



Universal framework for assessing the environmental impact of marine non-indigenous species in different situations of data availability

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Abstract Current methods for assessing the environmental impacts of marine non-indigenous species (NIS) are limited by insufficient data, an over-reliance on expert judgement and too coarse a spatial resolution, which hampers accurate local management. However, advances in data-driven analyses offer

significant potential for developing more comprehensive and accurate frameworks for assessing the impacts of NIS in marine ecosystems. This study fills this major gap in NIS management by proposing a comprehensive and practical framework that integrates systematic reviews, meta-analyses, species distribution modelling, and expert judgement to assess NIS impacts across varying levels of information availability. The framework also recommends complementary, under-utilised data sources, and tools to reduce significantly existing information constraints. The framework presented in this study not only advances scientific understanding of NIS impacts by providing a scalable and adaptable framework for assessing NIS impacts in different ecological contexts, but also provides practical tools for environmental managers implementing legislation on NIS. We recognise that although our data-driven approach to NIS management is best handled by specialists, maximising its potential requires making the information accessible and user-friendly to a broader audience. This can be achieved through digital tools that simplify and facilitate the understanding of these assessments for environmental managers.

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State of play on environmental impact assessment of marine non-indigenous species

The introduction of non-indigenous species (NIS) is recognised as one of the major global threats to marine biodiversity. NIS can significantly alter both biotic and abiotic ecosystem components, affecting important ecosystem functions, such as carbon and nutrient cycling, storage and sequestration, productivity, or habitat provision (e.g. Katsanevakis et al., 2014; Anton et al., 2019; Ojaveer et al., 2023). Ultimately, these changes can lead to dramatic regime shifts in ecosystems (Guy-Haim et al., 2018). These threats call for an assessment framework that thoroughly examines a wide range of NIS impacts on marine ecosystems, considering the complex interactions between biological communities and the physical–chemical environments they inhabit (Rilov et al., 2024).

Numerous methods have been proposed to quantify the environmental impacts of NIS, leading to the development of different impact assessment frameworks (Parker et al., 1999; Olenin et al., 2007; Kulhanek et al., 2010; Thomsen et al., 2011; Catford et al., 2012; Ricciardi et al., 2013; Blackburn et al., 2014; Ojaveer et al., 2015; Gallardo et al., 2016; González-Moreno et al., 2019; Corrales et al., 2020). While a detailed and exhaustive review of the myriad approaches for assessing the environmental impacts of NIS is beyond the scope of this paper, it is important to highlight the Environmental Impact Classification for Alien Taxa (EICAT) developed by Blackburn et al. (2014). This framework, further refined by Hawkins et al. (2015) and later endorsed by the International Union for Conservation of Nature (IUCN, 2020), has emerged as the most thorough and widely applicable method for assessing the environmental impacts of NIS. Although widely applied in terrestrial ecosystems, the application of this framework in marine ecosystems is stymied by a lack of knowledge and data on marine NIS, rendering the framework impractical for most marine taxa (Ojaveer et al., 2015). The EICAT assessment framework requires a wide range of information on impacts available for each NIS, including individual fitness, population size, community structure, and reversibility of impacts across a range of spatial and temporal scales. While the evaluation of these impacts relies primarily on published reports and studies providing concrete

quantitative evidence, the results are typically presented on a nominal scale with uncertainty analyses being qualitative. Consequentially, the development of a robust framework to assess quantitatively the impact of NIS in marine ecosystems under varying knowledge and data availability remains a challenging and elusive goal, particularly given the requirements of the European Union's Marine Strategy Framework Directive (MSFD), which mandates reporting on the impacts of NIS (European Commission, 2017). Likewise, the need to assess the environmental impacts of NIS is accentuated by key policy frameworks and legal treaties, including the United Nations Convention on the Law of the Sea (United Nations, 1982), the Convention on Biological Diversity (United Nations, 1992), and the International Convention for the Control and Management of Ships' Ballast Water and Sediments (IMO, 2004). In assessing the impact of NIS in different contexts, frameworks for action need to be adaptive and comprehensive. While various impact assessment protocols exist, such as those using numerical tools to assess NIS impacts and explore management options (González-Moreno et al., 2019), the need remains for innovative and flexible methodologies.

We are witnessing an era characterised by rapid increases in data and knowledge on the environmental impacts of NIS, which overwhelms the ability of experts to access and objectively assess these diverse data sources. Improving the quality of management decisions requires a shift from reliance on expert judgement to data-driven analysis or models. This transition entails the integration of all available information within a coherent analytical framework. Global models should evolve from examining the impacts of NIS on specific processes to understanding their overarching effects on the structure and functioning of marine ecosystems.

A promising approach to synthesising the quantitative impacts of NIS is through systematic reviews and meta-analyses of published scientific evidence (Ruiz et al., 1999; Katsanevakis et al., 2014; Guy-Haim et al., 2018; Anton et al., 2019). This approach allows for the provision of comprehensive syntheses that improve the identification of overarching trends in the impacts of NIS, deepen our understanding of the underlying processes and drivers, and identifying gaps in knowledge. When data are scarce or unevenly distributed for different NIS, the use of systematic

reviews with meta-analysis becomes particularly crucial. This approach could involve progressively extending search terms to include related geographical areas and species/groups, thereby compensating for local or sub-regional data deficiencies. This process requires a well-defined protocol to ensure a systematic, comprehensive, and transparent assessment of the impacts of NIS for different degrees of information availability.

A major limitation of NIS impact assessments is a lack of spatial detail (Corrales et al., 2020) or, when available, the tendency to use overly coarse spatial resolution, such as at the scale of whole seas or major sub-basins of regional seas (e.g. Ojaveer et al., 2023). Given that management initiatives are often local and therefore implemented at much finer spatial scales, for example through maritime spatial planning, it is essential to refine the spatial resolution of NIS impact assessments. Conversely, a wide range of spatial mapping techniques can combine species monitoring data with environmental proxies to predict the distribution of target species, including NIS, within a given area (Robinson et al., 2017; Qazi et al., 2022). This wealth of distributional data, coupled with advanced spatial modelling techniques, allows NIS impact models to incorporate a spatial dimension into their assessments, thereby enhancing their relevance and utility.

Assessment approaches and methodologies need to be tailored to the availability of data and information for different components of the marine ecosystem. For example, commercial fish stocks in the North Atlantic are categorised into six main groups based on available knowledge, which can be divided into two broad types: data-rich and data-limited stocks (ICES, 2023). Methodologies are also being developed to comply with various EU legislative instruments and policies, including the MSFD and the European Union's Restoration Action Plan on protecting and restoring marine ecosystems for sustainable and resilient fisheries (European Commission, 2023). These methodologies will complement the existing 'data-rich approach' by addressing data-limited situations, with the aim of accurately assessing bycatch of endangered, threatened, and protected species (ICES, 2024).

Based on the above considerations, this study developed a practical approach to assess the impact of NIS in marine ecosystems. The approach expands on Parker et al. (1999) basic equation, which takes

into account the area occupied, abundance, and per capita impact of NIS. Recognising situations where evidence of effects is limited or non-existent (Ojaveer et al., 2021, 2023), the proposed framework is designed to improve the versatility of Parker et al. (1999) equation by being robust to varying levels of data availability while retaining effectiveness in assessing ecological impacts. The framework combines systematic reviews and meta-analyses with species distribution modelling in data-rich scenarios and uses assessments of expected ecological impacts based on expert judgement and sparse distribution data in data-poor situations. This framework is tailored to address the challenges posed by possibly substantial time lags in the collection of evidence on impacts (Ojaveer et al., 2021). By alleviating existing deficiencies, the framework aims to provide the most accurate spatially explicit impact assessments possible within the constraints of limited data and knowledge, thereby improving our understanding of NIS impacts and supporting more informed management policy.

Practical method for quantifying the environmental impact of NIS

Assessing the spatial and quantitative impacts of NIS is compromised by the magnitude of impact mechanisms involved and the frequency of knowledge gaps. The process of quantifying the environmental impacts of NIS often relies on expert-based rankings (e.g. Blackburn et al., 2014). However, the accumulation of scientific evidence on impacts, advances in spatial modelling techniques, and the increasing quantity and accessibility of open-source datasets should allow assessment to change from qualitative, expert-based assessments to more quantitative assessments (Corrales et al., 2020).

The proposed framework stems from the seminal model by Parker et al. (1999), which is known for its simple yet effective approach to quantifying NIS impacts in marine ecosystems. The Parker et al. model includes the basic equation:

$$I = R \times A \times E$$

where the ecological impact (I) is expressed as the product of the distribution range (R), abundance (A), and per capita effect (E) of a NIS. This model, which

has undergone various adaptations and comparisons in subsequent studies (see review in Thomsen et al., 2011), provides a standardised metric that facilitates quantitative comparisons between and within sites.

Distribution range and abundance ($R \times A$)

Although information on the spatial distribution of species has become increasingly available for mapping and monitoring campaigns, these data are rarely used in the impact assessment of NIS. Regional or national data repositories often provide public access to maps showing the probability of occurrence or abundance of species including NIS. These maps are also frequently published in open-access journals. Even when maps of a specific species are not yet unavailable—possibly due to recent introductions or the occupation of species in habitats not regularly monitored—efficient methods exist to produce such maps. Species distribution modelling (SDM) involves correlating the presence or abundance of a species with spatial habitat data. These models map the probability or abundance of a species occurring within a landscape. SDM relies on open-access mapping and monitoring data on new species (e.g. the Ocean Biogeographic Information System (OBIS) portal at <https://obis.org/>) integrated with seamless maps of environmental variables available in regional repositories, most of which are model-derived (e.g. <https://marine.copernicus.eu/access-data>). In addition, a wide range of spatial modelling techniques allow species monitoring data to be associated with environmental proxies to predict the distribution of target species in the region of interest. In particular, recent advances in SDM have incorporated machine learning techniques, such as MaxEnt, Boosted Regression Trees (BRT), and Random Forest (RF) (Robinson et al., 2017; Qazi et al., 2022).

While a comprehensive overview of the vast field of species distribution modelling is beyond the scope of this study, numerous tutorials are available to help select the most appropriate method for specific needs. However, NIS modelling needs to distinguish between presence-only modelling and traditional SDM, which relies on both the presence and absence of data of species. NIS observations often record only NIS presences without providing sites where NIS species are absent, which leads to data bias. This bias necessitates the use of specific presence-only

modelling techniques such as MaxEnt (Elith et al., 2020; Valavi et al., 2022). Presence-only modelling is particularly appropriate for recently introduced species that may not yet occupy all potential niches in a region. Conversely, traditional modelling techniques are appropriate for long-established NIS that are likely occupy all suitable habitats and have stable distributions. Although SDM is a correlative approach and provides limited insight into species ecology (Lee-Yaw et al., 2022), it remains a valuable tool for conservation and management strategies, regardless of the quality of the underlying data. SDM produces comprehensive information that would otherwise take years to accumulate.

The proposed framework is based on the spatial information on abundance or probability of occurrence of NIS. When such information is not readily available, the framework advises using the aforementioned data sources and modelling approaches to predict the probability of occurrence or abundance of NIS within the region of interest. Spatial distribution models provide both the range (R) and abundance (A) of species within each modelled grid cell. Consequently, the Parker et al. (1999) equation can be simplified to include a single term that includes both R and A (as outlined below). Estimates of NIS abundance or probability of occurrence must be complemented by precision estimates. These estimates allow the calculation of confidence intervals for the estimated environmental impacts of NIS.

Per capita effect (E)

The explicit definition of the per capita effect, E , which recognises the multiple impacts of NIS is crucial to the framework. The proposed framework advocates the use of systematic literature reviews and meta-analyses covering a wide range of geographical and taxonomic scope as reliable methods for quantifying these effects.

Previous studies (e.g. Ojaveer et al., 2021) indicate that the number of publications on the ecological impacts of even the most widespread NIS in well-studied seas remains surprisingly low, making the overall evidence base vulnerable to biases, such as taxonomic and spatial biases. However, impact data need not be gleaned solely from scientific publications. Other sources of verified and properly documented information and data, such as cruise reports

and datasets from spatial mapping campaigns, environmental monitoring programmes, and research surveys, can provide applicable information, even if these sources are not designed specifically to monitor the effects of NIS. These sources may include other confounding human pressures, whose confounding effects can be distinguished from the effects of NIS by well-established data models (see, e.g. Nõomaa et al., 2022). The proposed framework recommends integrating impact data from both systematic literature reviews and standardised and verified datasets into combined meta-analyses to alleviate existing data limitations in assessing the impacts of NIS. In particular, all European Union countries are required to comply with directives such as the Water Framework Directive and the MSFD. The monitoring programmes associated with these directives generate extensive quantitative data over large geographical areas, diverse habitats, and a broad range of taxonomic groups including the abundances of both native and non-indigenous species. In addition, numerous mapping campaigns associated with surveys for nature conservation and the blue economy also contribute valuable data. These monitoring and mapping datasets, often well harmonised and aggregated in regional data repositories such as the ICES database and EUROBIS, provide a resource from which the impacts of NIS can be evaluated. The proposed framework allows for flexibility in data-poor situations, allowing for the expansion of search terms to include broader regions and groups, and even the use of expert judgement in the absence of empirical impact data. Furthermore, the above approach indirectly facilitates the clarification of the often ambiguous relationship between abundance and impact, particularly for data-rich settings (Yokomizo et al., 2009; Kulhanek et al., 2010).

Hedges' g is commonly used standardised measure of effect size in meta-analysis, because it enables comparisons from different studies, regardless of scale or units of measurement. It also adjusts for small sample bias, thereby improving the precision and reliability of aggregated results, which is particularly beneficial when integrating data from studies with heterogeneous sample sizes (Hedges and Olkin, 1985). Given these advantageous characteristics, Hedges' g is used in the proposed framework to estimate the global effect of the NIS.

When derived effect sizes are not available for all NIS under assessment due to data limitations, the proposed framework recommends impacts to be estimated by using expert-driven methods. Traditional expert-based methods designate impact by semi-quantitative scores ranging from very low to very high. In the proposed framework, experts are asked to estimate quantitatively the expected magnitude of change in nature value due to the presence of a NIS, specifically how it affects target species, habitats, or ecosystem processes. This approach allows expert judgements to be fully aligned with traditional meta-analytic methods and enables the calculation of expert-driven Hedges' g . However, as the proposed framework integrates scientific literature with monitoring and mapping datasets, reliance on expert input may be necessary for very rare or low abundance NIS. However, differing backgrounds and prior experience of the experts can significantly influence the assessment results. The disparity can be mitigated by assessing the variability of opinion among experts by which to determine an appropriate number of experts that minimises the confidence interval of the effects. As a rule of thumb, no fewer than five experts should be involved in the assessment of each alien species.

Hedges' g statistic typically takes into account the effects of whole samples, which can range from one to many individuals, providing a measure of the overall group effect rather than the effect on an individual basis. Because the per capita effects of NIS need to be estimated in the proposed framework, the standard formula for Hedges' g requires modification. This modification involves calculating the effect size based on changes per individual, rather than aggregate changes across groups.

The framework formulae

The original Hedges' g formula is as follows (Hedges and Olkin, 1985):

$$g = \frac{\bar{Y}_i - \bar{Y}_C}{SD_{pooled}} J$$

where \bar{Y}_i and \bar{Y}_C are the mean estimates of a response variable measured in impact and control treatments, SD_{pooled} is the pooled standard deviation of the two

groups, and J is the small sample size correction. The SD_{pooled} is calculated as:

$$SD_{pooled} = \sqrt{\frac{(n_i - 1)SD_i^2 + (n_c - 1)SD_c^2}{n_i + n_c - 2}}$$

where n_i and n_c are the sample sizes, and SD_i and SD_c are the standard deviations of impact and control treatments, respectively.

The small sample size correction J is calculated as:

$$J = 1 - \frac{3}{4(n_i + n_c - 2) - 1}$$

To adapt Hedges' g for the proposed framework, mean differences per capita are calculated by dividing the differences in means by the number of individuals (or other relevant units if necessary), using a pooled standard deviation that reflects variability across individuals rather than groups, and applying the standard Hedges' g formula to these mean differences per capita, thereby standardising the effect size relative to changes at the individual level rather than the group level.

The raw per capita difference between the experimental (treatment) and control groups is calculated as follows:

$$\text{Raw Per Capita Difference} = \frac{\bar{Y}_i - \bar{Y}_c}{a_i}$$

where \bar{Y}_i and \bar{Y}_c are the mean estimates of a response variable measured in impact and control treatments and a_i is the number of individual organisms (or other relevant units) of NIS. The pooled standard deviation of the two groups (SD_{pooled}) is calculated as above and the modified Hedges' g , which applies the standardisation to the per capita difference ($g_{per\ capita}$), is obtained as follows:

$$g_{per\ capita} = \frac{\text{Raw Per Capita Difference}}{SD_{pooled}} J$$

The small sample size correction J is calculated as above. This modified approach integrates the per capita consideration into the effect size calculation, providing a standardised measure that can be interpreted more directly in ecological or experimental contexts.

The proposed framework allows for a spatially explicit assessment of the environmental impacts of NIS, with the spatial resolution determined by the grid size used in the spatial modelling. To assess the overall ecological impact of a NIS, the proposed framework includes the basic equation:

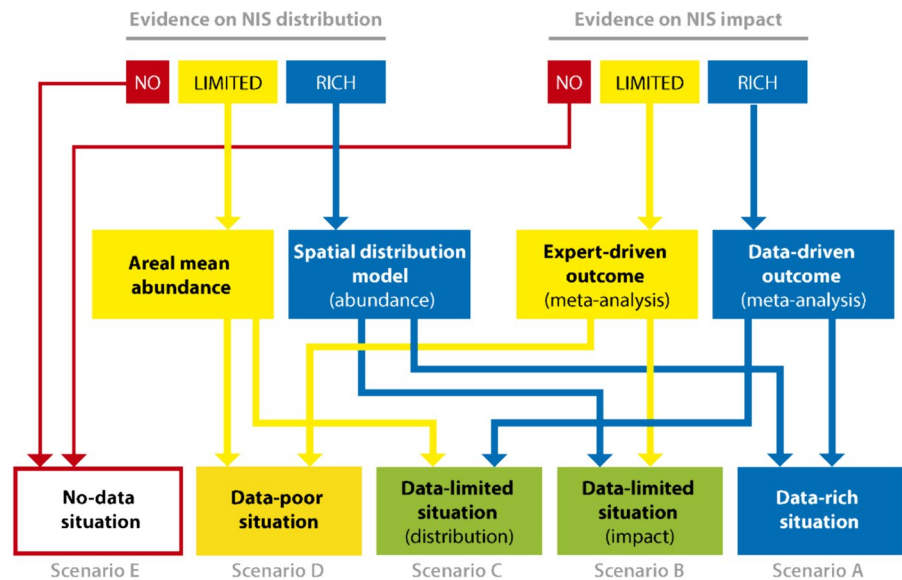
$$I_{ij} = A_{ij} \times g_{per\ capita\ j}$$

where I_{ij} represents the ecological impact of non-indigenous species j in each grid cell i within the target area. A_{ij} denotes the normalised abundance of species j in each grid cell i and $g_{per\ capita\ j}$ is the Hedges' g effect size standardised to per capita difference for species j . Spatial modelling produces regional maps of species abundance (see above), and normalisation entails dividing the abundance values in each grid cell by the regional maximum. This process ensures that a value of 0 indicates the absence of the species and a value of 1 represents the maximum regional abundance. Normalisation is crucial as it allows comparability among species that vary naturally in abundance due to intrinsic characteristics such as size. When abundance data are unavailable, the probability of occurrence can be used as an alternative.

The five-tier assessment scale

The framework can be used five different levels of data availability (Fig. 1): (A) Data-rich scenario, in which comprehensive quantitative data on NIS impacts (e.g. Hedges' g) and the seamless maps of NIS abundance are available, offers an opportunity to integrate meta-analysis with species distribution to derive spatially explicit evidence of impacts. The process involves multiplying the per capita effect size by the normalised species abundances, or by the probability of occurrence in cases where abundance data are unavailable. (B) Data-limited scenario (lack of impact information) in which seamless maps of NIS abundance are available but expert judgement is needed to assess the per capita effect of NIS. In this scenario, the per capita effect size is determined by expert judgement in which the expected magnitude of change in nature value estimated by the experts serves as input data to calculate Hedges' g . (C) Data-limited scenario (absence of seamless NIS maps) in which

Fig. 1 This decision tree outlines different pathways within the NIS impact assessment framework, determined by the availability of data and information. The diagram also details the specific actions required at different stages of data management



quantitative data on the impact of NIS are available but the amount of distribution data is insufficient to produce abundance maps. In this scenario, the per capita effect size is multiplied by the average abundance derived from observations over the whole area, implying that NIS impacts lack spatial variability. (D) Data-poor scenario, in which seamless maps of NIS abundance and impact data are unavailable, impacts must be inferred using expert judgement to estimate the per capita impact of NIS, or by analysing the impacts of similar species. This inference is made using meta-analysis with more flexible criteria. Similar to the previous scenario, this approach uses the average abundance of the NIS and assumes a uniform impact across the study area due to a lack of information on species distribution. (E) No-data scenario, in which abundance information is unavailable or impact assessment through expert judgement is not feasible. This situation often occurs with newly introduced NIS or in remote and under-researched areas.

Expressing uncertainty

In assessing the uncertainty associated with impact assessments, deviation in both effect size estimates and predicted abundances (or probabilities of occurrence) should be integrated. To do so, the framework

uses the following expression based on Taylor series expansion (Taylor and Kuyatt, 1994):

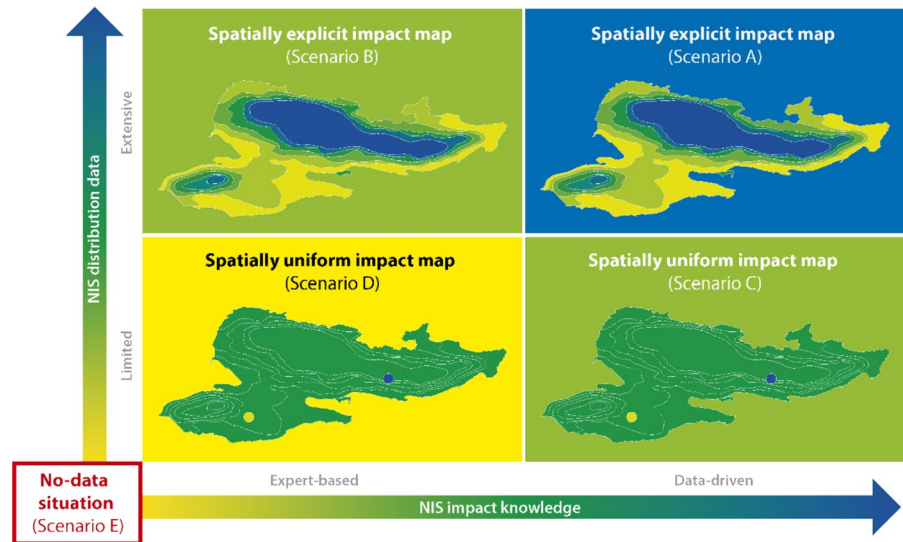
$$SE_{pooled} = \sqrt{p^2 SE_{effect}^2 + effect^2 SE_p^2}$$

where p and SE_p are the estimated abundance (or probability of occurrence) and its standard error, and $effect$ and SE_{effect} are the estimated per capita effects sizes and the associated standard error (Fig. 2).

Framework significance and future directions

The proposed assessment framework facilitates fully quantitative, spatially explicit environmental impact assessments of NIS under different scenarios of data and information availability, reflecting real-life situations. These assessments are achieved by integrating spatial distribution data into a common meta-analysis framework. In addition, the framework provides practical solutions to improve significantly the knowledge base of NIS distribution and impact evidence and provide guidance on the collection and incorporation of expert opinion in data-poor situations to better align with meta-analytic methods. By using recommended data sources, including scientific papers, standardised and verified datasets from monitoring and

Fig. 2 This schematic diagram presents the framework scenarios along gradients of available impact and distribution data and illustrates the detailed outcomes of each scenario



mapping inventories, regional data repositories, and analytical tools such as meta-analysis and spatial distribution models, reliance on expert judgement is minimised and generally reserved for cases involving very rare or low abundance NIS.

Currently, our knowledge of the dispersal and establishment of NIS is considerably more developed than our understanding of their environmental impacts (e.g. Ricciardi et al., 2013). In addition, the current mechanistic understanding of how the unique or universal attributes of invaded habitats—such as resource levels, abiotic conditions, or characteristics of the resident biota—interact with and influence the impact of NIS remains limited (e.g. as discussed in Thomsen et al., 2011). By implementing the proposed framework, existing limitations in understanding the ecological impacts of NIS on invaded ecosystems and how environmental attributes modulate these impacts can be substantially alleviated. Practical constraints often limit the number of factors and interactions in published experiments, leaving many potential interactive effects unexplored. In contrast, standardised and verified monitoring and mapping datasets typically include a wide range of habitat attributes and information on human pressures. Aggregating multiple regional datasets, such as OBIS, opens possibilities to assess the associations between different habitat features, human

pressures, and their influence on the relationships between NIS and resident species.

Information sources, methodological considerations, and reducing biases

In situations when the effects of NIS vary spatially and are influenced by local abiotic habitat characteristics rather than species abundance, and when such effects have been extracted from databases as described in the framework, it is possible to integrate the covariates that influence the intensity of impacts into the modelling framework. In particular, as impact data accumulate and new observation technologies become available, metaregressions (Crystal-Ornelas, 2020) in data-rich scenarios are emerging as a promising tool for accurate assessment of NIS impacts in water bodies with pronounced environmental gradients. Data limitations are less of an issue in this approach because seamless maps of habitat characteristics for SDM (e.g. salinity or bottom substrate) are readily available or can be accessed from regional data repositories such as Copernicus (<https://marine.copernicus.eu/access-data>) or EMODnet (<https://emodnet.ec.europa.eu/geoviewer/>). These portals also provide up-to-date digital maps of human pressures.

The proposed framework modifies Hedges' g effect size to assess the per capita impact of NIS. As impact data become more abundant, more complex data models can be applied. For example, the

original Hedges' g formula can be applied, followed by regressing effect sizes on NIS abundance. This method allows the assessment of an appropriate abundance-driven response curve and improves the prediction of the per capita effect of NIS. However, if the sample size is small, model-based extrapolation may greatly overestimate or underestimate effects and is therefore not recommended.

Data- and model-driven assessments of the environmental impacts of NIS are considered more robust than traditional expert-based assessments. The proposed framework provides practical tools for carrying out these quantitative assessments, adapted to the realities of data and information availability in marine ecosystems. Although initially more time-consuming, the framework approach becomes increasingly more efficient because the accumulation of distribution data and evidence of impacts allows assessments to be updated more rapidly. In addition, data-driven assessments provide more accurate results, independent of the background and number of the experts engaged. Expert-based assessments can be biased if based on a limited number of studies conducted in specific contexts. Such assessments often miss critical contextual details that are better captured by data-driven methods. Efforts to capture contextual details from primary studies and regional data repositories are critical but are more effectively used in data-driven methodologies than in subjective scoring systems that categorise impacts into broad confidence levels such as high, medium and low, with no associated confidence values.

Experts can exhibit significant differences in how impacts are different conceptualised, highlighting the need for clear protocols to minimise serious expert bias. To avoid this bias, the proposed framework recommends broadening the scope of systematic literature and dataset searches, either by expanding geographically or by including a wider range of species (e.g. researching all species within the same genus rather than focusing on a single species). This strategy allows impact assessments to be made using primary data that may have been collected in different contexts or on related species. Ultimately, this approach increases the effectiveness of data use by adapting to the limitations inherent in specific research scenarios.

The EICAT classification assesses the effects of NIS but tends to neglect their presence and abundance (Blackburn et al., 2014). However, both aspects

are important as the expected impact of NIS in a given region is proportional to their effect size and the spatial extent of their distribution. Meta-analytic studies, such as Thomsen et al. (2011), have shown that the abundance of a NIS determines the magnitude of its impact across different species and habitats. Therefore, all impact studies must include information on abundance to facilitate comparisons among studies. The proposed framework addresses this critical aspect by including both the per capita impact of NIS and their abundance. When assessing the spatially explicit environmental impacts of NIS in a target area, impacts can occur only in areas colonised by a given NIS.

The EICAT classification identifies six impact mechanisms—herbivory, competition, predation, disease transmission, hybridisation, and other ecosystem effects such as chemical, physical, or structural changes (Blackburn et al., 2014). Information on all these mechanisms must be provided to assess properly the potential impacts of NIS. Due to the wide variety of mechanisms by which NIS interact with ecosystems, it is not feasible to report all possible impacts along different mechanisms. Therefore, the practical framework should focus on those impacts that are relatively more severe. More severe effects are often published in the scientific literature, while less significant effects remain unpublished (Yang et al., 2023). This bias also applies to NIS (e.g. Ricciardi, 2007). Because the proposed framework is flexible in terms of the sources of information used and relies solely on the availability of data and knowledge, it is unlikely to omit important information.

Informing management

The availability of evidence on the impacts of NIS is crucial for assessing environmental status and informing management at multiple levels and spatial scales, from local to international. Of particular relevance is Descriptor 2 (non-indigenous species) of the EU MSFD, for which there is no common operational framework for impact assessment, although some proposed indices exist (e.g. Olenin et al., 2007; Outinen et al., 2024). MSFD D2 Criterion 2, which focuses on the '*Abundance and spatial distribution of established non-indigenous species, particularly of invasive species, contributing significantly to adverse effects on particular species*

groups or broad habitat types', and Criterion 3, which addresses the '*Proportion of the species group or spatial extent of the broad habitat type which is adversely altered due to non-indigenous species, particularly invasive non-indigenous species*' (European Commission, 2017), both directly benefit from the framework we have developed. Unfortunately, member states are left without clear guidance on the data requirements and common methodologies to be applied for the assessment of D2C2 and D2C3 (European Commission, 2022). The proposed framework assists in filling in such critical gap by providing a practical approach to integrating information and knowledge from meta-analyses and spatial modelling, allowing assessments to be made at management-relevant spatial scales.

In addition, the availability of robust information on NIS impacts is critically important in the context of several other recent policies and legislations, such as EU Biodiversity Strategy for 2030 with the key commitment of '50% reduction in the number of Red List species threatened by invasive alien species' (European Commission, 2021). Information on the impacts of NIS is also required to meet the objective of 'preventing the introduction of, controlling or eradicating those alien species that threaten ecosystems, habitats or species' as set out in the Convention on Biological Diversity (United Nations (UN), Biological Diversity, 1992). More importantly, the proposed framework not only provides guidance for managing different scenarios based on different levels of information availability, but also recommends the use of complementary sources of information (e.g. standardised and verified datasets from monitoring and mapping inventories) and tools (e.g. spatial distribution models). These currently under-utilised resources can significantly mitigate such information limitations. Furthermore, the widespread application of the proposed framework, together with such additional data extraction, would also allow for the strengthening of the NIS impact section of European regional seas assessments, e.g. the holistic assessments of the Baltic Sea performed by HELCOM (2023) and incorporate NIS into ecosystem-based management approaches.

Future opportunities

Maximising the management value of the established framework requires that the information used (such as spatial maps and effect sizes of NIS) is accessible and understandable to an audience beyond the scientific community and presented in an easy-to-use format. Digital tools offer a practical solution to facilitate such complex assessments and render them user-friendly for environmental managers. Web-based tools such as PlanWise4Blue are central to this effort (Kotta et al., 2020; <https://gis.sea.ee/bluebiosites/>). While currently focused on the Baltic Sea region, PlanWise4Blue has the potential to be extended to other areas. PlanWise4Blue links species distribution maps of NIS with their predicted impacts on different nature values using a meta-analytic approach, allowing comprehensive spatial assessments of the environmental impacts of NIS on different nature values in a region. Currently, the portal uses different calculation methods to those used in the current framework, but integration of the current framework's approaches is planned for the near future. Looking ahead, we aim to develop standardised AI models that can automatically extract numerical data from scientific publications and/or open-access datasets and dynamically integrate this information into digital tools, thereby reducing the time gap between paper publication and management application.

The application of the proposed framework extends beyond the assessment of the environmental impact of NIS and allows evaluation of effects on specific habitats, such as the pelagic or benthic realms, or specific nature values such as water quality, biodiversity, and habitat integrity.

Conclusions

The introduction of NIS poses a significant threat to marine biodiversity, altering both biotic and abiotic components of ecosystems and affecting key functions such as carbon and nutrient cycling, productivity, and habitat provision. Various frameworks have been developed to assess the environmental impact of NIS, with the Environmental Impact Classification for Alien Taxa (EICAT) emerging as a thorough method, although its application in marine ecosystems is limited by knowledge and

data availability. The increasing amount of data on NIS impacts and new analytical techniques require a shift from expert judgement to data-driven analysis that integrates all available information into a coherent framework to improve management decisions.

Considering the above-mentioned methodological limitations and the newly available analytical capacities, this paper proposed a comprehensive and practical framework for quantifying the environmental impacts of NIS in marine ecosystems. The framework effectively bridges the gap in current methodologies by integrating systematic reviews, meta-analyses, and species distribution modelling to assess NIS impacts under different data availability scenarios. The proposed framework also recommends complementary, under-utilised data sources, and tools to reduce significantly existing information limitations. This approach is particularly valuable in addressing the challenges posed by data limitations and the need for spatially explicit impact assessments. The framework developed in this study not only advances scientific understanding of NIS impacts by providing a scalable and adaptable framework for assessing NIS impacts in different ecological contexts, but also provides practical tools for environmental managers and policy makers. We recognise that while our complex, data-driven approach to NIS is best managed by specialists, maximising its management value requires making the information—such as spatial maps and effect sizes—accessible and user-friendly to a wider audience through digital tools that simplify and facilitate the understanding of these assessments for environmental managers.

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Data availability This article contains no raw data.

Declarations

Competing interests 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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