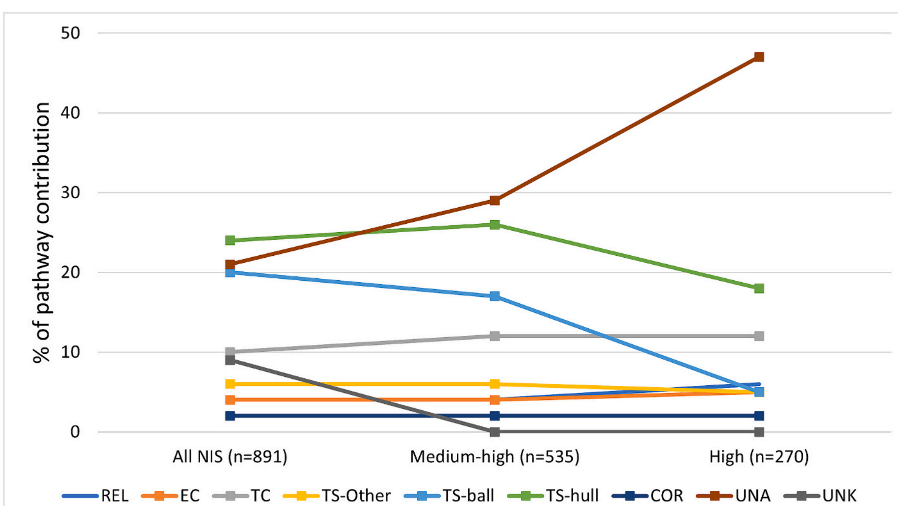

Fig. 8. Percentage contribution of introduction pathways into the EU for all NIS (left) compared to only those NIS with high or medium (middle), and only those NIS with high confidence level pathway designation (right). REL – Release in Nature, EC – Escape from Confinement, TC – Transport Contaminant, TS – Transport Stowaway (divided into TS-ball, TS-other and TS-hull), COR – Corridor, UNA – Unaided, and UNK – Unknown.

accelerated the research needs and thus research interests even further. As briefly described in the introduction, global and regional assessments, targets, regulations, and recommendations began to emerge in many places during the second half of the 20th century. Regional sea conventions in Europe, namely the Helsinki (HELCOM), Oslo-Paris (OSPAR), Barcelona, and Bucharest Conventions, were initiated in the 1970s to address marine pollution originating from land- and sea-based sources (Boyes and Elliott, 2014). Global policies quickly followed through the UN CBD (UNEP, 1994) and have continued ever since by setting goals via the Strategic Plan for Biodiversity 2011–2020 (Aichi targets), followed by the Kunming-Montreal Global Biodiversity Framework (UNEP, 2010, 2022). And as already described earlier,

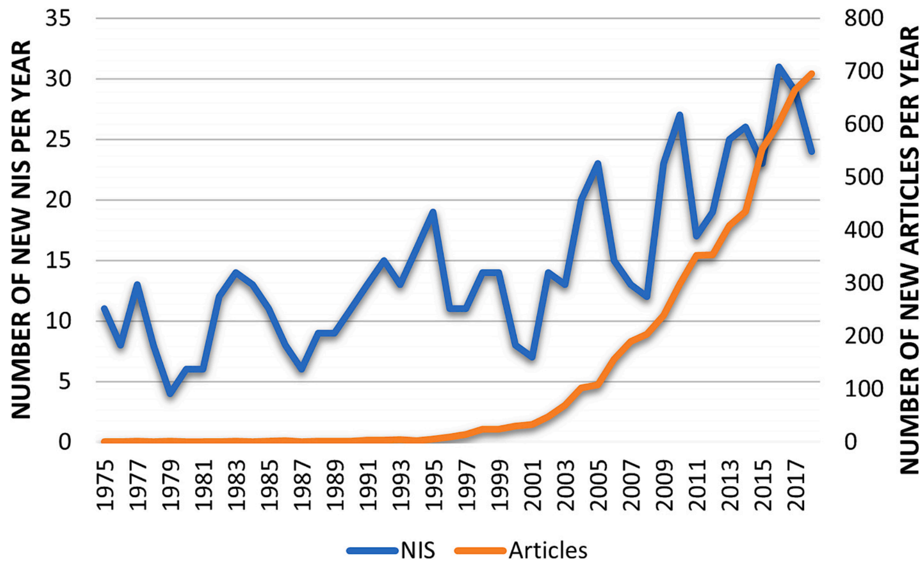

Fig. 9. The annual rates of new NIS introductions and published research articles from 1975 to 2018 using keywords "*Marine invasive species 'OR' Marine non-indigenous species 'OR' Marine non-native species*" in Web of Science online platform.

several EU regulations and policies emerging since the beginning of the third millennium equally promoted the improved monitoring efforts and research interests. For instance, global assessments of the impact of human activities on ecosystems and biodiversity pointed to IAS as one of the major drivers of biodiversity changes (e.g., IPBES, 2023). All these efforts explain the increasing focus on marine NIS. Simultaneously, all these efforts have undoubtedly affected the timeline of new NIS records and greatly improved our understanding of species introductions.

What does all this mean regarding marine invasions in the EU marine waters? The quadratic increase model was the most suitable fit for Pan-EU and North-East Atlantic Ocean datasets, linear increase fitted best for the Mediterranean Sea and Baltic Sea datasets, whereas the Black Sea experienced an abruptly increasing trajectory in new NIS introductions. Considering the accelerating increase towards the end of the time series for the Pan-EU and North-East Atlantic Ocean datasets, the impact of increased research and policy interests cannot be denied. Regional differences are inevitable, since the study areas are far from identical. Pan-EU, Mediterranean Sea and North-East Atlantic Ocean are relatively open and connected study areas, and the trends have remained smooth, regardless of the increased research and policy initiatives. Further, different subregions within the North-East Atlantic Ocean include distant Macaronesia archipelagos, and it is unclear how meaningful the assessment of this MSFD region as a single unit is, as some of the subregions within the region are far from connected regarding the natural distribution of marine species (Castro et al., 2022). Finally, even though the abrupt increase model provided the best fit for the Black Sea, the corresponding NRMSE value implies that 93% of the variance in the data remained unexplained by the model. This suggests that, despite being the best-fitting trajectory, the abruptly increasing trend exhibited only a relatively weak explanatory power for the dataset (Pélissié et al., 2024), perhaps due to the comparatively lower number of NIS than in other regions.

Altogether, the time series analyses did not reveal a common pattern regarding new NIS introductions for all regional seas, other than an increase was observed in all of them. In addition, several trajectories had similar AICc weight, NRMSE, and LOO values for the studied datasets, proposing that some of these trajectories were close to one another in terms of being the most suitable trajectory fits for the datasets. After all, the study areas have experienced increased anthropogenic connectivity contributing to new introductions, as well as elevated research and policy interests simultaneously – no wonder there is no common pattern to be found for these data. This finding indicates that it will remain challenging to set threshold values to evaluate good environmental status, as aimed for MSFD D2 (EC, 2017), since the previous assessments may not recover the true influx of new species but the increased research and monitoring efforts. However, this should not be an insurmountable challenge if a mandatory and standardised monitoring program for marine NIS is implemented on the European continent. Future threshold values and indicators could be linked to new monitoring procedures, eventually enabling assessments on the effects of potential management actions on NIS pathways (Olenin et al., 2016).

4.2. NIS pathways to European seas

The outcomes of this study indicate that the Transport Stowaway pathway, with 51% (25% TS-hull, 20% TS-ball, and 6% TS-other) and unaided introductions with 20% have contributed most to new NIS introductions to EU seas. The contribution of other pathways was proportionally smaller at a Pan-EU level. Previous studies have assessed NIS pathways to European seas, and some of them are more than ten years old (Katsanevakis et al., 2013; Nunes et al., 2014; Korpinen et al., 2019). Nevertheless, similar outcomes have been detected by those studies. The significant contribution of shipping has been identified by Katsanevakis et al. (2013) with 51.9%, Nunes et al. (2014) with 43.9%, and Korpinen et al. (2019) with 43.7%, as well as by Dobrzycka-Krahel and Medina-Villar (2023) in a more recent regional study from the Baltic Sea region. A notable difference between the earlier pan-EU studies and the current study is the proportional contribution of the corridor pathway, since it contributed significantly to new introductions in the previous studies but not in the present analyses. This is mainly due to the Mediterranean Sea introductions, where the Suez Canal has been assessed as a significant pathway for many NIS introductions in the non-EU countries within the Mediterranean Sea. However, when the study area includes only EU waters (current study), most of these introductions fall under the unaided category since these species were introduced to the non-EU waters of the Mediterranean Sea through the Suez Canal and then spread unaided to the adjacent EU waters. The remaining pathways have been slightly differently categorised by Katsanevakis et al. (2013) and Nunes et al. (2014), but they resulted in similar proportional contributions as in the current study.

Comparable results were detected from the regional sea datasets. As mentioned in the previous paragraph, unaided was the most contributing pathway to the Mediterranean Sea with 28%, followed by hull fouling (24%) and ballast (18%). Again, the contribution of other pathways was minor. Overall, the Mediterranean Sea is experiencing heavy propagule pressure of new NIS arriving via multiple human-mediated pathways and vectors. The most recent regional study by Galanidi et al. (2023) recorded more than a thousand new NIS in the Mediterranean Sea (including non-EU waters), with the majority of the new introductions being first recorded in the Eastern Mediterranean Sea. The North-East Atlantic Ocean has been experiencing the second-highest pressure from new NIS introductions within the EU. The absence of man-made corridors in the region can be seen from the results, and TS pathway dominated with 59% (30, 22, and 7% for TS-hull, TS-ball, and TS-other, respectively), followed by transport – contaminants with 16% contribution of all introductions. Although regional studies encompassing the entire North-East Atlantic Ocean have not been recently published with pathway analyses, the present findings align closely with the patterns reported by Nunes et al. (2014), who highlighted shipping and aquaculture as the dominant pathways for most countries in the region. A similar trend is also evident for Portugal, where recent analyses further reinforce the prominence of these same pathways (Ribeiro et al., unpublished data).

Shipping vectors showcased a proportionally high number of new NIS introductions to the semi-enclosed regional EU seas of the Baltic Sea and Black Sea, with 50% and 84%, respectively. Nevertheless, other notable NIS introduction pathways to the Baltic Sea included escape from confinement (16%), unaided introductions (13%), and release in nature (10%), whereas known introductions via corridors and transport-contaminants were minor. The Baltic Sea results are well in line with the most recent regional assessment (Ojaveer et al., 2017) that identified shipping having a smaller contribution, and stocking and unaided introductions a higher contribution to NIS introductions in comparison to the current study. The study by Ojaveer et al. (2017) included cryptogenic species in the analyses, which may explain the differences in the results regarding the number of NIS and pathways. For the Black Sea, a high proportion (84%) of new NIS introductions was assigned to the TS pathway, followed by unaided introductions (12%), and the contributions of the rest of the pathways were remarkably smaller. Similar findings have previously been reported for the region by Băncilă et al. (2022), who equally identified strong contributions by the TS pathway.

4.3. Uncertainties and levels of confidence

Sources of uncertainty in the present study primarily relate to the included NIS records and pathway confidence levels. Many taxa have questionable origins and may arrive via unknown or non-anthropogenic pathways to the EU waters, making it challenging to exclude some or all of them from the assessment. The decision to dismiss some groups, such as phytoplankton, follows earlier methodologies, but may bias the analysis results. Although some of these records may fall outside the MSFD scope, they may ultimately influence the ecosystem in undesirable directions, forcing member states to take evasive measures regardless of the pathways.

Pathway assessments have been done to aquatic NIS introductions in European seas utilising various spatial assessment levels and pathway categorisations (Katsanevakis et al., 2013; Nunes et al., 2014; Ojaveer et al., 2017; Băncilă et al., 2022; Galanidi et al., 2023). Further, studies by Katsanevakis et al. (2013), Ojaveer et al. (2017), and Băncilă et al. (2022) have provided estimates on the levels of confidence or uncertainty regarding the pathways.

The current study highlighted that the TS pathway and each of the three TS subcategories suffer from notable uncertainties regarding the confidence level assigned at all regional scales. At best, a high level of confidence (direct evidence) was identified for 50% of the NIS introduced into the Black Sea via TS-hull fouling. In regions outside of the Black Sea (that have many more introductions in total), the highest proportion of NIS with direct evidence supporting a TS pathway was recorded for TS-other in the North-East Atlantic Ocean, accounting for 43%. In contrast, all other TS pathway designations across the study regions exhibited even lower levels of confidence, highlighting the general paucity of direct evidence linking NIS introductions to specific TS vectors. The TS vectors had particularly low confidence levels in the Baltic Sea, where direct evidence was identified only for 7% of the new NIS arrivals via hull fouling and none via ballast. However, other study regions rarely had direct evidence of new NIS introductions via ballast either. These findings outline a concerning outlook regarding sampling and monitoring of ships and other vessels. Although shipping vectors are widely acknowledged as major contributors to the new NIS introductions in European Seas, direct empirical evidence supporting high contribution by shipping-related vectors remains scarce. This lack of direct evidence primarily reflects the current limitations of harmonised, long-term monitoring frameworks, which are explicitly designed to capture NIS from ships and other vessels within European waters. The BWMC entered into force in 2017, but it appears that the practical implementation of this legislative instrument is very much a work in progress on the European continent. Further, TS-Hull, an important pathway subcategory in our dataset is not managed at all by the BWMC, or any other legally binding instrument.

Direct evidence was not commonly detected for the other pathways either in the current study. Only unaided introductions to the Mediterranean Sea were assigned with a strong level of confidence (75% and 17% assessed with high and medium confidence level, respectively), likely due to NIS introductions via the Suez Canal that have since spread further unaided (Galanidi et al., 2023). Aquaculture-related pathways (REL, EC, and TC) did not contribute to the majority of new NIS detected in the current study, but these pathways had occasionally relatively high confidence levels. For example, 74% of the NIS released in nature in the Baltic Sea had a high level of confidence. Similarly, 49% and 21% of the NIS that had escaped from confinement in the North-East Atlantic Ocean had a high and medium level of confidence, respectively. Outside of these examples, the level of confidence tends to vary deeply among low, medium, and high designations for most of the pathways and study regions, and it is also common that levels of confidence have not been assigned at all (NA designation). It is understandable that a level of confidence is not assigned for historical NIS introductions, but even a low level of confidence can be assigned for a pathway using grey literature, suspicion, and ruling out other pathways where possible (Pergl et al., 2020). Therefore, this conclusion suggests that there is no uniform protocol to assign a confidence level for NIS pathways across the EU, and expert judgement still plays a significant role in this process.

Some of these uncertainties may be due to NIS that have been potentially simultaneously introduced by several distinct human activities over time. This phenomenon – described as polyvectism by Carlton and Ruiz (2005) – refers to NIS that have been continuously introduced to new areas via several pathways and vectors. This aspect was quickly visited by dividing the number of pathway designations by the number of NIS for each confidence level to obtain a ratio for the number of pathways per NIS. It appeared that medium and low confidence levels were particularly vulnerable to polyvectism, as the number of pathways per NIS ratio ranged between 1.62:1–1.87:1, and 1.8:1–2.11:1 for medium and low confidence levels, respectively, across all study regions. For a high confidence level, the ratio ranged from 1.12:1 to 1.14:1 for the Pan-EU, Mediterranean Sea and North-East Atlantic datasets, but was higher for the Baltic Sea (1.54:1) and Black Sea (1.36:1) NIS. This positive relationship between the confidence levels regarding pathways and polyvectism makes sense – in the absence of evidence of a single pathway, different possible pathways are proposed. A high proportion of these NIS in the current study likely reflect to the uncertainty where the true pathway is unknown, and multiple possible pathways have been assigned, but some of these NIS have also been likely introduced truly by several pathways simultaneously (true polyvectism). Understanding these aspects from the data provides clarity on the importance of polyvectism as it appears in the assessment, as pathway information may affect decision-making processes when new and targeted control measures on distinct pathways or vectors are proposed.

5. Conclusions

Aquatic NIS have been increasingly introduced to European seas throughout the 20th and early 21st centuries. The increase in new NIS introductions was observed in all regional seas from the end of the 1990s, and this increase has continued, particularly in the Mediterranean Sea and the North-East Atlantic Ocean, until the late 2010s. The results of the present study indicate that the observed annual rates of new NIS introductions have started to decrease after 2018 – new NIS introductions are still being recorded in all EU seas, but less than before. Although some of the more recent NIS arrivals are probably genuine records that have been recorded soon after their arrival, it is equally likely that this outcome is partially due to the increased research interest and policies regarding marine invasions, together with significant improvements in molecular detection techniques. This increased interest was particularly evident since the early 2000s, leading to an accelerated increase in NIS detections, and such acceleration can be expected to saturate to some degree over time. The shipping vectors were shown to be responsible for the most introductions into EU seas, but there are still remarkable uncertainties hindering effective pathway assessments. Many assessments rely heavily on circumstantial or indirect evidence, such as species distribution patterns, life-history traits, or historical shipping routes, and there are truly no other choices to conduct these assessments unless direct monitoring of vectors is significantly improved. This evidentiary gap highlights the need for more systematic and targeted surveillance efforts in European seas, particularly involving ballast water and ship hull inspections to strengthen causal linkages and improve the accuracy of pathway attributions in marine bioinvasions research. This effort is critical to initiate preventive measures on vectors and pathways, the only truly effective management approaches for marine systems. Therefore, improved harmonisation of NIS pathway assessments across the EU is increasingly necessary. Finally, even though the pathway classification methodology by Pergl et al. (2020) was provided five years ago, there is clearly a need to implement this or some other approach more efficiently among EU Member States and their national experts to improve future pathway assessments.

CRediT authorship contribution statement

Okko Outinen: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Data curation, Conceptualization. **Peter A.U. Stæhr:** Writing – review & editing, Validation, Data curation. **Romeu S. Ribeiro:** Writing – review & editing, Writing – original draft, Validation, Data curation. **Aina Carbonell:** Writing – review & editing, Validation, Data curation. **Robert Comas-González:** Writing – review & editing, Validation, Data curation. **Lydia Png-Gonzalez:** Writing – review & editing, Validation, Data curation. **Maite Vázquez-Luis:** Writing – review & editing, Validation, Data curation. **Ann-Britt Florin:** Writing – review & editing, Validation, Data curation. **Rahmat Naddafi:** Writing – review & editing, Validation, Data curation. **Arjan Gittenberger:** Writing – review & editing, Validation, Data curation. **Hans Jakobsen:** Writing – review & editing, Validation, Data curation. **Ana C. Costa:** Writing – review & editing, Validation, Data curation. **Manuela I. Parente:** Writing – review & editing, Validation, Data curation. **Branko Dragičević:** Writing – review & editing, Validation, Data curation. **Jakov Dulčić:** Writing – review & editing, Validation, Data curation. **Slavica Petović:** Writing – review & editing, Validation, Data curation. **Martina Orlando-Bonaca:** Writing – review & editing, Validation, Data curation. **Borut Mavrič:** Writing – review & editing, Validation, Data curation. **Cátia Bartilotti:** Writing – review & editing, Validation, Data curation. **Jorge Lobo-Arteaga:** Writing – review & editing, Validation, Data curation. **Miriam Tuaty-Guerra:** Writing – review & editing, Validation, Data curation. **Frédérique Viard:** Writing – review & editing, Visualization, Validation, Methodology, Data curation, Conceptualization. **Cécile Massé:** Writing – review & editing, Validation, Data curation. **Luca Castriota:** Writing – review & editing, Validation, Data curation. **Silvia Livi:** Writing – review & editing, Validation, Data curation. **Marika Galanidi:** Writing – review & editing, Validation, Data curation. **Argyro Zenetos:** Writing – review & editing, Validation, Methodology, Data curation, Conceptualization. **Natacha Carvalho:** Writing – review & editing, Validation, Data curation, Conceptualization. **João Canning-Clode:** Writing – review & editing, Validation, Data curation. **Paola Parretti:** Writing – review & editing, Validation, Data curation. **Patrício Ramalhosa:** Writing – review & editing, Validation, Data curation. **Nuno Castro:** Writing – review & editing, Validation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Time-series analyses for the Mediterranean Sea (Fig. A.1), North-East Atlantic Ocean (Fig. A.2), Baltic Sea (Fig. A.3), and Black Sea (Fig. A.4).

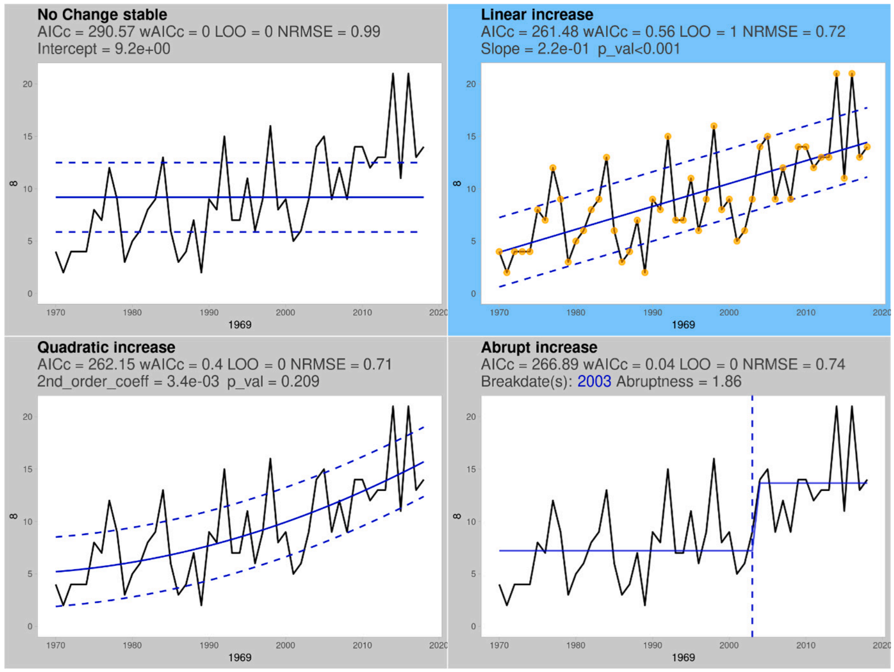

Fig. A.1. Results of the statistical time series analyses for new NIS introductions annually from 1969 to 2018 into the Mediterranean Sea. For the abrupt increase model, the blue-labelled year indicates an increasing breakpoint in the annual rate of new NIS. The number of new NIS per year is expressed on the y-axis, while the assessment years (datapoints from 1969 to 2018) are presented on the x-axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

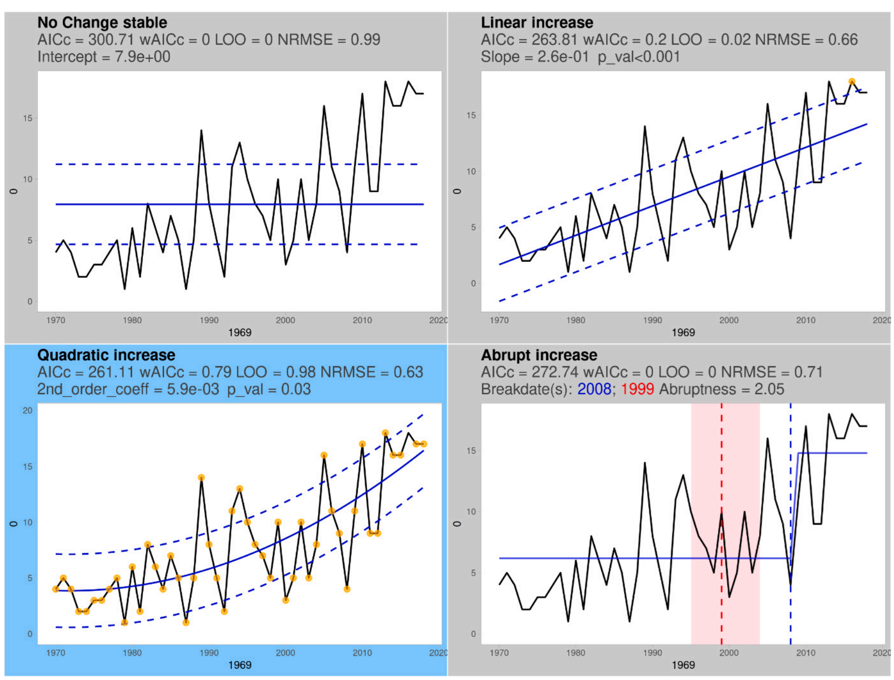

Fig. A.2. Results of the statistical time series analyses for new NIS introductions annually from 1969 to 2018 into the North-East Atlantic Ocean. For the abrupt increase model, the blue-labelled year indicates an increasing breakpoint in the annual rate of new NIS, whereas the red-labelled year indicates a decreasing breakpoint. The number of new NIS per year is expressed on the y-axis, while the assessment years (datapoints from 1969 to 2018) are presented on the x-axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

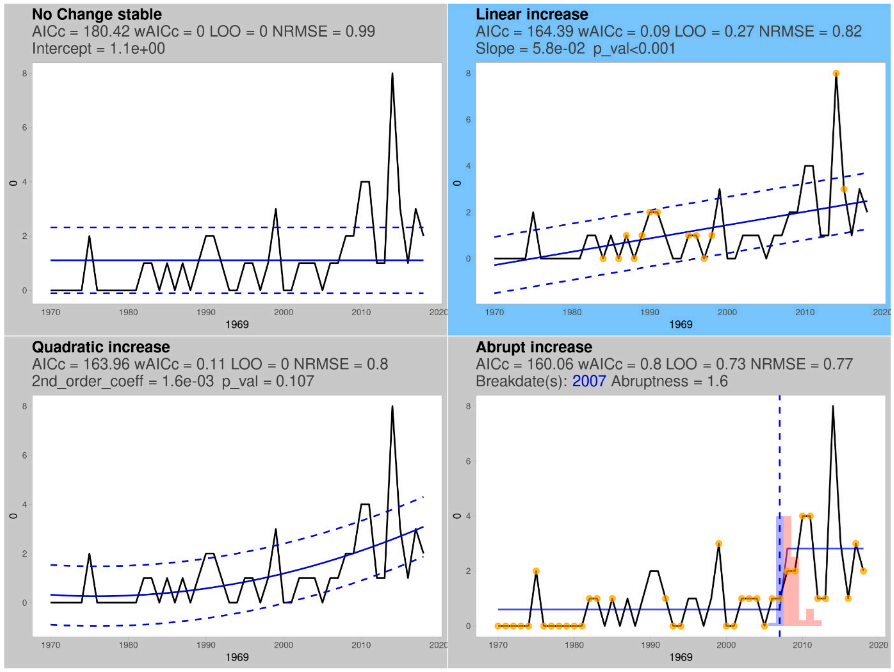

Fig. A.3. Results of the statistical time series analyses for new NIS introductions annually from 1969 to 2018 into the Baltic Sea. For the abrupt increase model, the blue-labelled year indicates an increasing breakpoint in the annual rate of new NIS. The number of new NIS per year is expressed on the y-axis, while the assessment years (datapoints from 1969 to 2018) are presented on the x-axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

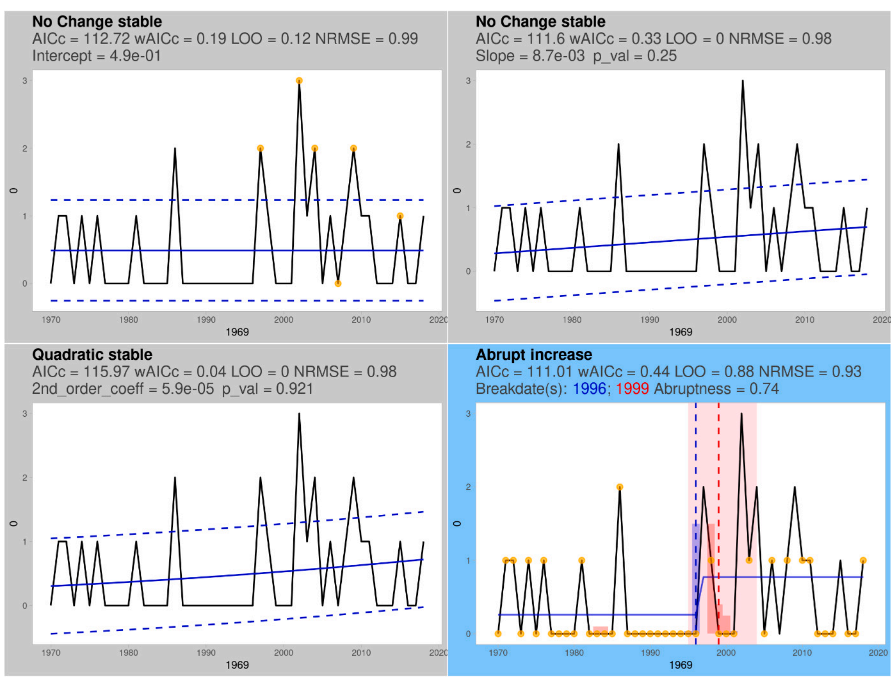

Fig. A.4. Results of the statistical time series analyses for new NIS introductions annually from 1969 to 2018 into the Black Sea. For the abrupt increase model, the blue-labelled year indicates an increasing breakpoint in the annual rate of new NIS, whereas the red-labelled year indicates a decreasing breakpoint. The number of new NIS per year is expressed on the y-axis, while the assessment years (datapoints from 1969 to 2018) are presented on the x-axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Appendix B

Time-series analysis for newly published articles during 1975–2018 (Fig. B.1).

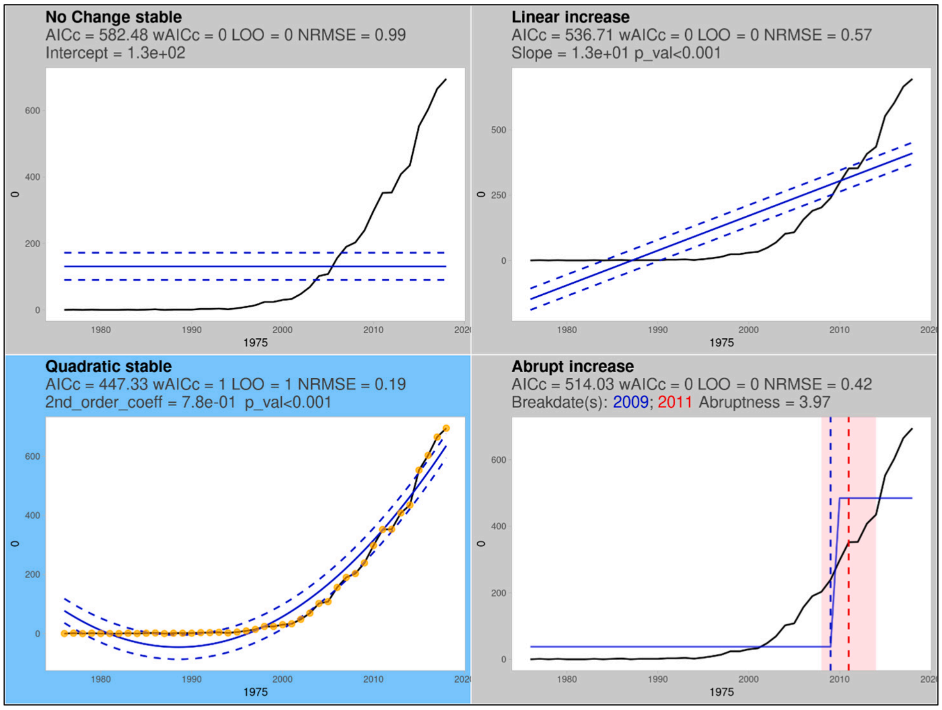

Fig. B.1. Results of the statistical time series analysis for newly published articles from 1975 to 2018 using keywords "*Marine invasive species 'OR' Marine non-indigenous species 'OR' Marine non-native species*" in Web of Science online platform.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2026.119407.

Data availability

Data shared as supplementary materials.

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