Research Article

Online pet markets: extent and risks of trade in alien reptiles and amphibians

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Abstract

The international pet trade is a major pathway for the introduction of invasive alien reptiles and amphibians. However, little is known about which species are currently offered online and what risks they pose to biodiversity, ecosystems, and human health. This study focuses on the Dutch online pet trade, analyzing data from a major online marketplace and 11 web shops. A total of 512 alien species were recorded for sale. Based on Köppen-Geiger climate data, 93 species show a climate match with Northwestern Europe, suggesting they could survive and establish in the wild if released or escaped. Of these, 39 species have already been observed outdoors in the Netherlands. Risk assessments were available for 43 of the 93 climate-matched species. Due to diversity in risk assessment protocols, all risk scores were harmonized to prioritize potential impacts. Sixteen species were identified as high risk, twelve as medium risk, and fifteen as low risk. Negative effects include hybridization, competition, and disease transmission. Some species, such as venomous snakes (e.g., *Vipera aspis* and *Crotalus* spp.) and large snapping turtles (e.g., *Chelydra serpentina* and *Macrochelys temminckii*), pose threats to human health through bites or zoonotic disease transmission. Continuous monitoring and assessing risks of the online pet trade is essential for the early detection of potentially harmful species. Effective management should prioritize awareness and prevention through public education, early warning systems, rapid response, and stricter regulations on high-risk species to protect native biodiversity and human well-being.

Key words: non-native species, online-marketplace, rapid prioritization, risk assessment, temperate climate, herpetofauna

Introduction

Worldwide, numerous introduction events of alien amphibian and reptile species have taken place, with over 780 herpetofauna species reported outside their native range through various anthropogenic introduction pathways (Kraus 2003, 2009, 2015). The international pet trade is frequently mentioned as a key introduction pathway for alien herpetofauna (Kraus 2009, 2015; Matthews et al. 2017; da Rosa et al. 2018; Lockwood et al. 2019; Dickey et al. 2023). For instance, at least 164 alien herpetofauna species in Florida have been introduced via this pathway (Krysko et al. 2011, 2016), mostly through escapes or intentional releases from hobbyists, pet stores, or breeders (Engeman et al. 2011; Krysko et al. 2016). A fraction of these species may pose potential ecological and societal risks, including predation, competition, disease transmission, hybridization, and zoonoses such as *Salmonella* infections (Kraus 2009; Devisscher et al. 2012; Martel et al. 2013; Kraus 2015; Marin et al. 2021; Zhang et al. 2022; Roy et al. 2023). In Europe, for example, the invasive American bullfrog *Aquarana catesbeiana* (syn. *Lithobates catesbeianus*) not only competes with and preys on native species but can also be a carrier of contagious diseases such as *Batrachochytrium dendrobatidis* (Bd) (Spitzen-van der Sluijs et al. 2014; O'Hanlon et al. 2018).

Reptiles and amphibians are popular pets in the Netherlands, a country that also serves as a major hub for herpetofauna imports and exports within Europe (Janssen and Leupen 2019). Some of these species may have the potential to survive and reproduce if they are introduced into the wild, depending on their ecological flexibility and suitability to local climatic conditions. Climate is a key factor influencing the establishment of alien species, as those introduced into regions with similar environmental conditions to their native range are more likely to persist (Williamson and Fitter 1996; Bomford et al. 2009). Although the global scale of alien herpetofauna introductions is well documented (Kraus 2003; Bomford et al. 2009; Kraus 2009, 2015), it remains unclear which species are currently traded in the Netherlands and which of them may plausibly establish under local climatic conditions. Identifying species with a climate match, defined here as overlap between the species' native Köppen-Geiger climate types and those present in northwestern Europe, can therefore provide a preliminary screening framework for early risk mitigation, while recognizing that finer-scale, more labor- and data-intensive approaches (e.g. Species Distribution Modelling (SDM)) are required to refine establishment probabilities (Srivastava et al. 2019).

Horizon scans and risk assessments are essential tools for evaluating the likelihood of establishment, spread and impact of alien species (Matthews et al. 2017). To date, only seven of such publications exist for the alien herpetofauna species recorded or expected in the Netherlands (Bugter et al. 2011; van de Koppel et al. 2012a, b; van Delft et al. 2012; van de Koppel and Vos 2013; Bugter et al. 2014; van Delft et al. 2018). Many more species have been recorded in pet trade, but their risks remain unassessed. Moreover, new taxa continue to emerge in this trade, creating unaccounted risks, while a systematic overview of traded species, the probability that they can survive the Dutch climate, and associated risks are lacking.

This study focuses on online markets because these platforms lower barriers between sellers and buyers, reduce transaction costs, and create a sense of anonymity, which may make them appealing in illegal trade contexts (Nekaris et al. 2013; La Laina et al. 2021). At the same time, illegal wildlife trade often adapts to enforcement pressure by using a mix of public and more private or closed online channels, meaning that publicly visible advertisements may represent only part of the trade landscape (Dominguez et al. 2024). Online platforms also receive increasing attention in ecological research as a novel data source to study biodiversity dynamics (Jarić et al. 2021; Yan et al. 2024; Novoa et al. 2025).

We use the Netherlands as a case study to investigate the role of the online pet trade in shaping alien herpetofauna risk levels (Figure 1). Specifically, this paper aims to answer the following research questions: (1) Which herpetofauna species are currently offered in the Dutch online pet trade? (2) Which of these herpetofauna species show a climate match with northwestern European conditions? (3) What are their potential ecological and human-health risks? (4) Which management strategies can mitigate these risks? Although focused on the Netherlands, the results are also relevant for surrounding regions with similar climates (i.e., Belgium, Denmark, Luxembourg, Ireland, most of France (apart from the Mediterranean), northwestern Germany, northwestern Switzerland, United Kingdom, south coast and western areas of Norway north to Lofoten, and southern Sweden).

Materials and methods

Species records from multiple sources were compiled and processed through a series of steps, including assignment to taxonomic groups, climate screening, and the collection and synthesis of existing risk assessments (Figure 2). No new risk assessments were conducted as part of this study; instead, available risk assessments were compiled from the literature and policy documents. Species found in the Dutch pet trade or identified as pet-trade related in national risk assessments were assigned to seven taxonomic groups (caecilians, caimans, frogs and toads, lizards, salamanders and newts, snakes, and turtles). These species were then assessed for their potential ability to survive under northwestern European climate conditions based on their native and introduced ranges (Supplementary material Tables S1–S2).

Data collection

Species presences in the Dutch pet trade were compiled from three sources:

1. an online e-commerce platform (Marktplaats.nl),
2. stock lists of online pet stores, and
3. national risk assessments.

The primary source of trade data was Marktplaats.nl, a frequently used Dutch online marketplace where various items are traded, including pets (Marktplaats 2021). Data were compiled using “web scraping”, a technique to harvest data from a website and transfer it to a database (Zhao 2017). Monthly data on all herpetofauna-related advertisements were collected over

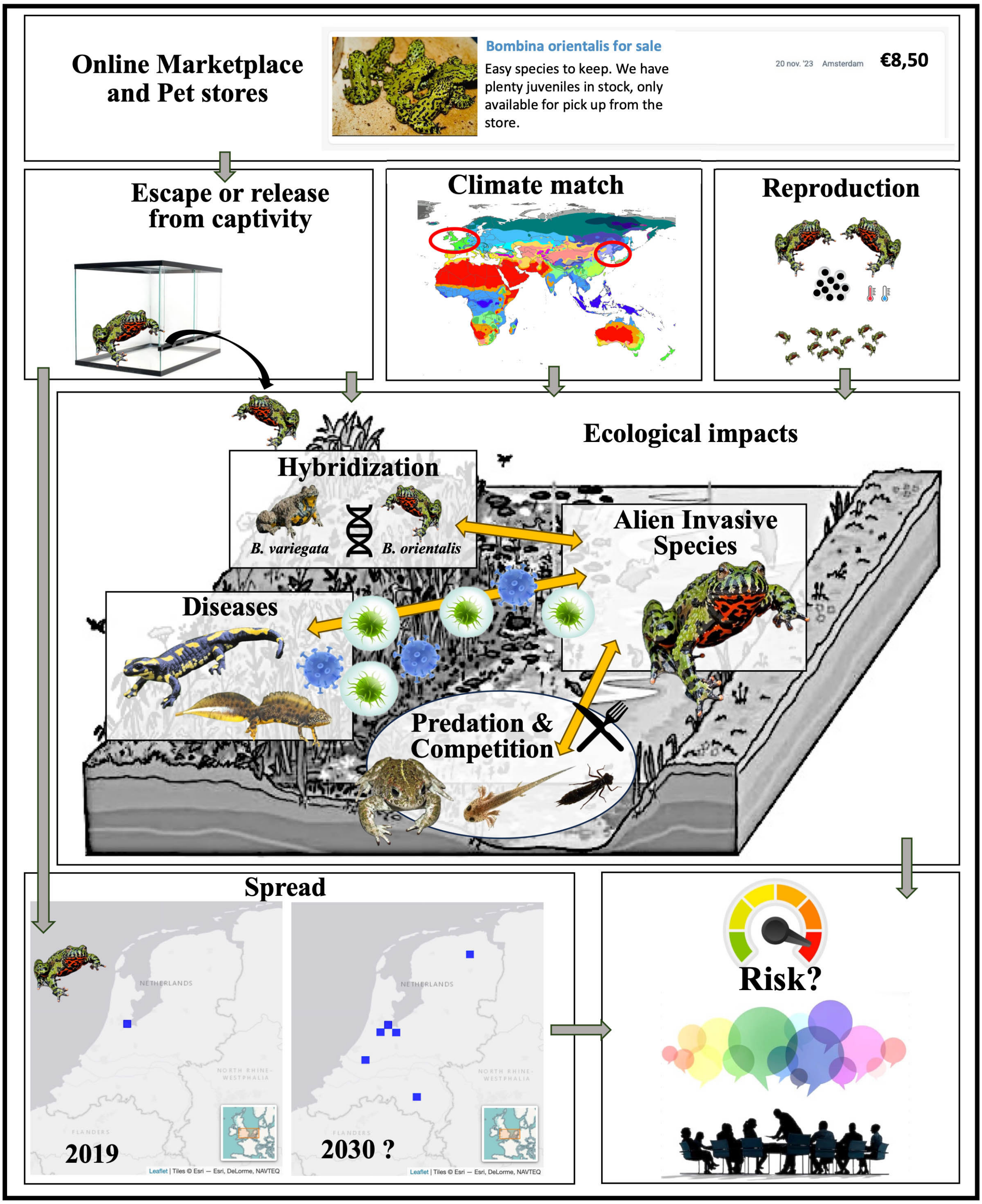

Figure 1. Conceptual overview of how herpetofauna species traded through online marketplaces and pet stores may escape or be released, establish under suitable climatic conditions, reproduce, and cause ecological impacts such as predation, competition, disease transmission and hybridization, potentially leading to invasive populations.

a 12-month period from January 2020 until December 2020. Additional species records were obtained from stock lists of 11 online Dutch pet stores accessed in March 2021 and August 2022 (Table S3). Risk assessments and horizon scans were retrieved from the Netherlands Food and Consumer Product Safety Authority (NVWA 2025).

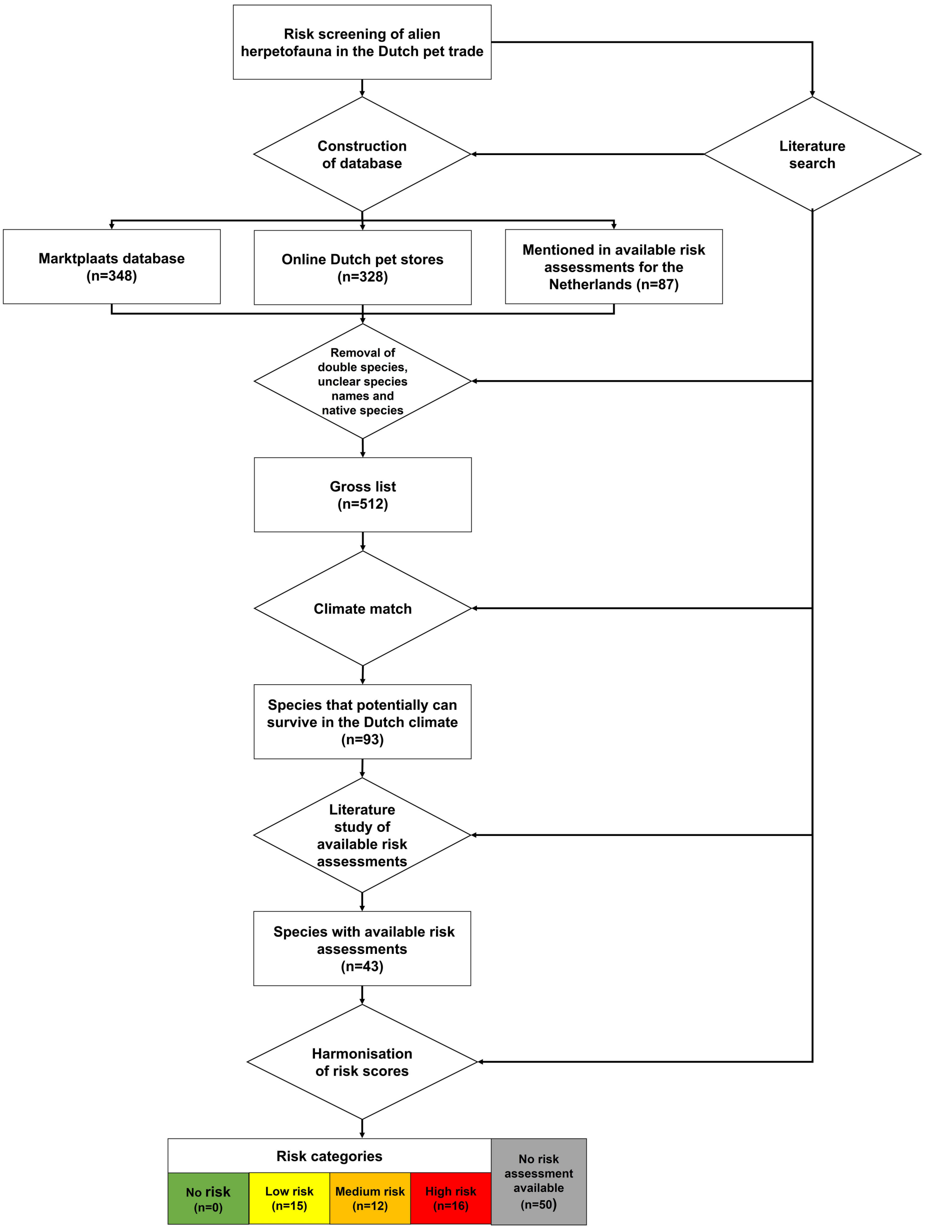

Figure 2. Flowchart visualizing the selection process to identify alien herpetofauna associated with the Dutch pet trade, and to filter the species with a climate match for reviewing and analyzing available risk assessments. Climate matching was based on Köppen-Geiger climate data. Other indicators of plausible climate match were not used in this species selection process but were applied later to evaluate the robustness of the applied climate filter.

Observation and literature sources

Information on outdoor presence and status of alien herpetofauna in the Netherlands was obtained from the NDFF Species Distribution Atlas (NDFF Verspreidingsatlas 2025a, b), the Dutch Species Register (Nederlands Soortenregister 2025a, b), and Waarneming.nl (2025). Observation data from Waarneming.nl were used exclusively to indicate whether species recorded in the online pet trade have been observed outdoors in the Netherlands and to provide contextual support for evaluating the robustness of the climate-matching results. These data were not used to infer pet-trade origin or introduction pathways.

A structured literature review was conducted to collect information on origin, introduced ranges, spread and management. Searches were carried out in Google, Google Scholar and Web of Science using three search strings: "invasive herpetofauna AND [country]", "invasive reptiles AND [country]" and "invasive amphibians AND [country]". The placeholder [country] was replaced by the Netherlands, Belgium, France, Germany, or the United Kingdom. Up to 50 hits (Google), 100 hits (Google Scholar) and all hits (Web of Science) were screened. Titles and abstracts were evaluated following Matthews et al. (2017). Nomenclature follows GBIF (2022).

Species list

The species list consisted of all alien herpetofauna detected in the Dutch online pet trade or linked to the pet trade through national risk assessments (Figure 2). Species from risk assessments were only included when the assessment explicitly identified the pet trade as a past or potential introduction pathway, ensuring that all species had a documented connection to the Dutch pet trade. Native species were excluded. For each alien species, information on geographic origin, climate match, first record in the Netherlands (if available) and plausibility indicators was compiled (Tables S1–S2).

Climate match of species

Climate suitability was evaluated using the Köppen-Geiger classification system (Peel et al. 2007; Beck et al. 2018, 2023). The Netherlands and most of northwestern Europe fall within the oceanic climate zone (Cfb). This climate type also occurs in Belgium, Denmark, Luxembourg, Ireland, most of France (apart from Mediterranean regions), northwestern Germany, northwestern Switzerland, the United Kingdom, south coast, and western areas of Norway north to Lofoten, and most southern parts of Sweden.

A species was identified as having a climate match when its native distribution included regions classified as Cfa, Cfb, or colder temperate categories (i.e., Cfc, Dsb, Dsc, Dfb, Dfc) according to Köppen-Geiger (Beck et al. 2018, 2023) (Table S3). Distribution data for reptiles and amphibians were obtained from the Reptile Database (Uetz et al. 2025) and AmphibiaWeb (2022). Outdoor presence in the Netherlands was verified using NDFF Verspreidingsatlas (2025a, b) and Waarneming.nl (2025). Species with a climate match were retained for later screening of risk assessments relevant to the Netherlands (Figure 2).

Climate matching served as a first indication of survival potential. Although climatic similarity is a strong predictor of establishment (Howeth et al. 2016; Du et al. 2024), limitations related to spatial transferability and the possibility of niche shifts may reduce predictive accuracy (Liu et al. 2020, 2022). For this reason, the Köppen-Geiger screening was complemented with plausibility indicators to provide additional context.

Plausibility indicators

Because a broad climatic screen may generate false positives, we compiled three plausibility indicators from literature and observation databases (Table S2):

- Records in Europe: whether the species has been documented in Europe outside its native range.
- Establishment in Europe: whether the species is known to maintain non-native populations elsewhere in Europe.
- Outdoor records in the Netherlands: whether the species has been documented outdoors in Dutch nature.

These indicators provide a transparent and reproducible means of contextualizing uncertainty, without relying on subjective expert judgment. These indicators served only as contextual information for interpreting the climate screen and did not determine species inclusion or exclusion.

Harmonization of risk scores

All species with a climate match were screened for available risk assessments. Because assessment protocols apply different scoring systems, all scores were harmonized into a four-point scale: no risk (0), low risk (1), medium risk (2), and high risk (3) (Table S4). When a single assessment source provided more than one risk score for the same species, the highest score was retained following the precautionary principle (Raffensperger and Tickner 1999). The precautionary principle is defined as "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, p. 75). Studies using outcomes or risk scores from earlier assessments were excluded to prevent duplication.

Subsequently, for each species, the number of unique risk assessments was recorded (Tables S4–S7), and an aggregated risk score was calculated as the average of the harmonized scores across independent assessments. Averaging reduces the influence of methodological variation, differences in expert group size, and context dependency of risk assessments, such as variation in biogeographical and climatic settings (Matthews et al. 2017). Certainty thresholds were based on the number of independent assessments. Species with fewer than five assessments when classified as low risk (score ≤ 1), or fewer than three assessments when classified as medium or high risk (score > 1), were placed in the category "based on insufficient risk assessments" (Figure 3). This designation reflects uncertainty due to limited evidence and does not represent an additional risk category, but rather qualifies the confidence in the assigned white, grey, or black list classification. Three lists were produced: white list (no or low risk), grey list (medium risk), and black list (high risk).

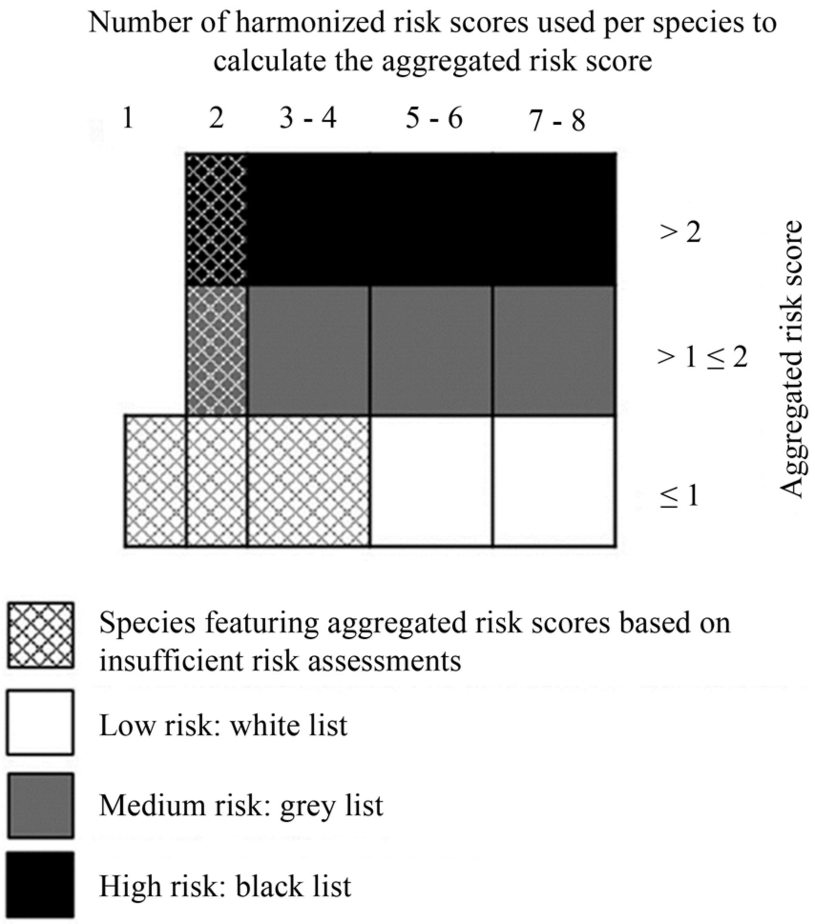

Figure 3. Matrix displaying the used prioritization method for harmonized risk classifications, adapted from Matthews et al. (2017). Hatched cells indicate classifications based on an insufficient number of risk assessments and therefore reflect increased uncertainty rather than a separate risk category.

Results

Inventory of alien herpetofauna species in the Dutch pet trade

Based on an inventory of the online marketplace database, online Dutch pet stores, and species listed in risk assessments, a total of 515 amphibian and reptile species were identified as either being present in the Dutch pet trade and/or previously evaluated for potential ecological risk in the Netherlands. Of these, 348 species were recorded from the online marketplace, 328 from online pet stores, and 87 were listed in national or EU risk assessments, of which 50 had an explicit risk evaluation. As these sources partially overlapped, some species were mentioned in more than one category. After excluding three native species, a final list of 512 alien herpetofauna species associated with the Dutch pet trade remained (Figure 2, Table S1). Of the 87 species mentioned in relevant risk assessments, 25 were not observed in the online trade data (the online marketplace or pet stores). However, these species were recorded outdoors in the Netherlands, confirming that the final dataset (512) captures mainly species in active trade and some that were not currently traded but already observed in the wild.

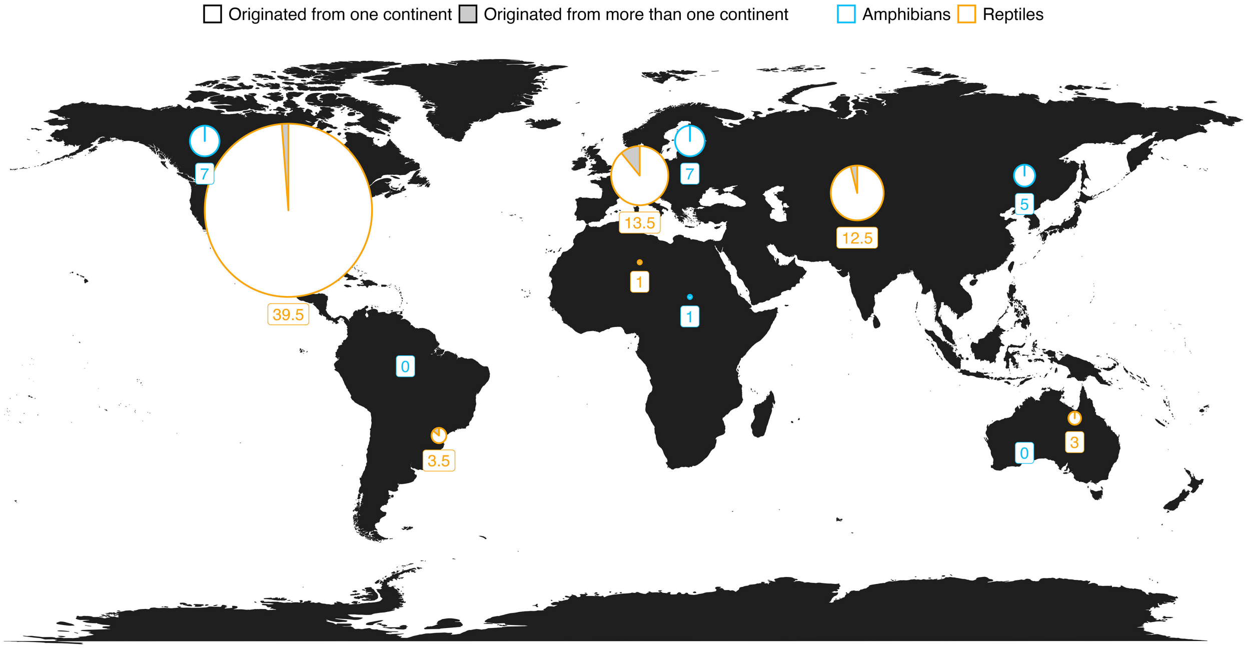

Figure 4. Continent of origin of all species with a broad climate match (n_{total} = 93). Numbers indicate the number of species originating from the corresponding continent. Numbers in blue refer to the number of amphibian species, and numbers in orange refer to the number of reptile species originating from that continent. Some species are native to more than one continent and are ascribed to these continents in equal proportions (dark-colored pie sections).

Geographic origin and climatic matching of alien species

From the 512 alien species identified, 93 species were classified as having a broad climatic match with northwestern Europe according to the Köppen–Geiger system (Table S2). These comprised 20 amphibians and 73 reptiles. The amphibians represented 21.5% of the climate-matched group and were distributed across eight families: Salamandridae (six species), Ranidae (four species), Hylidae (three species), Ambystomatidae (two species), Bombinatoridae (two species), Bufonidae (one species), Dicroglossidae (one species), and Pipidae (one species). Reptiles accounted for approximately 78.5% of the climate-matched group and were most strongly represented by Colubridae (28 species) and Emydidae (14 species). Smaller groups included Viperidae with six species, Geoemydidae with five species, Kinosternidae and Lacertidae with each four species, three species each of Testudinidae and Trionychidae, two species of Chelydridae and, and single representatives of Carphodactylidae, Chelidae, Pythonidae, and Teiidae.

The 93 climate-matched species originated primarily from North America (46 species, 49%), followed by Europe (19 species, 20%) and Asia (17 species, 18%). The remainder originated from South America, Oceania, and Africa (Figure 4; Table S2). Four species originated from more than one continent.

Plausibility indicators

Application of the three plausibility indicators showed that, among the 93 climate-matched species, 54 have already been recorded outdoors in Europe of which 39 have already been recorded outdoors in the Netherlands, and

22 of these 54 species have established populations as alien elsewhere in Europe (Table S2). In contrast, 39 species lacked all three indicators, indicating uncertainty about their establishment potential.

Outdoor records in the Netherlands date back to 1974 and 1975, when the African clawed frog *Xenopus laevis* and the pond slider *Trachemys scripta* (Emydidae) were first documented, respectively (Bugter et al. 2011; European Commission Directorate-General for Environment 2018). Since then, additional alien species taxa have been reported, reflecting a gradual accumulation of alien herpetofauna.

Impact risk inventory

Of the 93 species with a climatic match, 43 species (46%) had at least one available risk assessment, while the remaining 50 species (54%) had no assessment (Tables S5–S7). In total, 94 risk assessments were compiled from 15 distinct sources, representing 12 different protocols or tools (Table 1). Several sources contained assessments for multiple species.

The most frequently used protocols were the Invasive Species Environmental Impact Assessment (ISEIA; 17 species), the Environmental Impact Classification for Alien Taxa (EICAT; 13 species), and the full Risk Assessment Scheme for Non-native Species in Great Britain (GB NNRA; nine species). Additional protocols included German-Austrian Black List Information System (GABLIS), Generic Ecological Impact Assessment of Alien species (GEIAA), Generic Impact Scoring System (GISS), Harmonia$^+$, and rapid horizon scanning methods, as well as national assessments such as those by Bugter et al. (2011) on turtles. Each protocol applied different metrics and scoring systems, complicating direct comparison across sources.

For 37 of the 43 climate-matched species with available risk assessments, specific ecological effects were reported (Table S6; Figure 5). "Predation of" and "competition with" native taxa were the most frequently mentioned mechanisms, alongside biotic alterations to community structure and ecosystem functioning. Several amphibian species were identified as potential disease carriers, most notably the American bullfrog *Aquarana catesbeiana*, which is a known vector of ranaviruses and the chytrid fungus *Batrachochytrium dendrobatidis* (Bd) (Une et al. 2009; Sharifian-Fard et al. 2011; Spitzen-van der Sluijs et al. 2014; Miaud et al. 2016; O'Hanlon et al. 2018). Hybridization risks were also documented, for example in crested newts (*Triturus carnifex* hybridizing with *T. cristatus*) (Arntzen and Hedlund 1990; Arntzen and Wallis 1991; Arntzen and Thorpe 1999; Meilink et al. 2015). Effects on ecosystem services were not explicitly addressed in any of the reviewed assessments.

Harmonized risk scores

To enable comparison, risk scores from different protocols were harmonized into a four-level system (0 = no risk, 1 = low, 2 = medium, 3 = high) (Table S7).

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 risk scores are harmonized across invasive and potentially invasive alien herpetofauna species.

Risk assessment protocol	Acronym	Key reference for protocol	Assessment goal	Method assessment	Impact categories	# of sources used in this study	# of RAs	# of species	References for risk assessments
Environmental Impact Classification for Alien Taxa	EICAT	Hawkins et al. (2015)	Impact assessment	Questionnaire	Environmental impact	1	13	13	Carboneras et al. (2018)
German–Austrian Black List Information System	GABLIS	Essl et al. (2011)	Impact assessment	Questionnaire	Environmental impact	1	1	1	Rabitsch et al. (2013)
Full Risk Assessment Scheme for Non-native Species in Great Britain	GB NNRA	Baker et al. (2008)	Impact/risk assessment	Questionnaire	Environmental impact, Socio-economic impact	2	12	9	GB NNSS (2022); CIRCABC (2025)
Norwegian Generic Ecological Impact Assessments of Alien species	GEIAA	Sandvik et al. (2013)	Impact assessment	Excel sheet, Statistical program R	Environmental impact	1	14	14	Artsdatabanken (2023)
The generic impact scoring system	GISS	Nentwig et al. (2010)	Impact assessment	Questionnaire	Environmental impact, Socio-economic impact	1	5	5	Nentwig et al. (2018)
Harmonia +	Harmonia^{+}	D'hondt et al. (2015)	Impact assessment/ screening tool	Online tool	Environmental impact, Socio-economic impact	1	7	7	Helsloot (2021)
Invasive Species Environmental Impact Assessment	ISEIA	Branquart (2009)	Impact assessment/ screening tool	Online tool	Environmental impact	6	20	17	van de Koppel et al. (2012a); van de Koppel et al. (2012b); van Delft et al. (2012); van de Koppel and Vos (2013); Bugter et al. (2014); Belgium Biodiversity Platform (2025)
Horizon scanning for Great Britain/EU	–	Roy et al. (2014)	Screening/horizon scanning	Excel sheet/ Questionnaire	Overall risk scores, no categories	1	3	3	Roy et al. (2015)
Invasion of the turtles? - Exotic turtles in the Netherlands: a risk assessment	–	Bugter et al. (2011)	Impact assessment/ screening tool	Argumentation not based on a protocol	Environmental impact	1	11	11	Bugter et al. (2011)
Rapid environmental risk assessments for prioritization of alien species using expert panels	–	Verbrugge et al. (2019)	Screening/horizon scanning	Questionnaire	Environmental impact	1	4	4	Verbrugge et al. (2019)
World's worst invasive species	–	Lowe et al. (2000)	Screening	List not based on a protocol	No categories	1	2	2	Lowe et al. (2000)

Across the 43 assessed species, sixteen species (37%) were classified as high risk, twelve species (28%) as medium risk, and fifteen species (35%) as low risk (Table 2; Figure 6). High-risk species included both amphibians and reptiles, with well-documented ecological impacts such as predation, competition, hybridization, or pathogen transmission. Examples are the Italian wall lizard *Podarcis siculus,* known to outcompete native lizards (Capula and Aloise 2011; Grano et al. 2011; Damas-Moreira et al. 2020), and the chytrid fungus *Batrachochytrium salamandrivorans* (Bsal), introduced via the pet trade of Asian salamanders, which has caused severe declines in European fire salamander populations (Martel et al. 2013; Spitzen-van der

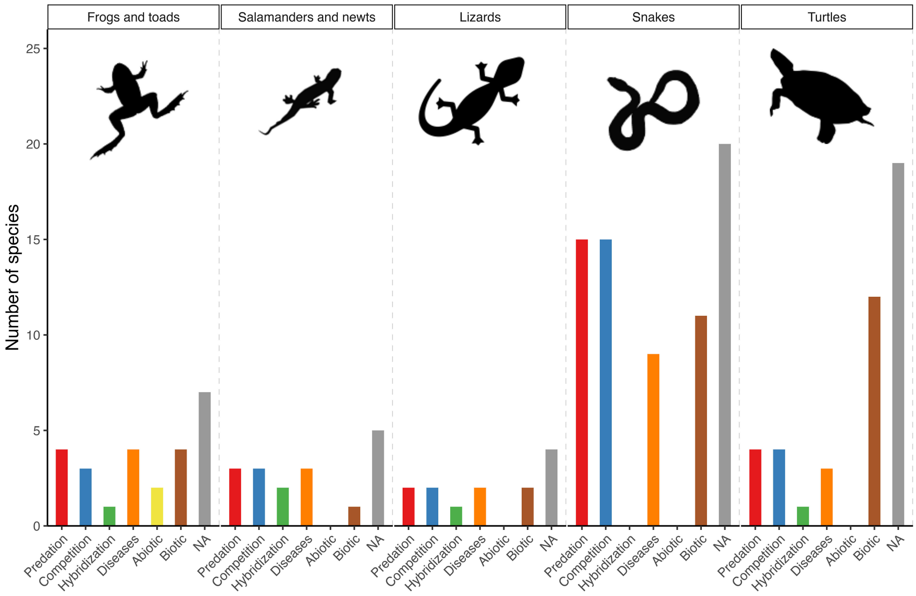

Figure 5. Distribution of potential effects of alien amphibian and reptilian species on biodiversity with a climate match (n_{total} = 93). Individual species may affect multiple categories. When risk was not specified or assessed, it was categorized under "NA".

Sluijs et al. 2013, 2014). Medium-risk species were typically those with localized impacts or for which available assessments provided divergent results. Low-risk species were primarily taxa with limited evidence of establishment or minimal expected impact under northwestern European conditions.

No risk category could be assigned to the 50 climate-matched species without risk assessments (Table S7). For these species, uncertainty about potential impacts remains high, and the plausibility indicators (observed and/or establishment elsewhere in Europe, and/or outdoor records in the Netherlands) provide the only independent evidence base currently available. In cases where risk categories were assigned based on a limited number of assessments, species were flagged as being classified on insufficient risk assessments, indicating elevated uncertainty rather than a distinct risk outcome.

Discussion

Alien herpetofauna in the Dutch pet trade and their climate match

A total of 512 alien amphibian and reptile species were documented in the Dutch pet trade, of which 93 can likely survive in the wild in northwestern Europe as assessed by matching climate (Köppen-Geiger) zones in their native or introduced ranges. This includes both amphibians (n = 20) and reptiles (n = 73), with half of the species originating from North America. However, these numbers must be interpreted with caution. The trade dataset reflects a single year (2020) and may be biased by temporal factors, such as COVID-19 lockdowns that increased online activity (Grant et al. 2017;

Table 2. Alien reptile and amphibian species with a climate match for the Netherlands and for which at least one risk assessment was available. Per assessment source, the highest reported score was retained (precautionary principle), after which final risk scores were calculated as averages across independent assessments (see Figure 3). A more detailed version of this table can be found in Table S7, which also includes species without available risk assessments.

Species	# of RA: min-max risk score	Average risk score	Risk classification	Listing
Apalone spinifera	3: 2-3	2.50	High	Black list
Bombina orientalis	1: 3	3.00	High	Black list
Chelodina longicollis	1: 1	1.00	Low	White list
Chelydra serpentina	3: 1-3	2.00	Medium	Grey list
Chrysemys picta	6: 1-3	2.20	High	Black list
Clemmys guttata	1: 1	1.00	Low	White list
Cynops pyrrhogaster	2: 3-3	3.00	High	Black list
Elaphe carinata	1: 2	2.00	Medium	Grey list
Elaphe climacophora	1: 2	2.00	Medium	Grey list
Elaphe schrenckii	4: 1-2	1.67	Medium	Grey list
Emys blandingii	1: 1	1.00	Low	White list
Graptemys geographica	2: 2-3	2.50	High	Black list
Graptemys pseudogeographica	3: 3-3	3.00	High	Black list
Heterodon nasicus	1: 1	1.00	Low	White list
Lacerta bilineata	2: 1-1	1.00	Low	White list
Lampropeltis getula	4: 1-3	2.50	High	Black list
Lampropeltis holbrooki	4: 1-3	2.50	High	Black list
Lampropeltis splendida	4: 1-3	2.50	High	Black list
Lampropeltis triangulum	1: 1	1.00	Low	White list
Lithobates catesbeianus (Aquarana catesbeiana)	7: 1-3	2.71	High	Black list
Macrochelys temminckii	2: 3-3	3.00	High	Black list
Mauremys sinensis	1: 2	2.00	Medium	Grey list
Morelia spilota	1: 1	1.00	Low	White list
Natrix maura	1: 1	1.00	Low	White list
Natrix natrix	1: 2	2.00	Medium	Grey list
Natrix tessellata	1: 1	1.00	Low	White list
Nerodia spp.	1: 1	1.00	Low	White list
Pantherophis guttatus	2: 2	2.00	Medium	Grey list
Pelodiscus sinensis	1: 3	3.00	High	Black list
Pelophylax spp.	2: 2-3	2.50	High	Black list
Pituophis catenifer / vertebralis	2: 1	1.00	Low	White list
Podarcis siculus	1: 3	3.00	High	Black list
Pseudemys concinna	1: 3	3.00	High	Black list
Pseudemys rubriventris	1: 1	1.00	Low	White list
Rana dalmatina	1: 1	1.00	Low	White list
Sternotherus odoratus	1: 3	3.00	High	Black list
Thamnophis spp	1: 2	2.00	Medium	Grey list
Trachemys scripta ssp.	7: 1-3	2.10	High	Black list
Tritrurus carnifex	3: 1-3	2.00	Medium	Grey list
Triturus marmoratus	2: 2	2.00	Medium	Grey list
Vipera aspis	2: 1	1.00	Low	White list
Xenopus laevis	6: 1-3	2.00	Medium	Grey list
Zamenis longissimus	1: 1	1.00	Low	White list

Altherr and Lameter 2020; Lenzi and Grasso 2020; Ho et al. 2021). Rare or illegal species without CITES documentation are also likely underrepresented in our dataset, as they are less frequently offered via public online platforms. Evidence from the Netherlands shows that reptile traders operate across multiple interconnected trade pathways, including publicly accessible online platforms as well as closed or encrypted groups and messaging apps (Dominguez et al. 2024). The present study explicitly focuses on the publicly accessible online segment of this trade, which provides a transparent and

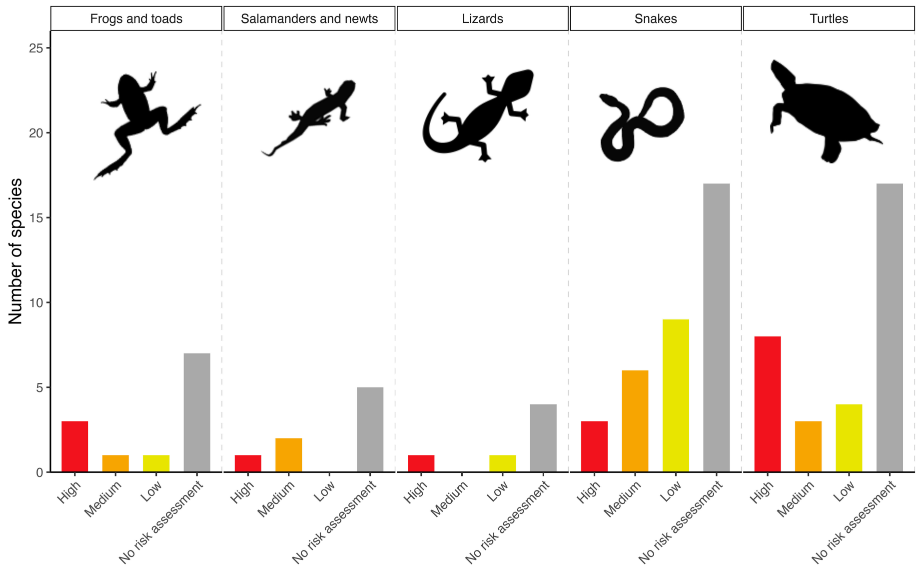

Figure 6. Harmonized risk classification of herpetofauna species encountered in the Dutch pet trade with a climate match with the Netherlands ($n_{total} = 93$).

reproducible basis for analyzing patterns in alien herpetofauna trade. From this perspective, our dataset captures a conservative subset of the species circulating within the broader Dutch pet trade, while remaining fully representative of the online trade segment analyzed here. Other trade pathways, such as private exchanges, direct imports, and herpetofauna fairs, may involve additional species beyond those observed online, reinforcing that online trade reflects a lower bound of total trade diversity.

Climatic matching is one of the strongest predictors of establishment potential (Bomford et al. 2009; Howeth et al. 2016; Du et al. 2024), supporting its use as an initial screening tool. Nevertheless, the predictive capacity of species distribution models and climate-based approaches may have limited transferability across regions, and niche shifts in invasive species or data gaps can reduce predictive accuracy (Kumschick and Richardson 2013; Liu et al. 2020, 2022). Some species classified as plausible may fail to establish, while others outside the broad climatic range may persist under favorable microclimatic conditions. Many herpetofauna are poikilothermic and sensitive to microclimatic variation. Urban heat islands (UHIs) can create warmer microhabitats, with Dutch cities experiencing temperature increases of up to 7–8 °C compared to surrounding areas (Rizwan et al. 2008; Atlas Leefomgeving 2024). Such conditions may facilitate establishment of thermophilic species and allow early reproduction under otherwise unsuitable climates (Borden and Flory 2021; Hidalgo García and Rezapouraghdam 2023). Observations of successful reproduction of *Testudo hermanni* and *Elaphe taeniura* in Belgium, and of *Trachemys scripta* subspecies in Germany illustrate this trend (Schradin 2020; van Doorn and Speybroeck 2021; van Doorn et al. 2021). Sporadic reproduction of *T. scripta* has also been reported in the Netherlands, and climate change is expected increase future establishment probabilities (Struijk 2022). A small reproducing population of *Lacerta bilineata* in the warm dune microclimate of Scheveningen (City of The Hague) further demonstrates that urban heat islands can temporarily enable breeding of thermophilic reptiles beyond their native range limits (Struijk et al. 2022).

Winter survival remains a key determinant of establishment in temperate regions. While prolonged sub-zero temperatures limit many species (Storey and Storey 2012), mild winters facilitated by UHIs or climate change may lower these thermal barriers, enabling species such as *Aquarana catesbeiana* and *Xenopus laevis* to expand into northern Europe (Ficetola et al. 2007; Bestion et al. 2015). Beyond UHIs, rail corridors and adjacent verges can generate locally warm, disturbed microhabitats and act as low-friction linear conduits for dispersal; ballast and sun-exposed embankments retain heat and provide stepping stones from urban release points to peri-urban wetlands, enabling secondary spread even where broad-scale climate appears marginal (Ascensão and Capinha 2017).

Role of the pet trade in the spread of alien herpetofauna

The pet trade is widely recognized as a dominant, but not the only, introduction pathway for alien herpetofauna (Kraus 2009; Lockwood et al. 2019). In this study, for 43 of the 93 species with a climate match risk assessments are available, indicating that many taxa currently or historically traded in the Netherlands have already been evaluated for their potential establishment and invasion risk. Although alternative pathways exist, such as hitchhiking with ornamental plants or accidental transport, only a few species are strongly linked to these routes (Kraus 2009). The Italian wall lizard (*Podarcis siculus*), for instance, has colonized new areas via the ornamental plant trade, hitchhiking on imported olive and palm trees, as well as through the transport of stone materials, such as tufa and other building stone imported from Italy (Rivera et al. 2011; Hodgkins et al. 2012; Tuniyev et al. 2020; CABI 2021). Most alien herpetofauna records in northwestern Europe are consistent with intentional or accidental releases of pets (Kraus 2003, 2009; Krysko et al. 2011, 2016). In Italy, for example, most records of the snapping turtle (*Chelydra serpentina*) occur near exotic-animal fairs or rescue facilities, suggesting such trade-related venues act as focal points releases and escapes (Ferri et al. 2024). Once released, transport networks (railways, roads, canals) can facilitate secondary spread, a process especially relevant to the highly connected Dutch landscape (Ascensão and Capinha 2017). Thus, while the pet trade is central, it is not the only route by which alien herpetofauna arrive and spread in the region.

Ecological and societal risks

Alien herpetofauna pose risks through competition, predation, hybridization, and pathogen transmission. The Italian wall lizard *P. siculus* can outcompete and prey on native lizards (*Zootoca vivipara*, *Podarcis muralis*, *Lacerta agilis*) and has been implicated in declines of the Iberian wall lizard (*P. virescens*) in Spain (Capula and Aloise 2011; Grano et al. 2011; Damas-Moreira et al. 2020). Hybridization with native species threatens the genetic integrity of native amphibians. The Italian crested newt *Triturus carnifex* and the marbled newt *T. marmoratus* both hybridize with the native great crested newt (*T. cristatus*) in the Netherlands and other European countries, creating fertile hybrids leading to ongoing introgression (Arntzen and Hedlund 1990; Arntzen and Wallis 1991; Arntzen and Thorpe 1999; Meilink et al. 2015). Similar risks exist for grass snakes, where introgression from alien *Natrix natrix* has been detected in native *N. helvetica* populations (van Riemsdijk et al. 2020).

Pathogen transmission represents a major concern. Amphibians are particularly vulnerable, with several alien taxa acting as reservoirs. Globally, the American bullfrog *Aquarana catesbeiana* is a well-documented carrier of *Batrachochytrium dendrobatidis* (Bd) and ranaviruses. Historically, its confirmed outdoor presence in the Netherlands was limited to isolated occurrences that were successfully eradicated, and the species is no longer considered a source of ongoing infection in Dutch ecosystems. However, recent environmental DNA (eDNA) detections in Zuidoost-Brabant indicate recent presence near the Dutch–Belgian border, although no live individuals have yet been confirmed (RAVON 2025). Elsewhere in Europe, traded amphibians have introduced Bd and ranaviruses, and such pathogens have caused mortality events in native species (Une et al. 2009; Sharifian-Fard et al. 2011; Spitzen-van der Sluijs et al. 2014; Miaud et al. 2016; O'Hanlon et al. 2018). The chytrid fungus *Batrachochytrium salamandrivorans* (Bsal), introduced via the pet trade through Asian salamanders, has devastated Dutch fire salamander populations, as infected individuals typically die within weeks, leading to rapid local population collapse (Martel et al. 2013; Spitzen-van der Sluijs et al. 2013; Martel et al. 2014; Lötters et al. 2020).

In addition to ecological effects, alien herpetofauna pose several other risks to society. Venomous species such as *Vipera aspis* and rattlesnakes (*Crotalus adamanteus* and *C. atrox*) are occasionally traded and could cause severe envenomation if released (van de Koppel et al. 2012a, b; Bugter et al. 2014). Escape incidents, such as a green mamba (*Dendroaspis angusticeps*) in Tilburg (Netherlands) in 2023, illustrate temporary but acute public-safety threats (NOS 2023). Reptiles and amphibians can also carry zoonotic pathogens, including *Salmonella*, *Cryptosporidium*, *Borrelia*, and various other bacteria, protozoans, and viruses (Une et al. 1999; Hervás et al. 2002; Soares et al. 2004; Takano et al. 2010; Široký et al. 2014; Ježková et al. 2016; Mitura et al. 2017; Mendoza-Roldan et al. 2019; Marin et al. 2021). Public-safety concerns have also arisen from large predatory turtles released into open waters, including several captures of *Chelydra* *serpentina* and *Macrochelys temminckii* in recent years (Omrop Fryslân 2018; Ferri et al. 2024; The Guardian 2024; VRT News 2024). Even single release events can generate substantial management costs, as demonstrated by the 2013 Irsee (Bavaria) incident, where authorities drained a bathing lake and conducted extensive searches after a presumed snapping turtle bite (AD 2013; Independent UK 2013; Süddeutsche Zeitung 2013, 2014, 2023).

Knowledge gaps

Despite numerous records of alien herpetofauna in northwestern Europe, quantitative data on ecological impacts remains scarce (Kraus 2009, 2015). Many risk assessments rely on expert judgment rather than empirical data (Gurevitch and Padilla 2004; Barney et al. 2013). Our use of a coarse Köppen-Geiger-based method for climate matching is appropriate for horizon scanning, but not for fine-scale predictions. While climatic similarity strongly predicts establishment success (Howeth et al. 2016; Du et al. 2024), climate matching alone cannot fully capture establishment likelihood due to issues of transferability across regions and species' potential for niche shifts (Liu et al. 2020, 2022). This creates uncertainty about which species will ultimately establish in northwestern Europe, especially under changing climates. Newer frameworks that explicitly test transferability between donor and recipient regions (e.g., Mobility-Oriented Parity; Escoriza et al. 2024) are informative, but equivalent analyses are still lacking for northwestern Europe, leaving fine-scale establishment probabilities uncertain. Combining physiological tolerances, species sensitivity distributions (Del Signore et al. 2016), and field data may substantially improve predictions (Collas et al. 2018, 2019; Thunnissen et al. 2019). Such data are currently lacking for most species included in this study.

Management implications

Prevention remains the most effective strategy to limit introductions (Blackburn et al. 2011; Matthews et al. 2017). In the context of the online pet trade examined here, prevention should focus not only on reducing the likelihood that traded animals are deliberately released or translocated after purchase, but also on regulating the online pet trade in invasive herpetofauna species with significant adverse ecological or socioeconomic impacts, in line with the Invasive Alien Species Regulation (Regulation (EU) 1143/2014). Such releases often occur when animals become too large, aggressive, or costly to maintain, or when owners lose interest (Stringham and Lockwood 2018). In the Netherlands, deliberate translocations by garden pond owners are widespread and driven by a range of motivations, illustrating the importance of human decision-making in post-purchase animal movements (Prins et al. 2025). In this context, education and awareness are key tools to address deliberate release and translocation of traded animals by pet owners and hobbyists. Evidence from religious animal release practices (like turtles and bullfrogs in Buddhist contexts in China), in which animals are deliberately purchased for ceremonial release, shows that increasing ecological knowledge can reduce the likelihood of deliberate animal release (Liu et al. 2013). Evaluations of education and training initiatives in other contexts further show that increasing ecological knowledge can be accompanied by improvements in biosecurity practices and management-related behavior among stakeholder groups (Li et al. 2021; Shannon et al. 2020).

The Dutch government is currently developing a "pet list" (de huis- en hobbydierenlijst) of herpetofauna permitted in trade, which may become an important tool to prevent import and sale of high-risk species (RVO 2025). Including climate match and risk-assessment evidence in such regulatory frameworks could substantially reduce invasion risks.

Quarantine and pathogen screening of imported animals remain critical (Lynch 2001). Containment and eradication are most effective when implemented early, as shown for *Podarcis siculus* invasions in the UK and Greece (Hodgkins et al. 2012; Adamopoulou and Pafilis 2019). In a highly connected country like the Netherlands, priority should be given to monitoring transport hubs, urban ponds near trade venues, and canal junctions (Ascensão and Capinha 2017; Ferri et al. 2024).

Conclusion

The Dutch pet trade acts as a major entry point for alien herpetofauna into northwestern Europe. Of the 93 climatically plausible species, nearly half of those with available risk assessments are associated with ecological or societal risks. The true proportion is likely higher because more than half of the climatically plausible species lack formal evaluations. Effective management requires proactive regulation, horizon scanning, education, and rapid detection and eradication. Given the Netherlands' combination of high import volumes and dense infrastructure, integrating biosecurity into transportation planning and pet-trade regulation will be essential to limit future invasions.

Authors' contribution

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

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Ethics and permits

The research pertaining to this article has been performed has been carried out in accordance with the Netherlands Code of Conduct for Research Integrity of the Association of Universities in the Netherlands (VSNU) and did not require research permit(s).

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Supplementary material

The following supplementary material is available for this article:

Table S1. List of herpetofauna species in the Dutch pet trade (n = 515).
Table S2. List of climate match species (n = 93) with plausibility indicators.
Table S3. List of on-line pet stores and forums that were queried for additional information on presence of herpetofauna species in the trade.
Table S4. Overview of risk assessments and scoring for four impact categories.
Table S5. Original risk scores of alien herpetofauna with a climate match to north-western Europe.
Table S6. Species with existing risk assessments for north-western Europe and effects on biodiversity (n = 93).
Table S7. Harmonized risk scores and assessment basis.

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