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EDITORIAL

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Advancing research on alien species and biological invasions

Editorial

Daniela Giannetto[1], Marina Piria[2], Ali Serhan Tarkan[3], Grzegorz Zięba[4]

1 Department of Biology, Faculty of Science, Muğla Sıtkı Koçman University, 48000 Menteşe, Muğla, Turkey **2** *University of Zagreb, Faculty of Agriculture, Department of Fisheries, Apiculture, Wildlife Management and Special Zoology, 10000 Zagreb, Croatia* **3** *Department of Basic Sciences, Faculty of Fisheries, Muğla Sıtkı Koçman University, 48000 Menteşe, Muğla, Turkey* **4** *Department of Ecology and Vertebrate Zoology, Faculty of Biology and Environmental Protection, University of Lodz, 90-237 Lodz, Poland*

Corresponding author: Grzegorz Zięba (grzegorz.zieba@biol.uni.lodz.pl)

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Species introductions are a major concern for ecosystem functioning, socio-economy and human well-being (Vilà et al. 2010; Lockwood et al. 2013; Diagne et al. 2021; Zenni et al. 2021). However, despite measures for prevention and control, a large number of non-native species have been identified in the last decades worldwide in both aquatic and terrestrial environments (IPBES 2019; Lowe et al. 2000; Guo et al. 2021). Although preventing introductions has proved to be the most effective management strategy (Wittenberg and Cock 2001; Pergl et al. 2016), extant non-native species are still expanding their distributional range and new non-native species are being recorded (Seebens et al. 2017). Non-native species introduced into new environments may represent a serious ecological and economical threat, especially if they spread rapidly in a new region and thus become invasive (Ricciardi et al. 2021; Cuthbert et al. 2021). Further, geographical areas that act as biodiversity hotspots with a high level of endemism are especially threatened by invasive species (Ribeiro and Leunda 2012). Hence, the identification of those non-native species that are likely to become invasive may be of crucial importance for the development of prevention measures, which can be achieved by risk screening studies (Adams and Lee 2012).

In the risk analysis process applied to non-native species (as defined in Copp et al. 2005), the first step is risk identification (a.k.a. risk screening), the second step is risk assessment, and the third step is risk management and communication (Canter 1993; UK Defra 2003). The risk screening of non-native species aims to identify which non-native species are likely to be invasive in a given risk assessment area, and the follow-up risk assessment for the highest risk species involves detailed examination of the likelihood and magnitude of risks of: (i) introduction (entry); (ii) establishment (of one or more self-sustaining populations); (iii) dispersal (more widely within the risk assessment area, i.e. so-called secondary spread or introductions); and (iv) impacts (to native biodiversity, ecosystem function and services, and the introduction and transmission of diseases) (see Vilizzi et al. 2022). Identification of potentially invasive species facilitates the development of policy and management procedures with regard to a specified risk assessment area to prevent and/or mitigate the impacts of biological invasions (Copp et al. 2016a).

Electronic decision-support tools for non-native species risk screening are becoming an essential component of government strategies to tackle non-native species invasions. The recent availability of user-friendly and widely deployable multilingual electronic tools (e.g. Copp et al. 2016b, 2021; Vilizzi et al. 2021) can facilitate early detection of potential threats, hence provide useful information to assist environmental managers and policy-makers in making decisions for the appropriate management and conservation of ecosystems. To this end, the Weed Risk Assessment (WRA: Pheloung et al. 1999) developed for terrestrial plants and later adapted to screening aquatic plants (Gordon et al. 2008) is a widely used decision-support tool. The WRA template inspired the '-ISK' (Invasiveness Screening Kit) family of decision-support tools developed for aquatic organisms (Copp et al. 2005; Copp 2013; Vilizzi et al. 2019), which were recently combined into the taxon-generic Aquatic Species Invasiveness Screening Kit (AS-ISK) to screen freshwater, brackish and marine aquatic organisms under current and future climatic conditions (Copp et al. 2016b, 2021; Vilizzi et al. 2021).

Despite the existence of the above-mentioned decision-support tools and a large number of published applications worldwide (e.g. Gordon et al. 2008; Vilizzi et al. 2019, 2021), there remain several knowledge gaps in the risk screening of non-native species with relevance to the following topics: (i) the relative dearth of information on the invasiveness of non-native aquatic species in taxonomic groups other than fishes and aquatic invertebrates; (ii) the paucity of risk screening studies focusing on biodiversity hotspots and/or tropical areas; (iii) the requirement for updated information on species invasiveness within a dynamic risk screening and comparative perspective; and (iv) the need for a taxon-generic decision-support toolkit for screening terrestrial animals and related applications.

All papers in this Special Issue were designed to address at least one of the research topics mentioned above so as to fill current knowledge gaps and provide novel information in the risk screening of freshwater and terrestrial non-native species.

Invasiveness of non-native aquatic plants and pathogens

The use of inconsistent and ambiguous terminology about invasive non-native species, together with the lack of focus on their potential impacts, limit understanding of their biology and role in the invaded ecosystems (Verbrugge et al. 2021). Insufficient understanding also causes a lack of public awareness and a consequent shortage of dedicated studies. **Fachinello et al. (2022)** emphasised this point by applying a scientometric approach to analyse academic documents on non-native plant species in Brazil published between 2002 and 2021. The authors found that only 13% of the 398 examined publications provided a clear definition of 'invasive species'. Of these publications, only 23.8% reported some type of damage caused by the invasive species and only 5% addressed economic or social damage. The authors also showed that only 17% of the publications proposed a method for control and/or mitigation of biological invasions and encouraged the use of further scientometric studies to guide future efforts to support more objective measures for management and decision-making.

There is still a lack of literature and relevant research on the distribution of non-native aquatic plants in some areas, despite their posing a serious threat to native macrophyte community composition by disrupting natural flow dynamics, depleting oxygen and altering food web structure and soil properties. To fill this knowledge gap and with the aim to help prioritisation measures for the proper management of non-native aquatic plants under projected climate conditions, **Piria et al. (2022)** identified and screened 10 extant and 14 aquatic plant species from a horizon scanning for their risk to become invasive in the Pannonian and Mediterranean regions of Croatia. The authors classified 90% and 60% of the extant aquatic plant species as carrying a high risk for the Pannonian and Mediterranean regions, respectively, under current and future climate conditions. Further, 42% of the species from a horizon scanning were classified as high-risk under current climatic conditions, but increased to 78% under a scenario of global warming.

Although most risk analyses in invasion biology have focused on the invasiveness of non-native species, some (dominant) native species can also pose a high risk of becoming invasive, especially under current global change. **Yazlık and Ambarlı (2022)** used an adaptation to Turkey's geographical and climatic conditions of the WRA decision-support tool to evaluate the risk of invasiveness of ten plant species (five non-native and five native) all known to be invasive in several parts of the world. Based on the resulting risk scores, all non-native species were classified as invasive and all native species as 'expanding' for Turkey. The outcomes of the study suggested that species can carry several risk-related traits resulting in high-risk scores irrespective of their origin. The authors also emphasised the importance of including dominant species with high environmental and socio-economic impacts in their habitats as part of priority lists for the implementation of management measures, hence irrespective of the species' origin (i.e. native or non-native).

Introductions of non-native species can drive disease emergence by extending the geographical range of associated parasites and pathogens (Foster et al. 2021), although limited research on this topic is available to date. The aquatic ornamental industry is one of the main introduction pathways for freshwater fish invasions, which can also act as a driver of disease emergence from associated parasites and pathogens by extending their geographical range (Chan et al. 2019). The increase in temperatures projected under future climate change scenarios is likely to increase the probability of survival and establishment of some commonly traded tropical and subtropical non-native ornamental fish species, even in geographical areas such as Northern Europe, which is currently not (yet) climatically suitable for their survival. **Guilder et al. (2022)** screened 24 of the 233 ornamental aquatic species (fishes and invertebrates) identified as traded in the UK for potential parasites and pathogens and reported a total of 155 of them of which the majority were platyhelminths, viruses and bacteria. Some potential parasites and pathogens currently absent from UK waters and with zoonotic potential were also identified, and their presence was highlighted in the context of understanding potential impacts in addition to the provision of evidence to inform risk assessment and mitigation approaches.

Biodiversity hotspots

Biological invasions are considered to be one of the most important threats to global biodiversity (Jeschke et al. 2022), particularly in biodiversity hotspots where non-native species may cause extensive damage to native species and ecosystems (Magalhães and Jacobi 2013). Preserving biodiversity and maintaining ecosystem function is of utmost importance not only in geographically large ecosystems but also in vulnerable biodiversity hotspots, which often host a large number of rare and/or endemic species. The South Caucasus represents one such biodiversity hotspot that includes the countries of Armenia, Azerbaijan and Georgia. **Mumladze et al. (2022)** screened 32 non-native extant and fish species from a horizon scanning for their risk of invasiveness under current and projected climate conditions in this risk assessment area. The number of very high-risk species increased from four (12.5%) under our current climate to 12 (37.5%) under projected climate conditions.

The Balkan Peninsula is also considered an important area for freshwater biodiversity due to the high number of endemic species (Hewitt 2011; Ćaleta et al. 2019). This region is particularly important for the high diversity of salmonid species that are being threatened by the introduction of non-native salmonids (Škraba Jurlina et al. 2020) and for which little is known about their potential risk of invasiveness, especially under predicted climate change conditions. **Marić et al. (2022)** screened 13 extant and four non-native salmonid species from a horizon scanning for their risk of becoming invasive in the Danube and Adriatic basins of four Balkan countries. Six (35%) of the screened species were ranked as high-risk under current climate conditions, although they decreased to three (17%) under projected conditions of global warming. Species ranked as medium-risk under current conditions were also medium-risk under future climate projections, although the relative risk score decreased. The authors concluded that global warming would influence salmonids and that only species with a wider temperature tolerance such as rainbow trout *Oncorhynchus mykiss* will likely prevail.

Comparative perspectives

One of the most important challenges in research (including risk screening studies) conducted simultaneously or repeated by several researchers to obtain reliable and reproducible results is to achieve the maximum possible compliance. A major challenge in risk assessment studies is to collect information on the overall severity and extent of consistency in responses, and empirical information on the factors influencing consistency across assessors is still not fully available. **Bernardo-Madrid et al. (2022)** quantified and compared the consistency in the scores of questions for impact assessment protocols with inter-rater reliability metrics. The authors provided an overview of impact assessment consistency and the factors altering it by evaluating 1,742 impact assessments of 60 terrestrials, freshwater and marine vertebrates, invertebrates and plants conducted using seven protocols applied in Europe. The authors reported that the great majority of assessments (67%) showed high consistency and only a small minority (13%) low consistency. Consistency of responses did not depend on species' identity or the amount of information on their impacts, but partly on the impact type evaluated and the protocol used.

Stable isotope analysis is commonly used to reconstruct species' feeding ecology and their trophic interactions within communities. Therefore, stable isotope analysis has been considered a sensitive and powerful tool to reveal competition and predation processes in food webs and used to quantify the ecological effects of non-native species (Sagouis et al. 2015). **Balzani and Haubrock (2022)** proposed the implementation of stable isotope analysis as an approach for assessment schemes to increase the accuracy in predicting invader impacts as well as the success of reintroductions and assisted migrations. The authors reviewed and discussed possibilities and limitations of using this method and suggested promising and useful applications for scientists and managers.

Development of a screening toolkit for terrestrial animals

Despite the availability of decision support tools for terrestrial animals, they are often in spreadsheet format which can make their usage time-consuming, if not counter-intuitive, to the end user. However, still there is no user-friendly, dialog-driven electronic decision-support tool, such as AS-ISK screening toolkit, available for terrestrial animals. Kopecký et al. (2019) remedied the lack of a dedicated screening tool using the AS-ISK as a 'surrogate' to screen terrestrial reptiles which highlighted need for its development. In this special issue, **Vilizzi et al. (2022)** described the development of a multilingual decision-support tool for screening terrestrial animals, namely the Terrestrial Animal Species Invasiveness Screening Kit (TAS-ISK). Based on the programming architecture of the AS-ISK and the questionnaire template common to the WRA-type toolkits, the TAS-ISK consists of 55 questions of which 49 deal with the species' biogeographical/historical traits and biological/ecological interactions and six are aimed to predicting the potential influence of climate change on the risks of introduction, establishment, dispersal and impact of the screened species. The authors also reported the results of nine trial screenings for each representative species in the main taxonomic groups of terrestrial animals supported by the toolkit: mammals, birds, reptiles, amphibians, annelids, insects, molluscs, nematodes, and platyhelminths.

Conclusions

Although the current research findings may not solve all identified shortcomings related to research in the risk screening of non-native species, all papers in this Special Issue have contributed to fill at least partially the existing gaps. The content of the Special Issue has helped to emphasise the importance not only of using appropriate nomenclature but also of a comprehensive approach to understanding the threat posed by non-native species and to multi-author risk screening studies. Alarming data have arisen on how many non-native species of aquatic plants could pose a threat to local communities, especially under projected conditions of global warming. These data are even more worrying considering the high potential invasiveness emerged also for some native plant species. At the same time, projected conditions of global warming may mitigate the invasiveness risk of some non-native species such as some salmonids that are not tolerant to high temperature fluctuations. The accidental spread of aquatic potential parasites and pathogens is also of concern and especially with regard to the fate of biodiversity hotspots. Finally, the proposal of novel approaches for assessment schemes based on different techniques such as stable isotope analysis together with the availability of the newly developed TAS-ISK decision-support tool for the risk screening of terrestrial animals, is expected to assist researchers and stakeholders and increase accuracy in predicting the impacts of biological invasions.

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