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Review

Pathways and gateways of freshwater invasions in Europe

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Abstract

Taking into account the continuous increase in freshwater introductions, and to support the recent European legislation on invasive alien species, the identification of priority pathways and gateways of introductions is of utmost importance to develop adequate control strategies. The aim of this paper was to analyse the main pathways and gateways of introductions of freshwater alien species in Europe. Based on a thorough review of the scientific and grey literature, information on pathways, country and year of initial introduction of all freshwater alien species in Europe, was retrieved. The spatial and temporal patterns and trends of biological invasions in freshwater ecosystems in Europe, in relation to different pathways, were assessed. Our results pinpoint the major importance of aquaculture, pet/aquarium trade and stocking activities as pathways of introduction of freshwater alien species in Europe. For species native to some European countries, shipping and inland canals were the most important pathways, highly responsible for the entry of many harmful species. Germany, the United Kingdom and Italy were the main entry gateways of freshwater alien species in Europe. We found a geographical pattern related to some pathways of introduction in Europe: introductions through inland canals were concentrated in Central/North-eastern Europe, while introductions through pet/terrarium/aquarium trade were mainly observed in Central/Western Europe. While Chordata species entered Europe mainly through the three major above mentioned pathways, many harmful Arthropoda and Mollusca entered through shipping and inland canals. The information gathered in this study clearly indicates the entry routes that should be prioritised by Member States, for which stronger control and management actions should be implemented and prevention efforts concentrated under the scope of the related new EU Regulation.

Key words: alien species, aquaculture, aquarium trade, country of introduction, Europe, pathway of first introduction

Introduction

Freshwater ecosystems are subject to a full range of anthropogenic threats such as habitat loss and fragmentation, hydrological alteration, climate change, overexploitation, pollution and introduction of alien species (Dudgeon et al. 2006). Therefore, rates of biodiversity loss in these ecosystems are currently greater than those recorded in the most affected terrestrial biomes (Ricciardi and Rasmussen 1999; Jenkins 2003). Among the most important hazards, the introduction of species outside their natural range is widely recognised to be one of the main threats to biodiversity and the second leading cause of animal extinctions (MEA 2005). For example, 20% of the 680 species extinctions listed by the IUCN were caused by invasive alien species (Clavero and García-Berthou 2005). The global number of introduced species has increased exponentially due to globalisation, and the pathways of their introduction have proliferated (Hulme et al. 2008; Hulme 2009; Vilà et al. 2010). This is also true for Europe where the number of invasive alien species (IAS) showed an increase of 76% between 1970 and 2007 (Butchart et al. 2010), representing a constant pressure on native ecosystems,

particularly inland waters. For centuries, freshwaters have been subject to more widespread invasions than terrestrial systems (Sala et al. 2000; McKinney 2001; Gherardi 2007; Karatayev et al. 2007). This vulnerability is the effect of intensive human use, natural linkages among streams and lakes, and the dispersal capability of aquatic organisms (Beisel 2001; Ricciardi 2001). Understanding the mechanisms of biological invasions is crucial for the management and conservation of freshwater ecosystems.

Since 1992, the Convention on Biological Diversity (CBD) has recognised the importance of managing invasive alien species, calling for a rigorous and categorised approach to this issue in 2002 through prevention, eradication and control. In the last Strategic Plan for Biodiversity (2011–2020), Target 9 of the Aichi Biodiversity Targets states that "By 2020, invasive alien species and pathways are identified and prioritised, priority species are controlled or eradicated, and measures are in place to manage pathways to prevent their introduction and establishment."

Since IAS are extremely difficult to be managed after their establishment (Genovesi 2005; Vilà et al. 2010), scientific effort should be directed at finding appropriate means to prevent their entry into new areas, including through surveillance of potential pathways and identification of main recipient areas of introductions. According to Article 11 of the new European Regulation on IAS (EU 2014), Member States will have to carry out a comprehensive analysis of the pathways of introduction of IAS in their territory and identify the pathways that require priority action. Moreover, identification of key recipient regions of introductions may help to prevent, control or eradicate new introductions, pinpointing geographical areas where management should be focused (Vermeij 1996).

The main pathways of introduction of freshwater alien species in Europe are associated with a wide range of human activities and the intensity with which humans utilise freshwater systems for recreation, food sources and commercial purposes. Aquaculture - the farming of aquatic organisms such as fishes, shellfishes and aquatic plants under controlled conditions - is one of the fastest-growing sectors of the world food economy (Naylor et al. 2001). In Europe, the general trend is to farm mostly alien species (Turchini and De Silva 2008), which has caused the introduction of numerous species as commodities or accidental contaminants of the introduced commodities, often leading to irreversible ecological impacts (Naylor et al. 2001; Gozlan 2008; Keller et al. 2011). Transport by ships has been particularly important for freshwater animal introductions to Europe, with many species becoming harmful invaders after dispersal via ballast water of ships or following attachment to hulls as fouling organisms (Gherardi et al. 2009). Many alien fish species have been deliberately stocked in the wild, aiming to promote the development of commercial fisheries and recreational angling (Gherardi et al. 2009; Tricarico 2012). In fact, the introduction of alien fish species for recreational angling is recognised as a global environmental problem and considered one of the principal causes of biodiversity loss in freshwater ecosystems (Cambray 2003). The ornamental/aquarium trade, an activity involving the movement of thousands of species around the globe for ornamental reasons, has been increasingly recognised as a major driver of introductions of freshwater organisms (Copp et al. 2010; Strecker et al. 2011). In Europe, the aquarium trade has been identified as an important source of freshwater fish introductions, involving an enormous diversity of species (Copp et al. 2010; Maceda-Veiga et al. 2013). The European network of inland waterways, made up of >28000 km of navigable rivers and constructed canals, connects catchments of southern European seas (Caspian, Azov, Black, Mediterranean) to northern European seas (Baltic, North, Wadden, White). The construction of these inland canals connecting previously isolated waterbodies has enabled introductions of a high number of aquatic alien species within Europe (Bij de Vaate et al. 2002; Galil et al. 2007; Panov et al. 2009).

The aim of this study was to analyse the spatial and temporal patterns of the main pathways of first introduction of all freshwater alien species in Europe. The information gathered here could be a crucial contribution for assisting the achievement of CBD's Aichi Biodiversity Target 9 and for Member States to accomplish some of their obligations - identification of priority pathways in their territories - under the scope of the new EU Regulation on IAS. Ultimately, our goal is to assist the prioritisation of management measures on both national and European levels aiming at halting the current trend of increasing freshwater alien species introductions in Europe.

Methods

In order to analyse the spatial and temporal patterns and trends of the main pathways and gateways of initial introductions of freshwater alien species in Europe, we used the inventory of

freshwater alien species present in Europe archived by the European Alien Species Information Network (EASIN; Katsanevakis et al. 2012) and updated as of February 2014 (version 3.2 of the EASIN Catalogue; see Supplementary Material Table S1). This inventory is regularly updated (usually every 2–3 months) and publicly available online (http://easin.jrc.ec.europa.eu/use-easin/species-search/combined-criteria-search). It currently (February 2014) includes 756 freshwater species reported as established aliens or suspected to be alien in European inland waters. The latter include 45 cryptogenic species (species for which there is no certainty about their native or introduced status in the area) and 160 questionable species (species for which there is insufficient information, with unresolved taxonomic status or new introductions not yet verified by experts). Species that are partly native to Europe, i.e. species that are native to a certain region in Europe, but have been introduced in other parts of Europe (also referred to as aliens within Europe), were also included in this study and analysed separately. EU overseas territories were not considered.

The classification of pathways of initial introduction of alien freshwater species used here followed Hulme et al. (2008), with slight modifications adapted to freshwater environments. Alien species can be introduced as a direct or indirect result of human activities, through three major mechanisms: the importation of a commodity, the arrival of a transport vector, or dispersal from a neighbouring/connected region. Five out of the six main pathways of introduction resulting from these mechanisms have been considered here (each one divided into more specific sub-categories): Release (due to Biocontrol; Fisheries/angling; Pets, Terrarium-Aquarium species; Other); Escape (Cultivation and Livestock; Aquaculture; Ornamental planting; Use of live food-bait; Pets, Terrarium-Aquarium species; Zoos, botanical gardens); Contaminant (Trade of contaminated commodities; Aquaculture); Stowaway (Shipping; Land transport); Corridor (Inland canals). Species introduced through minor pathways, other than the abovementioned ones, were pooled together in a category named “Other”. Species for which reliable information on their pathway of introduction could not be found were classified as “Unknown”. The sixth pathway proposed by Hulme et al. (2008) refers to alien species that may arrive unaided to a region, as a result of natural spread following a human-mediated introduction into a neighbouring region; this pathway was not considered here, as we focus on the pathways of first introduction of species in Europe (or in a non-native region within Europe). Of the 756 freshwater alien species introduced in Europe, a single pathway of initial introduction was associated with the introduction of 472 species, while 78 species had more than one pathway, and no pathway could be inferred for 206 species.

Based on a thorough review of the scientific and grey literature, the country of initial introduction of freshwater species in Europe (hereafter ‘recipient country’) was identified for all 756 species, and the year of initial introduction for 703 species. For 20 species, more than one recipient country was associated with their introduction into Europe. This may occur when a species has been collected independently in the same year in different countries such as, for example, the mollusc *Helisoma duryi* (Wetherby, 1879) in Austria and Germany. In some cases, recipient countries can be identified with certainty (e.g. for most species introduced through aquaculture) but, when this was not possible, the country of first observation of the species in Europe was assumed to be the recipient country. The year of first observation of an alien species in Europe was also used as the best available estimate of the year of its initial introduction when the latter could not be determined with certainty. In the case of species partly native to Europe, the country and year of a species initial introduction/observation in a new non-native European region was used.

The number of initial introductions of freshwater alien species in Europe, as well as temporal trends of these invasions, in relation to different pathways of initial introduction, was assessed. The main gateways (i.e. recipient countries) of species introductions in Europe, and associated pathways per country, were also analysed. Finally, the number of introductions for each of the most common introduced freshwater taxa, considering the different status of alien species (established, cryptogenic and questionable) and different pathways of introduction, was investigated. Patterns and trends of species introductions were analysed separately for species alien to Europe and species partly native to Europe.

In order to look with more detail into freshwater alien species considered to have higher ecological or economic impact in Europe and try to understand if there are important pathways that are specifically associated with their introductions, we also looked at patterns and trends of ‘high-impact’ introduced species.

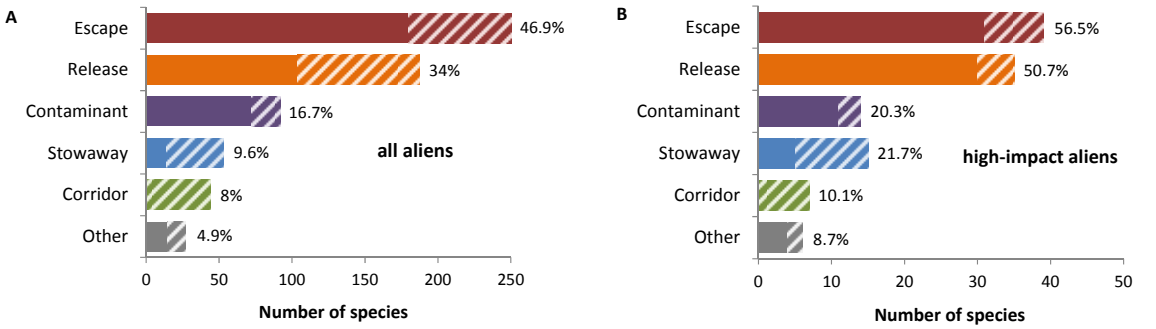


Figure 1. Number (and percentage) of freshwater alien species introduced for the first time in Europe through each of the six main pathways of introduction for **(A)** all species and **(B)** high-impact species. The diagonal white areas in each bar represent the proportion of partly native species to Europe introduced through a specific pathway. Percentages add to more than 100% because some species are represented in more than one category.

Species were characterised as 'high-impact' if they have been included in at least one of the following inventories: the '100 of The Worst' list of DAISIE (Delivering Alien Invasive Species Inventories for Europe; http://www.europe-aliens.org/speciesTheWorst.do), the NOBANIS factsheets on Invasive Alien Species (European Network on Invasive Alien Species; http://www.nobanis.org/Fact-sheets/), the SEBI 'List of worst invasive alien species threatening biodiversity in Europe' (Streamlining European 2010 Biodiversity Indicators; http://biodiversity.europa.eu/topics/sebi-indicators), or the GISD '100 of the World's Worst Invasive Alien Species' (Global Invasive Species Database; http://www.issg.org/database/species/search.asp?st=100ss).

Results

Analysis of pathways of introduction

Our results show that 43.9% of all the freshwater alien species of Europe are partly native to some region in Europe, and that 9.1% of all alien species are considered of high impact in Europe (27.5% of which are partly native).

The most important pathway of initial introduction, considering all alien species, was 'escape', while the second most common pathway was 'release', followed by 'contaminant', 'stowaway' and 'corridor' (Figure 1A). Most of the species introduced in Europe as stowaways (74%), and especially through corridors (98%), are partly native to Europe (Figure 1A). For the high-impact alien species, the importance of different pathways was quite similar to the one found for all alien species, except that stowaway was the third most important pathway, instead of contaminant (Figure 1B).

Concerning pathway sub-categories, more than half (53%) of the introductions through escapes have been due to escapes from aquaculture facilities, this percentage increasing to 55% for partly native species (Figure 2A). The majority of the releases into the wild have been due to aquarium trade, followed by fisheries/angling. Introductions through the contaminant pathway have been mostly due to aquaculture, but also due to the trade of contaminated commodities. Species introduced in Europe through stowaway and corridors (inland canals) are mainly partly native species, and the former have been essentially introduced due to shipping (98% of the species). Aquaculture and aquarium trade, both through escapes or releases, constitute the most important sub-categories of pathways of freshwater species introductions in Europe (Figure 2A).

For high-impact species, the importance of pathway sub-categories was quite similar to the one found for all aliens, except that in this case introductions of partly native species were represented in only half of the sub-categories, being mainly due to shipping, escape from aquaculture and inland canals (Figure 2B).

Temporal trends of new introductions in relation to pathways

There has been a continuous increase in the number of new introductions of freshwater alien species in Europe, especially in the last 60 years. From 1850 until 1949, the number of new introductions was <30, and then rose to over 60 for each subsequent 10-year period (Figure 3A). This has been accompanied by an increased

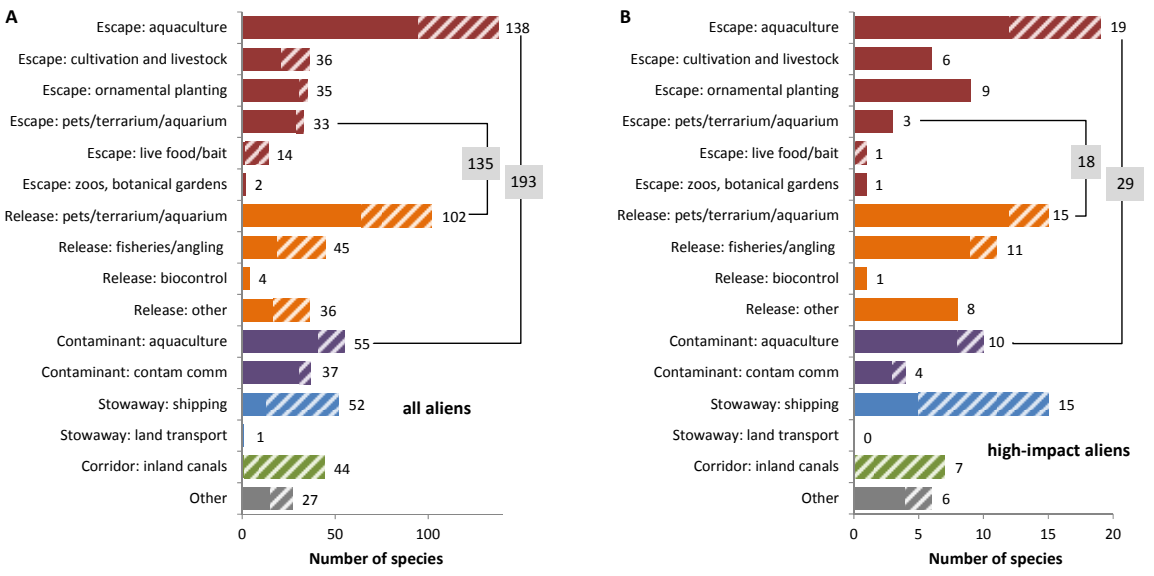


Figure 2. Number of freshwater alien species introduced for the first time in Europe through different sub-categories of each of the main pathways of introduction for **(A)** all species and **(B)** high-impact species. The diagonal white areas in each bar represent the proportion of partly native species to Europe introduced through a specific pathway. *Contaminant: contam comm* stands for trade of contaminated commodities.

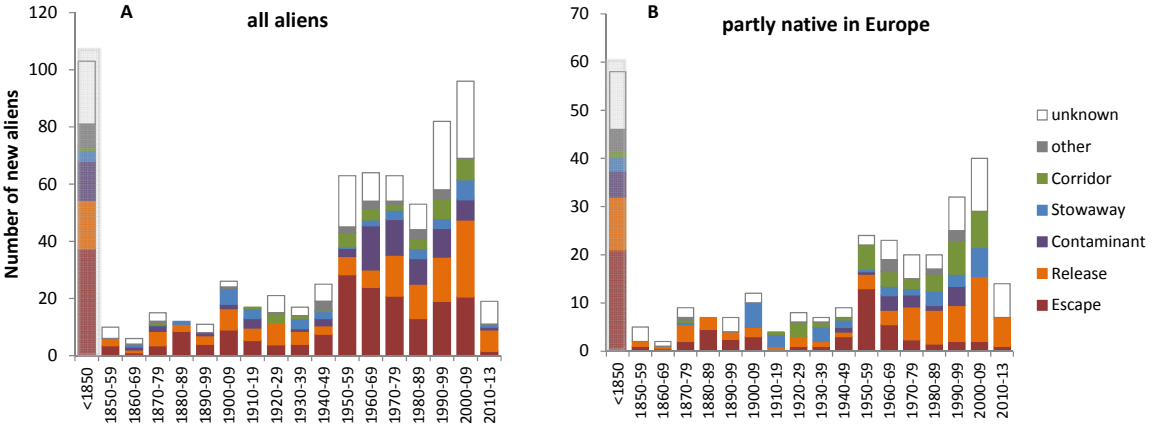


Figure 1. Temporal trends (over 10-year intervals) of new introductions of freshwater alien species in Europe considering the six main pathways of initial introduction for **(A)** all alien species and **(B)** partly native species to Europe. Species that were linked to more than one pathway (n= 78) were given a value of 1/k for each of the k associated pathways so that the overall contribution of each species to the total number of new alien species per period was always 1.

importance of 'stowaway', and especially 'corridor', as pathways of introduction. Overall, escapes have been the most important pathway of introduction throughout the years; however, in the period 2000–2009, introductions through releases peaked and exceeded the ones due to escapes. Although introductions as contaminants substantially increased in 1960, they have been gradually decreasing in importance to present. It is worth noting that the amount of introduced species with unknown pathways is still very high (Figure 3A).

For partly native species, there has been a gradual increase of introductions over time, more marked from the 1950s onwards. Once again, the corridor pathway has largely increased in importance during the same period. However, in

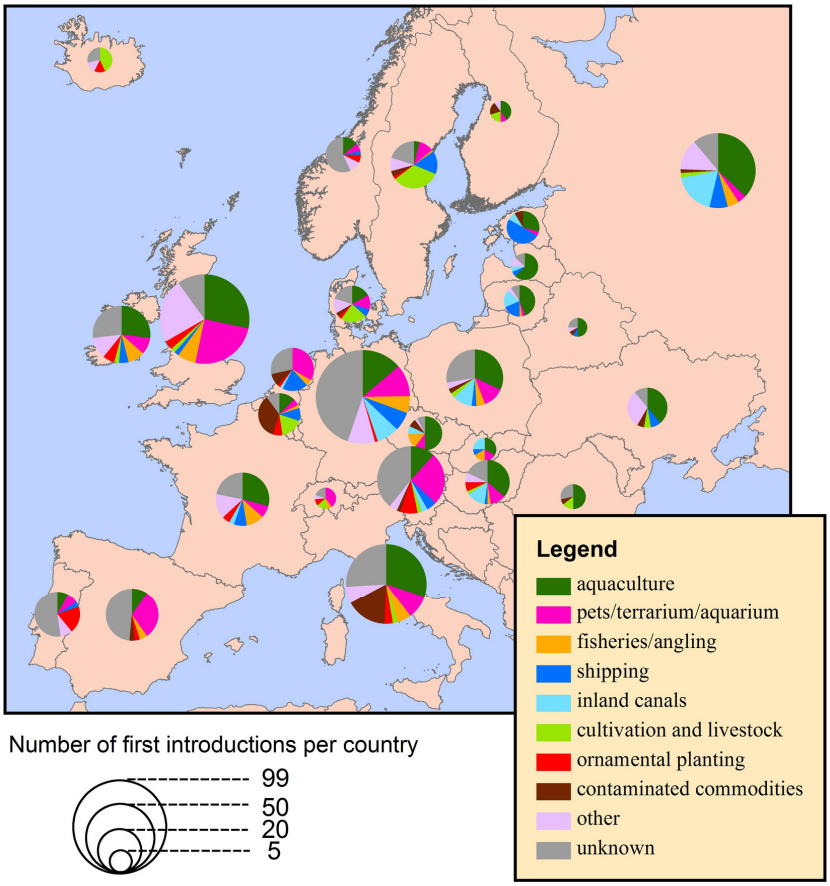


Figure 4. Proportion of freshwater alien species introduced for the first time in Europe through different pathways of introduction, per recipient country (i.e. countries of initial introduction in Europe). The size of the pie chart represents the number of species introduced for the first time in a specific country, with increasing intermediate sizes indicating an increasing number of species. Species that were linked to more than one pathway (n= 78) were given a value of 1/k for each of the k associated pathways so that the overall contribution of each species to each country was always 1.

this case, releases (and not escapes) have generally been the most important pathway throughout the years, especially since the period 1970–79. Fourteen out of the 19 new introductions registered in the period 2010–13 involved partly native species.

Gateways of introduction and associated pathways

Germany had the highest number of first introductions of freshwater alien species in Europe (99 species), followed by the UK (90), Italy (73), Russia (63), Austria (51) and Ireland (37) (Figure 4). For all these countries, except Austria, aquaculture was the most important pathway of introduction, with percentages ranging from 14 to 37%. In fact, 24 out of the examined 27 countries in Europe have reported first introductions through aquaculture and, for 17 of those recipient countries this was the most important pathway. In Austria, the main pathway was pet/aquarium/terrarium trade, being responsible for 25% of the introductions. In most of the Central/Western European countries, although aquaculture is still usually the major pathway, a high number of introductions (a maximum of 15 for the UK) have occurred due to releases and escapes of pet/aquarium species (Figure 4). Although few countries report species introductions through inland canals, most of them are located in Central and North-eastern Europe, with Russia and Germany having the highest number of introductions through this pathway. Like for aquaculture, introductions through shipping and fisheries/angling were quite widespread and distributed throughout many different countries, with Germany having the highest number of introductions through shipping and the UK through fisheries/angling. No country reported introductions through all the pathways, but Russia, Germany, Austria, Poland, Hungary and Sweden registered the highest diversity in pathways of initial introduction (Figure 4).

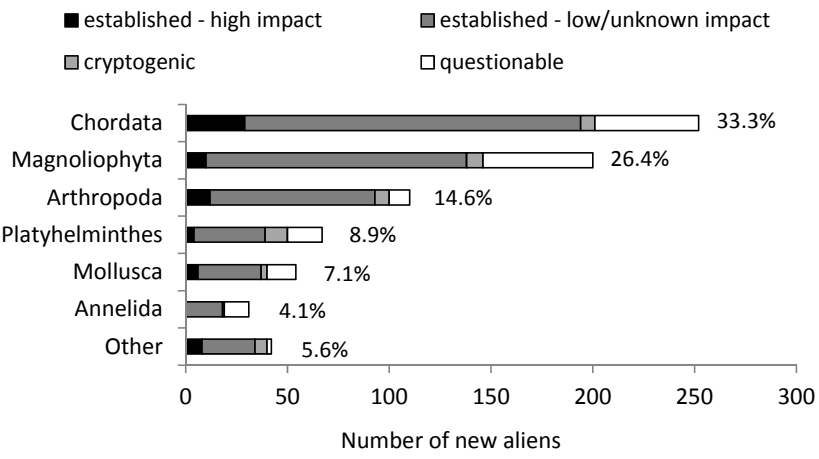
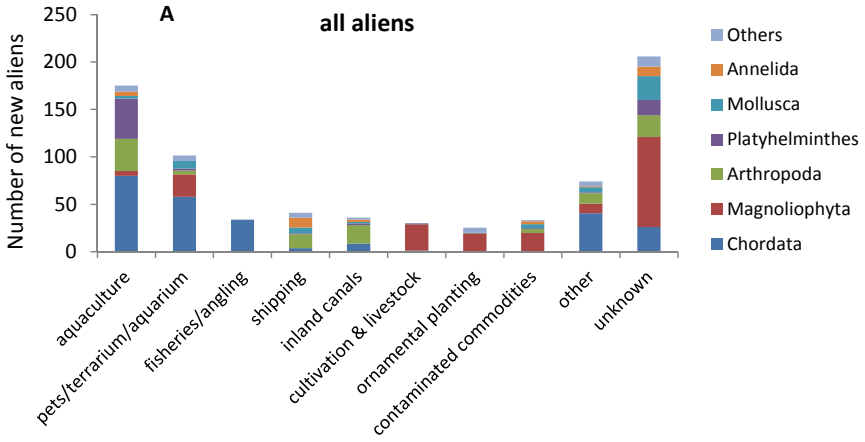


Figure 5. Number (and percentage) of freshwater alien species of the major taxonomic groups introduced for the first time in Europe, according to their status (established, cryptogenic or questionable) and impact (high or low/unknown).



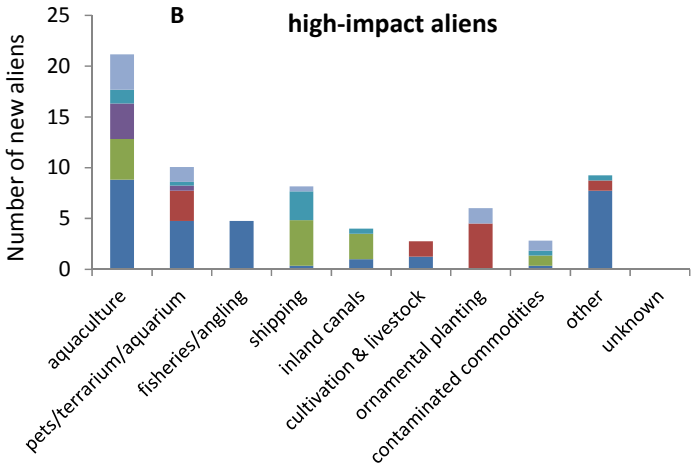


Figure 6. Number of freshwater alien species of the major taxonomic groups introduced for the first time in Europe through different pathways of introduction for **(A)** all species and **(B)** high-impact species. Species that were linked to more than one pathway (n= 78) were given a value of 1/k for each of the k associated pathways so that the overall contribution of each species to the total number of new alien species was always 1.

Main taxa introduced according to species status and introduction pathways

The taxa of freshwater species most commonly represented in first introductions in Europe were Chordata, followed by Magnoliophyta, Arthropoda, Platyhelminthes, Mollusca and Annelida; only few introductions have been reported for other minor taxa (Figure 5). Most of the introduced species have established populations in Europe, but for Chordata and Magnoliophyta a large proportion of these introductions concerns questionable species (20 and 27%, respectively). In all main taxonomic groups, there is a small proportion of species for which there is no certainty about their native or introduced status (cryptogenic species). Chordata, Arthropoda and Magnoliophyta have the highest proportions of species established with high-impact in Europe (Figure 5).

For all the freshwater alien species introduced in Europe, aquaculture was mostly responsible for the introduction of Chordata, followed by Platyhelminthes and Arthropoda (Figure 6A). Chordata was also the taxon most often detected in introductions due to pet/terrarium/aquarium trade (followed by Magnoliophyta and Mollusca) and the only taxon detected for introductions through fisheries/angling. Arthropoda was the main group introduced through both shipping and inland canals, and Magnoliophyta the main group introduced through cultivation and livestock, ornamental planting and trade of contaminated commodities. Freshwater species from the phylum Annelida were largely introduced into Europe through shipping. Aquaculture and trade of contaminated commodities were the only pathways having introductions of species from all the major alien freshwater taxa (excluding the 'unknown' pathway). There is a large proportion of species for which the pathway of first introduction in Europe is unknown, especially for Magnoliophyta (Figure 6A).

Concerning high-impact species, pathways of first introduction in Europe have all been identified (no 'unknown' category). Most of the harmful Chordata and Platyhelminthes seem to enter Europe through aquaculture. Shipping was responsible for most of the introductions of high-impact Arthropoda and Mollusca, and ornamental planting for introductions of high-impact Magnoliophyta. No freshwater Annelida species are classified as high-impact in Europe (Figure 6B).

Discussion

To the best of our knowledge, this study provides the first European-wide assessment of both the major pathways and gateways of first introductions for freshwater alien species in Europe. It also considers also patterns for species partly native to Europe and species with high impact in the environment. Aquaculture, pet/aquarium/terrarium trade, shipping and fisheries/angling were the most important pathways of initial introduction in Europe. Similar conclusions, based on smaller datasets, have been reached before (Gozlan 2008; Gherardi et al. 2009; Tricarico 2012). This clearly indicates the entry routes that should be prioritised in Europe and where stronger control and management actions should be implemented and prevention efforts concentrated.

Although aquaculture could seem a less complicated pathway to control given its fixed locations and associated regular procedures (Savini et al. 2010), existing control measures are not efficient, considering its relevant role in first introductions found here and elsewhere. Nevertheless, as this is a sector of great economic importance, invasions through this pathway will probably persist (Olenin et al. 2008). However, a framework ruling aquaculture practices for alien and locally absent species has recently become effective in the European Union (Council Regulation No 708/2007; EU 2014).

The pet/aquarium/terrarium trade, a pathway that has usually received less attention, especially in Europe, represents a multi-billion dollar industry responsible for the introduction of numerous alien plants, fishes and invertebrates worldwide (Padilla and Williams 2004; Maceda-Veiga et al. 2013). For example, in England, the distribution of alien fish occurrences is explained by demographic variables such as human population density, and numbers of pet shops and garden centres per unit area (Copp et al. 2010). The recent growth of aquarium trade (Maceda-Veiga et al. 2013) underlines the need of implementing specific regulations to prevent further invasions in Europe. Some of the possible management options are the implementation of enhanced education programs targeting the general public, particularly retailers and consumers, the improvement of regulation and monitoring of the pet/aquarium industry and the development of thorough monitoring systems for targeted contaminant species in aquarium trade (Strecker et al. 2011; Maceda-Veiga et al. 2013). At present, only a recommendation (154/2011) on a European code of conduct on pets and IAS exists.

Stocking activities for commercial fisheries or recreational angling (fisheries/angling) have been very important drivers of introductions of alien species in freshwater ecosystems in Europe for many decades (Gherardi et al. 2009; Savini et al. 2010). They are very challenging to manage because of the variety of target species involved in this pathway and greater efforts should be exerted to improve controls on these activities (Marr et al. 2010). Public education would be a good way to cut back unauthorised introductions and to increase awareness of the risks posed by IAS introductions in freshwater ecosystems (Gozlan 2008; Britton et al. 2011). In addition, agencies that regulate sport fishing should implement much more strict regulations on the use of alien species for stocking.

We found that introductions of freshwater alien species in Europe have been continuously increasing throughout the years, especially in the last 60 years, as also observed by Gherardi et al. (2009). This is likely explained by the marked increase in mobility and economic trade observed in Europe after World War II, as well as by the development of advanced aquaculture techniques and the opening of major inland waterway canals in Europe (Gherardi et al. 2009; Panov et al. 2009). Although introductions by aquaculture have always been important worldwide, they increased in the late 1900s with the development of salmonid aquaculture in Europe, and again in the 1960s and 1970s with the aquaculture of tilapiine species and carps (Gozlan 2008; Olenin et al. 2008). This explains why escapes (mostly due to aquaculture) have been the most important pathway of introduction of freshwater alien species in the late 20th century. However, since 2000, introductions through releases (mostly due to aquarium trade) have exceeded those due to escapes, reflecting the increasing importance that the ornamental market has recently acquired as a key driver of freshwater alien introductions (Padilla and Williams 2004; Tricarico 2012).

Our results show that a large proportion of the freshwater species introduced into Europe are partly native to some region in Europe. Intentional releases should be quite straightforward to monitor and regulate (Hulme et al. 2008) but, in practice, new introductions still occur, as shown by the continuous increase in the number of new partly native alien species introduced through this pathway in Europe, especially in the last 40 years. Furthermore, 14 out of the 19 total new freshwater alien species introduced in Europe between 2010 and 2013 were partly native species, indicating that the transport of species within Europe is currently relevant. The pathways stowaway/shipping, and especially corridor/inland canals, were mostly responsible for introductions of partly native species indicating that, in the case of freshwater environments, these pathways represent main routes for translocations of alien species within Europe. Indeed, the construction of numerous inland canals interconnecting different European river basins and countries, as well as ship transport through these canals or in coastal waters, has facilitated dispersal of many aquatic species within Europe (Galil et al. 2007; Panov et al. 2009). Currently, 30 main inland canals with over 100 branch canals exist in Europe and projects to deepen these canals are planned, which will most likely promote increased spread of alien species across the European inland waterways (Panov et al. 2009). No easy solution allowing for the prevention of species dispersal through inland canals seems to exist but, since these waterways cross many different regions and countries, coordinated cooperation at regional and national levels is crucial to address this problem.

Similarly to the pattern found for all freshwater alien species in Europe, high-impact species have been mainly introduced through escapes, followed by releases. However, many of these species have also been unintentionally introduced through stowaway/shipping, which seems to be an important pathway of introduction for highly harmful species in Europe. Some of these high-impact species are partly native to Europe, indicating that a certain risk is associated to the movement of alien species within Europe. This assessment of the main pathways of introduction for some of the most harmful freshwater alien species in Europe can support the identification of priority pathways of IAS in Europe, as required by the new EC Regulation.

The number of first introductions of alien species into European freshwaters varied considerably among countries. Germany had the highest number of first introductions and also, after the UK, the most introductions due to fisheries/ angling. In fact, Germany is one of the countries with the highest freshwater area in Europe (considering lakes, reservoirs and rivers) and it is the country that has introduced most alien fish species in Europe (García-Berthou et al. 2005; Olenin et al. 2008). Island countries such as the UK, which tend to have less fish fauna richness, usually have a high interest in enhancing their species diversity, which in the UK's case occurred through the introduction of several fish

species in the 19th century (Olenin et al. 2008). The UK was also the country mostly responsible for introductions through aquaculture and pet/aquarium trade, the most important pathways of freshwater introductions in Europe.

We found a noticeable geographical pattern associated with some pathways of introduction of freshwater alien species in Europe. While introductions through aquaculture, shipping and fisheries/angling were quite widespread and observed in several different European countries, introductions through inland canals and through pet/terrarium/aquarium trade have been mainly observed in Central/North-eastern Europe and Central/Western Europe, respectively. The geographic pattern of freshwater species introduced through inland canals is similar to that of marine species introduced by the same pathway (Nunes et al. 2014), with introduction events peaking in Russia, Germany, Poland and Lithuania. This is explained by the presence of many large navigable artificial canals in Central and North-eastern Europe, specifically in these four countries (Panov et al. 2009).

Most of the freshwater alien species introduced in Europe are Chordata, followed by Magnoliophyta, Arthropoda, Platyhelminthes, Mollusca and Annelida. The fact that Chordata is the most represented phylum is probably due to freshwater fishes being the most frequently introduced aquatic taxon around the world (García-Berthou et al. 2005), and also the most scientifically studied due to their greater attractiveness and economic importance (Gherardi et al. 2008; 2009). Likewise, Chordata dominate introductions through the three main freshwater pathways (aquaculture, pets/terrarium/aquarium trade and fisheries/angling) because teleost fishes are the dominant group in introductions used for aquaculture and stocking activities in Europe (Olenin et al. 2008; Savini et al. 2010), and also the most represented in the aquarium trade (Maceda-Veiga et al. 2013). Shipping and inland canals are responsible for the introduction of many Arthropoda and Mollusca, usually invertebrate species with some tolerance to salinity that unintentionally travel in ships, entering Europe through estuaries or big lakes (García-Berthou et al. 2005); many of these species seem to become invasive and have a high impact in Europe.

In conclusion, considering all the environmental challenges that freshwater ecosystems may encounter in the future, biological invasions will surely be a pervasive and highly diffused one, very likely to increase in the next decades, aided also by climate change. Therefore, there is an urgent need for the implementation of more efficient and realistic policy and management measures that minimise the likelihood of species entry through the main pathways of introduction in Europe. However, as these main pathways are associated with strong economic activities that benefit millions worldwide, an inevitable conflict between economic interests and the need to control or halt the introduction of new IAS arises and should be considered when taking management and political decisions (Gherardi et al. 2009; Gozlan et al. 2010). Since a clear policy for the prevention, containment and monitoring of invasive alien species is finally available in Europe, adequate measures tackling priority pathways and gateways of introductions in Europe are expected to be implemented in the near future.

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The following supplementary material is available for this article:

Table S1. Freshwater alien species included in the EASIN database.

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