Research Article

Harmonizing risk scores for alien freshwater and brackish molluscs

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Abstract

In Northwestern Europe, effective management of alien freshwater and brackish water molluscs requires timely and comparable information on their invasion status and potential impacts. By harmonizing various types of risk scores from existing risk assessments, this study provides an up-to-date overview of the invasion status and impacts of invasive and potentially invasive molluscs in the Netherlands, with relevance for Northwestern Europe as a whole. We compiled a comprehensive list of 70 species, including 27 already established in surface waters, 41 present in the aquarium and water gardening trade, and two additional species included based on their invasive history in surrounding countries. Based on climate matching, 30 species are likely able to survive in the wild in Northwestern Europe. For 29 of these 30 species with a climate match, a total of 130 published risk assessments from 19 sources were available and harmonized to enable comparison among species. These assessments primarily address impacts on biodiversity and ecosystems, but also consider human health and the safety of infrastructure. Harmonization showed that 16 species pose a high risk, 9 a medium risk, and 4 a low risk. While harmonization provides an efficient way to synthesize existing risk information, differences among assessment protocols and the types of risks considered can lead to inconsistencies. Overall, this study supports more consistent and timely risk evaluations and provides a robust basis for prioritizing alien mollusc species for management.

Key words: harmonization of risk scores, horizon scanning, introduction pathways, alien species, risk scanning, bivalves, aquatic snails

Introduction

In spite of their slow movements, molluscs can disperse rapidly via multiple pathways and vectors (Kappes and Haase 2012). In Europe, the number of alien fresh- and brackish water mollusc species has increased steadily, particularly since the late twentieth century (Seebens et al. 2017, 2021). Unless stated otherwise, the term "molluscs" refers to freshwater and brackish water snail and bivalve species throughout this study. In the Netherlands, at least 27 alien mollusc species have already been recorded in surface waters since 1826 (Meeuse and Hubert 1949; Gittenberger et al. 1998; Stichting ANEMOON 2022; Waarneming.nl 2022).

Alien fresh- and brackish water molluscs are introduced through multiple pathways, including ballast water and hull fouling, as well as through intentional or accidental introductions associated with the aquarium and water gardening plant trade (Madsen and Frandsen 1989; bij de Vaate et al. 2002; Holeck et al. 2004; Leuven et al. 2009; Kappes and Haase 2012; Collas et al. 2017). Additional pathways include escape when used as bait and transport on wetsuits, angling equipment, or boat overland transport via trailers (Counts 1986; Rosa et al. 2011; van Leeuwen et al. 2012a, 2013; Collas et al. 2018, 2021). Following introduction, species may spread further through secondary spread, which includes both natural dispersal and unintentional human-mediated distribution within hydrologically connected waterways, (larval) drift, attachment to plants and wildlife or internal transport in and passage through animal guts (Kappes and Haase 2012; van Leeuwen and van der Velde 2012; van Leeuwen et al. 2012a, b, 2013; Therriault et al. 2013). Together, these pathways have resulted in an increasing pool of alien mollusc species that are either already established or may establish in the near future, highlighting the need for timely assessment of their potential risks.

Fresh- and brackish water molluscs influence nutrient cycling, modify habitat structure, and alter food webs both directly (e.g. through grazing, filtering, predation and prey interactions) and indirectly (e.g. via benthic–pelagic coupling of nutrients and energy) (Vaughn and Hoellein 2018; Atkinson et al. 2023). Once established, alien molluscs can strongly affect biodiversity and ecosystem functioning. For example, the quagga mussel *Dreissena rostriformis bugensis*, now widespread in the Netherlands, acts as a biological filter of algae, pathogens and suspended solids, potentially improving water clarity and quality (Dionisio Pires et al. 2005; Waajen et al. 2014; de Hoop et al. 2015; Matthews et al. 2015). At the same time, it illustrates invasive impacts through overgrowth of hard substrates and hydraulic infrastructure, shifts in fish species composition, increased competition for food, and starvation and mortality of native freshwater bivalves (Unionidae) caused by attachment with byssus threads (Therriault et al. 2013; de Hoop et al. 2015). Like other dreissenid mussels, it can also clog cooling systems and pump stations and negatively affect public health, fisheries and recreation (MacIsaac et al. 1992; Wong et al. 2010; de Hoop et al. 2015). In this study, the term invasive is used for alien species whose introduction or spread causes, or is likely to cause, harmful ecological, economic, or social impacts (EU Regulation 1143/2014; Verbrugge et al. 2016). These examples illustrate that alien molluscs can pose substantial and diverse risks, underscoring the importance of identifying which species are most likely to cause harmful impacts.

Although the number of records of alien fresh- and brackish water molluscs in Northwestern Europe are increasing, information on the establishment of viable populations and their potential ecological, socio-economic and infrastructural impacts remains fragmented. The present study focuses on the Netherlands as the primary area of concern, but the results are also relevant for Northwestern Europe climatic similarity among countries, allowing meaningful comparison of invasion risk across multiple countries. In the Netherlands, three official standardized risk assessments and distribution studies have been conducted for freshwater species, i.e. for apple snails (*Pomacea* spp.), the quagga mussel (*D. rostriformis bugensis*), and the Chinese mystery snail (*Cipangopaludina chinensis*) (Gmelig Meyling and van Lente 2013; de Hoop et al. 2015; Collas et al. 2017). In addition, several detailed risk assessments have been performed for alien mollusc species in other European countries. However, an up-to-date and comprehensive overview of available risk assessments for alien fresh- and brackish water molluscs in Northwestern Europe is lacking. To address this gap, this study brings together existing risk assessments to provide a coherent overview of invasion status and potential impacts across a broad range of alien mollusc species.

Risk screenings, also referred to as horizon scanning, aim to identify and prioritize species that are, or may become, invasive within an area of concern, thereby supporting timely preventive or management actions. Such screening are typically based on expert judgement or on the application of a single risk assessment protocol (Parrott et al. 2009; Roy et al. 2015; Matthews et al. 2017c; Verbrugge et al. 2019; Vilizzi et al. 2021; Cano-Barbacil et al. 2023). In this context, horizon scanning refers to the early identification and prioritization of species that are, or may become, invasive within an area of concern, supporting timely preventive or management actions where area-specific assessments are lacking. Recent screening-level risk assessment (SLRA) studies, such as the CMIST-based evaluation for Quebec (Guerin et al. 2025), illustrate how multiple non-indigenous species can be rapidly prioritized across regions. In contrast, our study synthesizes existing assessments through harmonization of heterogeneous risk scores to enable consistent cross-species comparisons. However, existing risk information is often dispersed across studies using diverse methodologies, making direct comparison across species difficult. Moreover, compiling and validating information from multiple data sources and expert judgements across many species and regions remains labour-intensive (Faulkner et al. 2014; Matthews et al. 2017a). Applying harmonization approaches offers a potential solution by enabling synthesis of heterogeneous risk assessments while retaining their original information content.

Reusing existing risk assessments provides an efficient alternative to conducting new assessments for all species, but meaningful comparison is complicated by the wide variety of assessment tools currently in use worldwide (Roy et al. 2018; Srėbalienė et al. 2019). Matthews et al. (2017a) proposed a harmonization framework for continental scale risk screening that enables synthesis risk assessments derived from different scoring systems. However, this harmonization framework has not yet been systematically applied to a single taxonomic group to evaluate both the benefits and challenges of harmonizing methodologically diverse risk assessments.

Building on this framework, the present study applies the harmonization method of Matthews et al. (2017a) to existing risk assessments for alien fresh- and brackish water molluscs in Northwestern Europe with a focus on the Netherlands. Specifically, the study aggregates risk assessments per species, provides a comprehensive overview of ecological and socio-economic risks and identifies potentially invasive mollusc relevant for regional prioritization. Identifying feasible management options is considered a supporting outcome of this prioritization exercise rather than a primary objective. Accordingly, this study addresses the following research questions:

1. Which alien fresh- and brackish water molluscs have been introduced and established in Northwestern Europe or can be expected to arrive in the near future?
2. What ecological and socio-economic risks do these alien mollusc species pose, and how are these risks evaluated across different risk assessment?
3. What are the advantages and challenges of harmonizing existing, methodologically diverse risk assessments?

Materials and methods

We conducted an extensive literature review and used data from surveys of alien fresh- and brackish water molluscs in Europe. The risk screening focused on alien fresh- and brackish water snails and bivalves occurring in, or expected to reach, inland waters in the Netherlands. The primary focus was the Netherlands, but the results are also relevant for surrounding countries and other regions with similar climatic and habitat conditions and introduction pathways. Unless stated otherwise, the term "molluscs" in this study refers to freshwater and brackish water bivalve and snail species.

Data collection

We performed literature searches in search engines "Google", "Google Scholar" and "Web of Science" using the scientific names of all assessed species (Supplementary material Table S2) following the taxonomic classification and nomenclature in MolluscaBase (2022). Each species name was combined with the following set of search terms "*species name*", "*species name* invasive" and "*species name* risk". For example, the query "*Sinanodonta woodiana*" AND "invasive" was used to identify relevant studies. For each search engine and species combination, the first 100 hits were reviewed on relevance for the risk screening by checking titles and abstracts (Table S1).

Studies were included if they provided species-level risk assessments relevant to alien freshwater and brackish water molluscs in Europe. Studies were excluded if they (i) did not assign species to explicit risk categories (e.g. low, medium or high risk), (ii) lacked sufficient methodological transparency to allow interpretation of risk scores (e.g. absence of clearly described assessment criteria, scoring procedures or weighting schemes), or (iii) lacked geographical relevance. Geographical relevance was defined as assessments conducted in Europe or in regions with comparable climatic conditions and freshwater or brackish habitats to Northwestern Europe, such that the results could reasonably inform invasion risk in the Netherlands and surrounding countries.

Information from the included studies was subsequently used to identify introduction pathways, assess invasion risk, and extract management-relevant information reported in the risk assessments.

Introduction and dispersal pathways were extracted from the included risk assessments and supporting literature and classified according to the UNEP pathway classification framework (UNEP 2014). Pathways were assigned to the UNEP categories Release in nature, Escape from confinement, Transport–Contaminant, Transport–Stowaway, Corridor, Unaided, and Unknown, including UNEP subcategories where explicitly reported (Tables S5–S7). Introduction pathways and subsequent dispersal pathways were recorded separately. When multiple pathways were reported for a species, all were recorded; no additional pathways were inferred.

Climate match of species

The occurrence of alien species in countries with similar climatic conditions is generally a strong predictor for the invasiveness of species in newly colonized regions (Williamson and Fitter 1996). Therefore, species were considered if they occurred in countries classified as Cfb under the Köppen-Geiger climate system, which corresponds to the climate of the Netherlands (Kottek et al. 2006; Peel et al. 2007; Beck et al. 2018). This temperate oceanic climate is characterized by mild summers (average < 22 °C), cool winters (average > -3 °C), and evenly distributed precipitation. In Northwestern Europe, this climate occurs in countries near the Netherlands, including Belgium, Luxembourg, Germany, France, the United Kingdom, Ireland, and northern Spain.

Where available, detailed information on the origin and current distribution of alien molluscs was used to assess climatic similarity. The geographic occurrence data were derived from the literature (Tables S1, S3, S4).

Air temperature was used as a proxy for water temperature to ensure consistent climatic comparison across regions, following established approaches in large-scale freshwater invasion and climate-matching studies (e.g. Vermonden et al. 2010; Leuven et al. 2011; Verbrugge et al. 2012; Collas et al. 2014; Matthews et al. 2017a). This approach provided a practical and standardized approximation of thermal regimes relevant to freshwater habitats.

Species lists

Three mutually exclusive species lists were compiled to which each of the assessed species of alien fresh- and brackish water molluscs belongs (Table S2):

1. Alien mollusc species that are already introduced in surface waters in the Netherlands (some with established populations).
2. Species not yet introduced to the Netherlands but:
    a. That are established in fresh or brackish surface waters in surrounding countries,
    b. That are found in aquarium or water gardening trade in the Netherlands, and/or
    c. Are expected to be introduced in the near future and may establish viable populations in surface waters in the Netherlands due to climatic comparability and invasiveness elsewhere.
3. Species that are found in aquarium or water gardening trade in the Netherlands that are not expected to establish viable populations in surface waters in the Netherlands prevented by climatic constraints.

Species were evaluated based on their observed or expected capability to survive at winter air temperatures below zero and on their potential impacts on biodiversity, ecosystem functioning, ecosystem services, human health, safety, and infrastructure. For each species, we recorded origin, potential survival under climate conditions in the Netherlands (Table S3), first records in the Netherlands and neighbouring countries (Table S4), introduction pathways (Table S5, S7), and dispersal pathways (Table S6, S7).

Harmonization of risk scores

All available risk scores for species with a climate match to the Netherlands (Table S3) were harmonized into a four-point scoring system: no risk (0), low risk (1), medium risk (2), and high risk (3) (Table S8). These risk scores originating from risk assessments are overall risk scores (Table S9). In some cases, multiple scores for a species were available from the same source because several assessors within a multi-expert evaluation provided separate judgments. In such cases, the highest score was adopted following the precautionary principle (Raffensperger and Tickner 1999). The precautionary principle states that "when an activity raises threats of harm to the environment or human health, precautionary measures should be taken even if some cause-and-effect relationships are not fully established scientifically" (Tickner and Raffensperger 1998). Sources that reused previous risk assessments were excluded to avoid duplication of data. For instance, we included the data underlying Sturtevant et al. (2014), but not GLANSIS database (Great Lakes Aquatic Nonindigenous Species Information System 2022) as that database directly relies on Sturtevant et al. (2014).

Each original risk classification was assigned a harmonized value (0–3) according to interpretative rules (e.g. "black-listed" species = high risk). For each species, the average, minimum, and maximum harmonized scores were calculated (Table S10). Following Matthews et al. (2017a), we used average scores as aggregated risk indicators, as this approach minimizes bias from differing assessment methods, assessor groups, habitat types, and national conservation priorities.

The number of harmonized risk assessments determined the certainty level of each aggregated score. Certainty thresholds were set following Matthews et al. (2017a), assuming that reliability increases with the number of available classifications. For species with fewer than three assessments (high or medium risk) or fewer than five (low risk), results were labelled "based on relatively few risk assessments" (hatched areas, Figure S1).

As an example, the harmonization procedure can be exemplified for the Chinese pond mussel (*Sinanodonta woodiana*). This species was assessed in five risk assessments: Verbrugge et al. (2019) (1 – Lage impact = Low risk), Rabitsch and Nehring (2017) (Potenziell invasive Art = Medium risk), the U.S. Fish and Wildlife Service (2022) (High = High risk), Carboneras et al. (2018) (MN – Minimal concern = Low risk), and Patoka et al. (2017) (High = High risk). These classifications were harmonized to numerical scores of 1, 2, 3, 1 and 3, respectively. The aggregated risk score (average = 2.0) therefore placed the species in the "medium risk" category with "No" in the column "Only based on relatively few risk assessments" (five assessments available). This stepwise example clarifies how individual assessments were standardized and combined to obtain harmonized risk outcomes.

Relating risk scores to establishment status

To explore whether harmonized risk scores corresponded with observed establishment in the Netherlands, we compared them with the national rarity classification system used in biodiversity monitoring (van der Meijden et al. 2000; Odé et al. 2006). Species were categorized as absent (x; 0 km-squares), very rare (rrr; 1 km-square), rare (rr; 36–189 km-squares), fairly common (r; 190–550 km-squares), or common (c; ≥ 551 km-squares) based on their recorded distribution in kilometre grid cells according to the National Database Flora and Fauna Species Distribution Atlas (NDFF Verspreidingsatlas 2025) in the period between 1990 and 2025 (Table S11). This qualitative comparison provided an initial indication of the relationship between potential (harmonized) and realized establishment levels. To quantify this relationship, Spearman's rank correlation coefficients were calculated in R (Table S12).

Results

Species lists

Based on the literature review, a total of 70 mollusc species were considered in this study, of which 27 alien species have already been recorded in surface waters in the Netherlands (Table S2). Of these 27 species, *Helisoma nigricans* has been observed outdoors, likely as an escape, as it cannot survive under climatic conditions in the Netherlands (Table S3). An additional 41 species were found in aquarium and water gardening trade but have not yet been recorded in surface waters in the Netherlands (Table S2). The remaining two species are expected to be introduced in the Netherlands in the near future: i.e., Japanese mystery snail (*Cipangopaludina japonica*, synonym: *Heterogen japonica*) and golden mussel (*Limnoperna fortunei*). These species have not yet been observed in the Netherlands or surrounding Northwestern Europe, nor found in trade in the Netherlands. The Japanese mystery snail (*C. japonica*) can be confused with the Chinese mystery snail (*Cipangopaludina chinensis*) and is considered an invasive species in North America (David and Cote 2019). This species shares physical similarities and similar abiotic requirements with *C. chinensis*, suggesting potential establishment in the Netherlands. The golden mussel *L. fortunei* is comparable to the zebra mussel (*Dreissena polymorpha*) in terms of species characteristics and potential effects (Karatayev et al. 2007) and may also establish under the climatic conditions in the Netherlands (de Hoop et al. 2015).

Alien species origin

Information on the continent of origin was available for 63 of the 70 species (Figure S2; Table S3). Most originated from Asia, followed by North America, Africa, South America, Europe, and Oceania. Several species have multiple native ranges and were attributed to each relevant continent. This information was used to inform the climate-match analysis relevant to the Netherlands.

Using the Köppen–Geiger classification system, we estimated that 26 species are expected to survive in surface waters under prevailing climatic conditions in the Netherlands (Table S3). Four additional species have been observed in European surface waters and are also likely to survive winters in the Netherlands.

Harmonization of risk scores

Only species able to survive under climatic conditions in the Netherlands were considered for the risk inventory (Table S3), resulting in a species list of 30 species. Risk assessments were available for 29 of those 30 species (Tables 1 and S9). *Euglesa compressa* was the only species without any available risk score.

Across the 19 data sources consulted, 16 different risk assessment protocols or tools were identified, yielding 130 risk assessments for 29 species (Tables 1 and S9). The harmonization process based on Matthews et al. (2017a) classified 16 species as high risk, nine as medium risk, and four as low risk. Of these, one high-risk, two medium-risk, and three low-risk species were categorized as "based on relatively few risk assessments" (Figure 1; Table S10).

Harmonized risk outcomes and species status in the Netherlands

Of the 29 species with at least one available risk assessment, 27 have been recorded in surface waters in the Netherlands. Their occurrence ranged from single local records to widespread distribution across the country. No consistent relationship was observed between harmonized risk categories and recorded distribution (Spearman rho = 0.117; $p = 0.596$; Table S12). High-risk species included both widespread taxa (e.g. *Dreissena polymorpha* and *Potamopyrgus antipodarum*) and taxa with a more localized spread (e.g. *Melanoides tuberculatus* and *Sinanodonta woodiana*). Similarly, medium- and low-risk species occurred across a range of rarity classes (from very rare to fairly common). The comparison between harmonized risk outcomes and distribution patterns therefore did not reveal a clear correspondence between risk level and establishment status.

Alien species introduction and establishment in the Netherlands and surrounding countries

The cumulative number of first records of alien molluscs has increased markedly across Northwestern Europe over the past decades (Figure 2). Most introductions were reported from the Netherlands (Table S4). For all countries, the rate of new introductions accelerated after the 1970s. Earlier introductions were also recorded: *Potamopyrgus antipodarum* was first reported in the United Kingdom in 1852 (GB NNSS 2022), *Lithoglyphus naticoides* and *Physa acuta* were first recorded in the Netherlands in 1870 (Verdonschot et al. 2013), and *Mytilopsis leucophaeata* was detected in the United Kingdom between 1800 and 1830 (Oliver 2015). The first alien bivalve in the Netherlands was *D. polymorpha*, recorded in 1826 (Verdonschot et al. 2013). These results illustrate how introduction dynamics in the Netherlands compare with those observed in surrounding countries, providing a regional perspective on the development of alien mollusc records over time.

Pathways for introduction and dispersal

The most frequently reported introduction pathway for alien molluscs was transport via hull fouling and ballast water (Transport–Stowaway), which was

Table 1. Overview of different risk assessment (RA) protocols and classification methods that were harmonized in this study. For each of the different protocols, the number of sources is indicated, based on which we harmonized risk scores across invasive and potentially invasive alien fresh- and brackish water mollusc species.

Risk assessment protocol	Key reference for protocol	Assessment goal	Method assessment	Introduction, establishment and spread included?	Impact categories	# of sources used in this study	# of RAs	# of different species	References for risk assessments
Expert judgement	–	–	–	Not mentioned	–	2	24	19	1, 2
Ecological Risk Screening Summary (ERSS)	U.S. Fish and Wildlife Service (2022)	Screening	Questionnaire	Yes	Environmental impact, Socio–economic impact	1	15	15	3
Environmental Impact Classification for Alien Taxa (EICAT)	Hawkins et al. (2015)	Impact assessment	Questionnaire	Yes	Environmental impact	1	11	11	4
Freshwater Invertebrate Invasiveness Scoring Kit (FI-ISK)	Vilizzi et al. (2019)	Screening/horizon scanning	Excel sheet	Yes	Environmental impact	1	12	12	5
German–Austrian Black List Information System (GABLIS)	Essl et al. (2011)	Impact assessment	Questionnaire	Yes	Environmental impact	1	6	6	6
Full Risk Assessment Scheme for Non-native Species in Great Britain (GB NNRA)	Baker et al. (2008)	Impact/risk assessment	Questionnaire	Yes	Environmental impact, Socio–economic impact	2	7	7	7, 8
Norwegian Generic Ecological Impact Assessments of Alien species (GEIAA)	Sandvik et al. (2013)	Impact assessment	Excel sheet, Statistical program R	No, only establishment and spread are included.	Environmental impact	1	5	5	9
The generic impact scoring system (GISS)	Nentwig et al. (2010)	Impact assessment	Questionnaire	Yes	Environmental impact, Socio–economic impact	1	5	5	10
Great Lakes Aquatic Nonindigenous Species Information System (GLANSIS)	Sturtevant et al. (2014)	Impact assessment	Questionnaire	No, only the impacts are included	Environmental impact, Socio–economic impact	1	6	6	11
Harmonia+	D'hondt et al. (2015)	Impact assessment/ screening tool	Online tool	Yes	Environmental impact, Socio–economic impact	1	2	2	12
Invasive Species Environmental Impact Assessment (ISEIA)	Branquart (2009)	Impact assessment/ screening tool	Online tool	Yes	Environmental impact	2	10	10	12, 13
New York Fish & Aquatic Invertebrate Invasiveness Ranking Form	Jordan et al. (2008)	Impact assessment	Questionnaire	Yes	Environmental impact	1	6	6	14
Risk assessment for Ireland and Northern Ireland (NAPRA)	Kelly et al. (2013)	Impact assessment	Questionnaire	Yes	Environmental impact, Socio–economic impact	2	9	6	15, 16
Horizon scanning for Great Britain/EU	Roy et al. (2014)	Screening/horizon scanning	Excel sheet/Questionnaire	Yes	Overall risk scores, no categories	2	12	7	17
Rapid environmental risk assessments for prioritization of alien species using expert panels	Verbrugge et al. (2019)	Screening/horizon scanning	Questionnaire	Yes	Environmental impact	1	4	4	18
World's worst invasive species	Lowe et al. (2000)	–	–	No, only a listing of 100 species.	–	1	3	3	19

1: Nederlands soortenregister (2022); 2: Inventaire national du patrimoine naturel (INPN) (2022); 3: U.S. Fish and Wildlife Service (2022); 4: Carboneras et al. (2018); 5: Patoka et al. (2017); 6: Rabitsch and Nehring (2017); 7: CIRCABC (2022); 8: GB NNSS (2022); 9: Norwegian Biodiversity Information Centre (2018); 10: Nentwig et al. (2018); 11: Sturtevant et al. (2014); 12: NVWA (2022); 13: Parrott et al. (2009); 14: New York Invasive Species Information (2024); 15: Kelly et al. (2013); 16: National Biodiversity Data Centre (2022); 17: Roy et al. (2015); 18: Verbrugge et al. (2019); 19: Lowe et al. (2000).

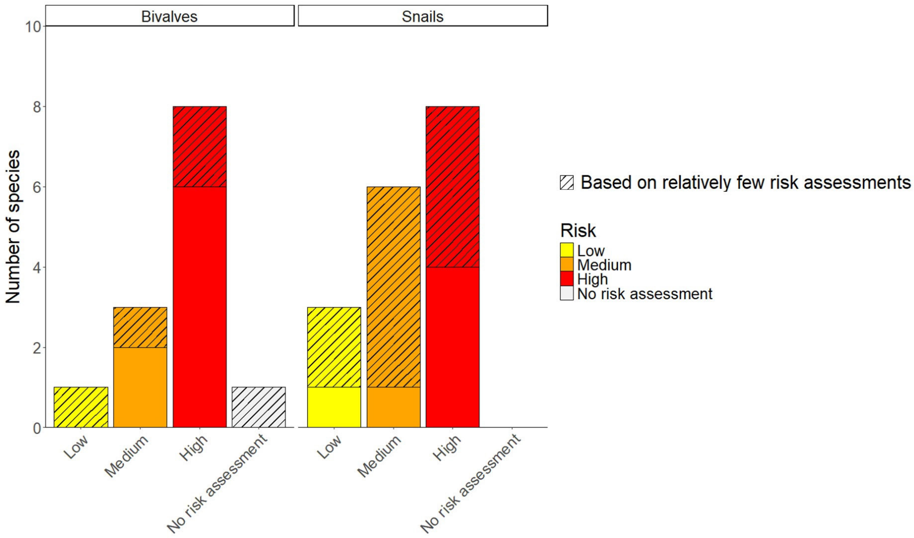

Figure 1. Harmonization of average total risk scores of molluscs with a climate match with the Netherlands (n_{total} = 30). For species with fewer than three assessments (high or medium risk) or fewer than five (low risk), results were labelled "based on relatively few risk assessments" according to the prioritization method) are indicated with shaded areas.

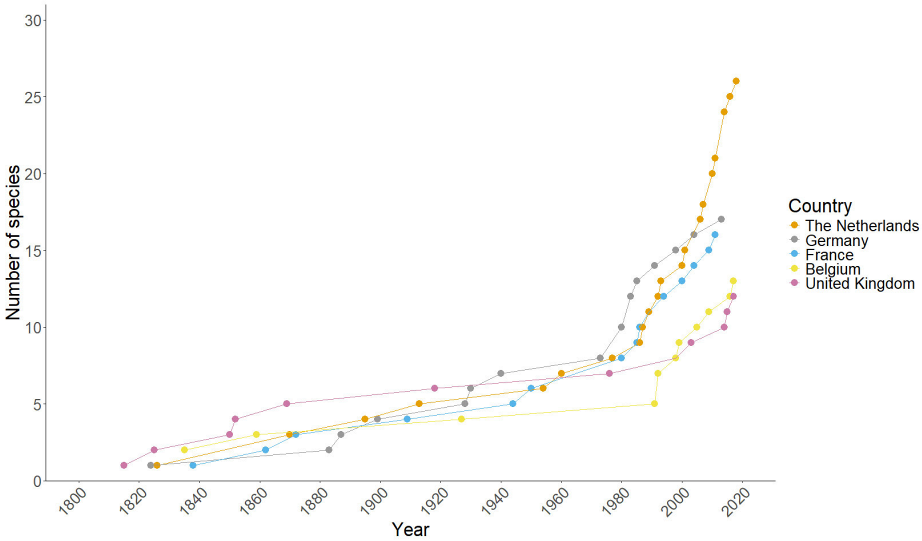

Figure 2. Cumulative number of alien mollusc species in fresh and brackish surface waters in the Netherlands and surrounding countries in relation to the year of first reporting.

reported for 39 of the 70 assessed species (Tables S5, S7). Other important pathways included dispersal through newly constructed canals connecting previously separated river systems (Corridor; 14 species) and the aquarium and water gardening trade (29 species).

Once introduced, species may spread further through interconnected waterways, as contaminants on aquatic plants or floating substrates (e.g. wood, plastic), via ballast water, or through escape and release from aquariums and ponds. These secondary dispersal pathways were reported for 42 species (Transport–Stowaway) and 30 species (Transport–Contaminant), respectively (Tables S6, S7; Appendix 1), indicating a high potential for wider establishment within the Netherlands.

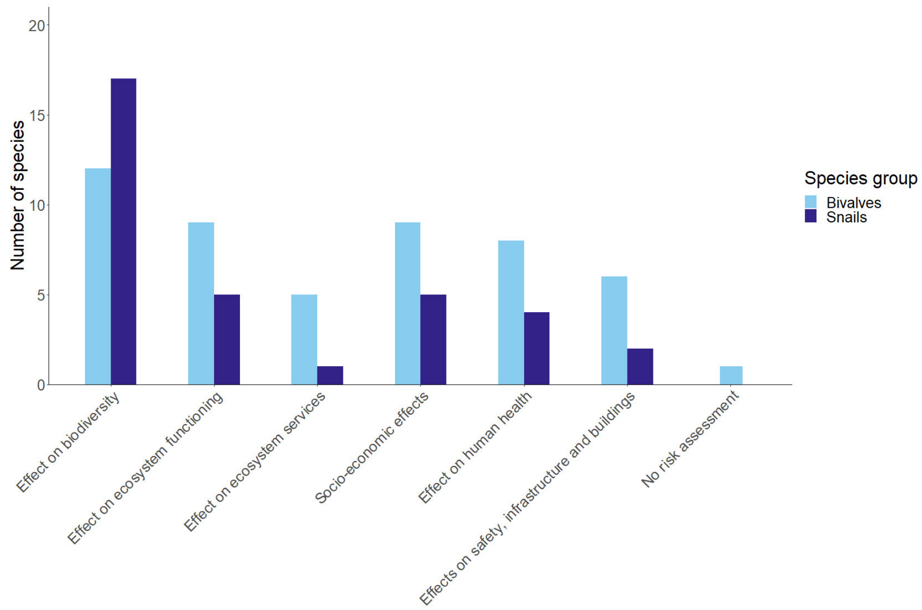

Figure 3. Distribution of potential effects of alien molluscs with a climate match with the Cfb region (n_{total} = 30). Species may affect multiple categories.

The aquarium and water gardening trade plays a particularly important role in both introduction and subsequent dispersal. Introduction pathways related to Escape from confinement were reported for 29 species, while aquarium-related secondary dispersal pathways were reported for 23 species (Tables S5–S7). In addition, Bok (2018) reported that at least 50 of the 70 alien mollusc species assessed in this study are currently sold in the (online) aquarium and water gardening trade in the Netherlands, either intentionally as ornamental species or algae controllers, or unintentionally as contaminants. Together, these results highlight the aquarium and water gardening trade as a major pathway contributing to both the introduction and spread of alien molluscs in the Netherlands.

Impact risk inventory

Potential impacts on biodiversity were identified for all 29 assessed species (Figure 3). Fourteen species were associated with effects on ecosystem functioning, six with effects on ecosystem services, and 12 with potential impacts on human health. Nine bivalve and five snail species were linked to socio-economic effects.

Bivalves such as *Dreissena polymorpha* can negatively affect biodiversity through smothering, habitat occupation, and reduction of phytoplankton. Individual *D. polymorpha* can filter approximately one litre of water per day (Maguire and Sykes 2004), reducing turbidity and increasing macrophyte and algal growth due to enhanced light penetration (Strayer et al. 1999; Higgins and Vander Zanden 2010).

Alien snails such as *Cipangopaludina chinensis* may reduce native snail populations through competition, alteration of food cycles, and reduced algal biomass (Collas et al. 2017). Their large body size and strong shells can provide protection against predators (Waltz 2008; Johnson et al. 2009). Other high-filtration species (*D. polymorpha*, *D. rostriformis bugensis*, *L. fortunei*) can substantially reduce phytoplankton biomass and sentinels (MacIsaac et al. 1992; Bunt et al. 1993).

Impacts on human health mainly concern the transmission of pathogens and parasites. For instance, *Melanoides tuberculatus* is a carrier of the trematode parasites *Paragonimus westermani* and *Clonorchis sinensis* (Derraik 2008), although these are largely confined to Asia (Qian et al. 2012; CDC 2023). Other public health risks include cuts from broken sharp shells by swimming and bathing or shells on the shores, the promotion of algal blooms (Sarnelle et al. 2012; de Hoop et al. 2015), and bioaccumulation of heavy metals in edible species (Sturtevant et al. 2014).

Effects on infrastructure were reported for eight species, primarily through biofouling on ships and clogging of pipes in industrial systems. Such fouling increases drag and fuel consumption of vessels (New York Invasive Species Information 2022). Snails which can occur in high masses such as *Potamopyrgus antipodarum* can also block water intake systems (Global Invasive Species Database 2022).

Discussion

By harmonizing various types of risk scores from existing risk assessments, this study provides an up-to-date overview of the invasion status and impact of 70 invasive or potentially invasive fresh- and brackish-water molluscs in the Netherlands, with relevance for Northwestern Europe as a whole. Of these, 30 species can likely survive in the wild in Northwestern Europe, based on their climate match. For 29 of these 30 species with a climate match, risk assessments were available. These assessments primarily focus on their impact on biodiversity and ecosystems, but also on human health and the safety of infrastructure. Furthermore, our study applied the framework for horizon scanning of Matthews et al. (2017c) for the first time to a coherent group of species. Harmonizing risk assessments offers several advantages, including quicker evaluations, facilitating comparison of risk scores, and improved aggregation for specific species. Rapid comparisons are particularly important for timely policy and management decisions, allowing for prioritization of invasive species. However, harmonizing these assessments also presents challenges due to the diversity of protocols used and the varying types of risks considered. Different risk assessment protocols apply distinct scoring systems for evaluating effects on biodiversity, ecosystems, human health, and infrastructure, leading to difficulties in direct comparisons.

Harmonization challenges

The use of existing classifications greatly reduces the number of species requiring expert judgment compared to traditional risk assessment methods

(Matthews et al. 2017a). By aggregating risk classifications, multiple expert opinions contribute to assessments, minimizing individual error.

However, a key challenge encountered during the harmonization process was that different protocols assess varying types of impacts, including biodiversity loss, economic damage, and public health risks. These differences in focus can lead to inconsistencies in risk classifications and complicate direct comparisons across assessments. Despite these variations, rapid overviews remain crucial for informing policy and management decisions, particularly when quick prioritization is necessary. Therefore, it is important not only to report the overall scores but also to provide insights into the underlying data and used risk categories. Acknowledging these limitations allows for a more transparent interpretation of the results and highlights the need to use harmonized frameworks alongside other assessment tools. Similar challenges were noted by Guerin et al. (2025), who showed that variation in the weighting of likelihood and impact across SLRA tools can substantially influence species rankings. This reinforces the importance of transparent cross-protocol mapping when comparing or integrating risk outcomes.

During the harmonization of risk scores, uncertainties arose from regional variations in risk classifications and assessment methodologies, which affected the consistency of invasiveness predictions. Wittenberg and Cock (2001) supported applying existing risk classifications to climatically similar regions, but differences persist due to varied ecological impacts and weighting influenced by habitat characteristics and conservation goals. While harmonization assumes a degree of uniformity in risk levels, local environmental factors beyond climate matching can introduce further variations (Matthews et al. 2017a). Applying the precautionary principle during harmonization and risk score aggregation mitigates potential underestimation (Raffensperger and Tickner 1999; Matthews et al. 2017a).

The aggregated risk score for a species can be derived using either the average or maximum harmonized risk score. The average score minimizes the influence of protocol-specific factors and assessor variation (Matthews et al. 2017a), whereas the maximum score aligns with the precautionary principle and reflects a potential worst-case scenario (Raffensperger and Tickner 1999). However, it produces a longer list of high-risk species, requiring further prioritization and potentially straining limited budgets. In this study, no formal comparison between the use of average and maximum scores was performed, as harmonization was intended primarily as a synthesis tool to integrate available risk assessment outcomes rather than a comparative analysis. The use of both values in combination with the number of risk scores serves exploratory purposes, namely, to identify variability in invasiveness among species within their introduced ranges. The harmonized results should therefore be regarded as a first-pass overview of species risks, which can help to identify potentially high-risk taxa and inform more detailed, species- and region-specific assessments to support management prioritization (Roy et al. 2014). Climate change and urbanization further complicate risk predictions by altering establishment patterns, emphasizing the need for precautionary climate-matching approaches that consider temperature extremes (Vermonden et al. 2010; Leuven et al. 2011; Verbrugge et al. 2012; Collas et al. 2014; Matthews et al. 2017a). Recognizing these limitations, the harmonization framework should complement other measures to design effective management interventions against potential invasive alien species impacts.

Interpreting harmonized outcomes and species distributions

The absence of a clear relationship between harmonized risk categories and current establishment levels in the Netherlands indicates that the harmonized scores primarily reflect potential rather than realized invasiveness. This outcome aligns with the objective of horizon scanning, which is to anticipate future invasion risks rather than describe the current situation. Lack of correlation is therefore not unexpected: species differ in invasion stage, time since introduction, and exposure to limiting environmental or biotic factors. In addition, climate change may alter the suitability of habitats, meaning that species currently restricted or absent could become invasive in the future.

These findings highlight that harmonized assessments are best interpreted as early-warning indicators of invasion potential. When combined with monitoring data and information on invasion history, they can help to identify species likely to expand or establish under changing environmental conditions.

A qualitative comparison of the species classified as high risk supports this interpretation. Several taxa identified as high risk in the harmonization, such as the zebra mussel (*Dreissena polymorpha*), and quagga mussel (*D. rostriformis bugensis*), are well established and recognized as invasive in surface waters in the Netherlands. These species are associated with biofouling of ships and industrial cooling-water systems, as well as ecosystem-level changes due to intense filter feeding (bij de Vaate et al. 2002; Karatayev et al. 2007; de Hoop et al. 2015). Conversely, a few taxa with high-risk classifications remain rare or locally restricted, such as the dark false mussel (*Mytilopsis leucophaeata*) and *Potamocorbula amurensis*, likely reflecting early invasion stages or environmental limitations rather than inconsistencies in risk categorization. These examples illustrate that the harmonized scores effectively identify species with high invasion potential while underscoring the need to interpret them as indicators of potential, not realized, invasiveness.

Secondary spread, defined here as the expansion of a species within a region after its initial introduction, provides valuable insight into its potential range expansion, rather than a reflection of present distribution patterns (Gallardo and Aldridge 2015). Our findings indicate that harmonized assessments are particularly useful for identifying species with a high potential for such secondary spread and thus should be interpreted in combination with up-to-date occurrence and monitoring data. Combining harmonized risk outcomes with empirical distribution trends will improve early detection and prioritization of management for emerging non-native molluscs.

For large-scale climate matching, air temperature was used as a proxy for water temperature, consistent with previous studies (e.g. Vermonden et al. 2010; Leuven et al. 2011; Verbrugge et al. 2012; Collas et al. 2014; Matthews et al. 2017a). While this approach facilitates comparison across datasets, it may overestimate temperature-related risks in aquatic environments due to the buffering effect of water (Comte and Olden 2017; Walsh et al. 2020; Kirk and Rahel 2022). This limitation should be acknowledged when interpreting the climate suitability component of the harmonized risk results.

Possible impact of alien molluscs

Although many alien species have been established worldwide, the environmental risks of only a fraction have been studied in detail (Gurevitch and Padilla 2004; Barney et al. 2013). Among molluscs, several species (*Corbicula leana* (*C. fluminea*), *Cipangopaludina chinensis*, *Dreissena polymorpha*, *D. rostriformis bugensis*, *Mytilopsis leucophaeata* and *Potamopyrgus antipodarum*) have been studied extensively (Karatayev and Burlakova 2025). Despite this, quantitative information on ecological, public health, and socio-economic impacts remains limited (Thunnissen et al. 2022). Based on the information reviewed in this study, the principal risks are adverse effects on native biodiversity, ecosystem functioning, and socio-economic sectors, as well as risks to human health, safety, and infrastructure. Most assessed species are classified as high risk for biodiversity and ecosystem functioning. For twelve species, fewer than three risk assessments were available, indicating high uncertainty. Impacts on ecosystem services are seldom quantified and warrant further study, for example through empirical field studies linking alien mollusc abundance to changes in ecosystem services (e.g. water purification), standardized economic valuation of infrastructure damage and management costs, or experimental and modelling approaches that quantify service trade-offs across invasion stages.

Management strategies

Because eradication of invasive molluscs after establishment is extremely difficult, prevention and early intervention remain the most effective management strategies (Wittenberg and Cock 2001; Ruesink et al. 1995; Simberloff 2003; Ahmed et al. 2022; Cuthbert et al. 2022). Pre-invasion management spending is typically 25 times lower than post-invasion costs (Cuthbert et al. 2022). The harmonized risk scores presented in this study provide a basis for identifying species that warrant priority attention before establishment, particularly those classified as high risk and currently present in trade or transport pathways.

Early recognition of potential high-risk species in trade and transport is therefore essential. Our results show that a large proportion of high- and medium-risk species are associated with the aquarium and water gardening trade and with transport-related pathways, highlighting these pathways as priority targets for preventive measures. Raising public awareness and improving identification capacity can further reduce unintentional introductions, particularly for taxa frequently moved as contaminants or ornamental species (Kikillus et al. 2012; Holmberg et al. 2015; Humair et al. 2015).

At the international level, the Ballast Water Management Convention (International Maritime Organisation 2022) and related IMO measures on hull fouling are key for preventing new introductions via maritime transport (Karatayev et al. 2007; Bradie et al. 2010). In this context, the harmonized risk outcomes can be used to prioritize surveillance and compliance efforts towards high-risk species linked to Transport–Stowaway pathways, for example by focusing monitoring on ports and inland waterways with frequent shipping connections. Additional prevention can be achieved through trade restrictions for high-risk species, as illustrated by bans on *Pomacea* spp. in the EU and *C. chinensis* in the United States (Commission Implementing Decision 2012/697/EU; USGS 2022).

Where prevention fails, physical, biological, and chemical control measures, such as manual removal, CO_2 pelletizing, *Pseudomonas fluorescens* treatments, and chlorine-based molluscicides may be applied (Claudi and Mackie 1994; Molloy et al. 2013; Breedveld 2015; Collas et al. 2017; Matthews et al. 2017b), although non-target effects must be carefully considered. The harmonized risk classification can support decision-making by indicating which species and pathways justify investment in such control measures, particularly where high-risk species are already present or detected at an early stage.

Recommendations for further research

Monitoring and further research into the distribution, effects, and control of alien molluscs are essential to improve risk assessment and management. Standardized "quick-scan" procedures could help to evaluate the potential invasiveness of new species before import. Structural monitoring of ships' hulls, ballast water, and the aquarium and water gardening trade will also aid in early detection. Moreover, detailed data on species traits, such as diet, lifespan, dispersal capacity, reproduction, and habitat preference, would enhance prediction of invasiveness. Linking such trait data with the harmonized database developed in this study can support more targeted horizon scanning and prioritization for prevention and management.

Author's contribution

N.W. Thunnissen: research conceptualization, sample design and methodology, investigation and data collection, data analysis and interpretation, writing: original draft. R.S.E.W. Leuven: acquiring funding, research conceptualization, data analysis and interpretation, writing: original draft, supervision. F.P.L. Collas: research conceptualization, data analysis and interpretation, writing: review and editing. G. van der Velde: investigation and data collection, data analysis and interpretation, writing: review and editing. E. Jongejans: acquiring funding, data analysis and interpretation, writing: review and editing.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Metadata of literature search.
Table S2. Overview of alien molluscs in the Netherlands, alien molluscs found in the Netherlands only in aquarium trade and species expected in the Netherlands.
Table S3. Origin and possible survival in the climate of the Netherlands of alien molluscs observed in the Netherlands, in neighboring countries and in trade.
Table S4. Overview of first records of alien molluscs in the Netherlands and neighboring countries.
Table S5. Pathways of introduction of alien molluscs in the Netherlands according to the UNEP-methodology (UNEP 2014).
Table S6. Pathways of dispersal of alien molluscs in the Netherlands according to the UNEP-methodology (UNEP 2014).
Table S7. Pathways of introduction and subsequent dispersal of alien molluscs in the Netherlands according to the UNEP-methodology (UNEP 2014).
Table S8. Assessment scheme for overall risk score.
Table S9. Original risk scores from risk assessments of alien freshwater molluscs with a climate match.
Table S10. Harmonisation of risk scores.
Table S11. Distribution and rarity classes in the Netherlands based on NDFF Verspreidingsatlas.
Table S12. Correlation between risk score and establishment.
Figure S1. Matrix displaying the used prioritization method for harmonized risk classifications (adapted from Matthews et al. (2017a)).
Figure S2. Continent of origin of all species considered for this study (n_{total}=70).
Appendix 1. Additional information: ecosystem services, pathways, temporal trends, and management.

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