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Research Article

Alien aquatics in Europe: assessing the relative environmental and socio-economic impacts of invasive aquatic macroinvertebrates and other taxa

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Abstract

Invasive alien aquatic species, including marine and freshwater macroinvertebrates, have become increasingly important in terms of both environmental and socio-economic impacts. In order to assess their environmental and economic costs, we applied the Generic Impact Scoring System (GISS) and performed a comparison with other taxa of invaders in Europe. Impacts were scored into six environmental and six socio-economic categories, with each category containing five impact levels. Among 49 aquatic macroinvertebrates, the most impacting species were the Chinese mitten crab, *Eriocheir sinensis* (Milne-Edwards, 1853) and the zebra mussel, *Dreissena polymorpha* (Pallas, 1771). The highest impacts found per GISS impact category were, separately; on ecosystems, through predation, as competitors, and on animal production. Eleven species have an impact score > 10 (high impact) and seven reach impact level 5 in at least one impact category (EU blacklist candidates), the maximum score that can be given is 60 impact points. Comparisons were drawn between aquatic macroinvertebrates and vertebrate invaders such as fish, mammals and birds, as well as terrestrial arthropods, revealing invasive freshwater macroinvertebrates to be voracious predators of native prey and damaging to native ecosystems compared with other taxa. GISS can be used to compare these taxa and will aid policy making and targeting of invasive species for management by relevant agencies, or to assist in producing species blacklist candidates.

Key words: GISS, impact assessment, Europe, freshwater, marine

Introduction

Invasive species are considered one of the main drivers of biodiversity decline, contributing an increasing threat to both the environment and economy (Simberloff et al. 2013) and reducing ecosystem services worldwide (MEA 2005). The tempo of invasions is increasing due mainly to increasing global trade and travel (Dick and Platvoet 2000; Keller et al. 2011).

The spread of aquatic invertebrate alien species is a continuing threat in Europe mainly because of the historic development of inland water transport systems. This began with the construction of canal systems through Europe and Russia, between the 18th and 20th centuries, linking networks of major river drainage systems and creating three major invasion corridors (southern, northern and central) (Bij de Vaate et al. 2002; Panov et al. 2009; Bidwell 2010). An historic example is the spread of the zebra mussel, *Dreissena polymorpha* from the Black Sea drainage to the Baltic made possible by the development of the Oginskij Canal, in present day Belarus, allowing the zebra mussels to move from the Black Sea drainage to the Curonian Coastal lagoon (Minchin et al. 2002; Olenin 2002; Bidwell 2010) and subsequently via ballast water and/or attached to ship hulls to the North American Great Lakes (Tittizer 1996; MacIsaac et al. 2002). Further important pathways include deliberate introductions and releases through aquaculture, as is the case with many oyster species and the fouling species introduced alongside them unintentionally (Carlton 1979). For example, the slipper limpet, *Crepidula fornicata* (Linnaeus, 1758), was introduced when the eastern oyster, *Crassostrea virginica* (Gmelin, 1791), was introduced for aquaculture. Similarly, the signal crayfish, *Pacifastacus leniusculus* (Dana, 1852), was introduced for aquaculture and has spread rapidly around Europe causing mass mortalities of native crayfish (McNeill et al. 2010; Filipová et al. 2013).

Deciding which species should be targeted for control or eradication using limited resources is a key question for effective invasion management (Kumschick and Nentwig 2010; Gallardo and Aldridge 2013; Roy et al. 2014). Therefore, there is a requirement for assessment methods to predict invader impacts before a region is invaded, or in the early stages of an invasion (Olenin et al. 2007; Hewitt et al. 2011; Blackburn et al. 2014; Dick et al. 2014). This may allow the prevention and mitigation of the environmental and economic damage caused by invasive species (Kolar and Lodge 2001; Dick et al. 2014).

Furthermore, the impacts of aquatic invertebrate aliens are varied (Jeschke et al. 2014). Therefore, the application of a method which allows impact comparisons between many species is required and could allow stakeholders to view their own important categories of impact individually (Nentwig et al. 2010). The Generic Impact Scoring System (GISS) developed by Nentwig et al. (2010) allows quantification of impact and the ranking of invaders based on published scientific data. It is broadly applicable and has thus far been applied to vertebrates and terrestrial arthropods (Nentwig et al. 2010; Kumschick and Nentwig 2010; Vaes-Petignat and Nentwig 2014; Kumschick et al. 2015). GISS allows policy-makers and stakeholders to benefit from collective knowledge on both the origin of the highest impact aquatic alien species and associated species impacts when addressing policy issues, such as the risks of new invaders due to the importation of goods (*sensu lato* Lodge et al. 2006). Therefore, the aims of the present study were to apply GISS to both marine and freshwater alien aquatic macroinvertebrates in Europe to quantify and compare their impacts across taxa and origin.

Methods

To obtain manageable and targeted invasive species lists, we started with species named by DAISIE (2014) (http://www.europe-aliens.org) and NOBANIS (2014), while also considering the 100 worst alien species for Europe (DAISIE 2014). From these databases, we then obtained a list of 279 aquatic macroinvertebrate alien species in European waters; from this we deleted any species with a native distribution inside Europe, as these species have invasion histories different to those invaders that have a native distribution entirely outside of Europe. Europe was defined biogeographically as the European continent and its islands, excluding the Azores, Canary Islands and Madeira, but including Ukraine and Belarus. The corresponding marine areas included the North Eastern Atlantic, the Mediterranean Sea, the North Sea and the Baltic Sea. Cryptogenic species were not included because their native range is unknown or disputed (Boelens and Minchin 2013). For the purposes of this study, species from the Ponto-Caspian region were included as alien to Europe as it is: (1) at the edge of the considered biogeographical area; (2) an invasion donor "hotspot"; plus (3) these species have reached the other parts of Europe generally via human aid, i.e. canals and shipping (Karatayev et al. 1998; Ricciardi and MacIsaac 2000) and (4) many of these species generate high impact. Because of their European borderline status, Ponto-Caspian species are identified as (PC) in supplementary Table S1.

In the next step, species were ranked by the number of countries or maritime areas in which each had been reported. Comparable to the procedure in Vaes-Petignat and Nentwig (2014), any species present in less than five countries was excluded for the purpose of ensuring enough information was available to score the species and to allow concentration on the most impacting species. The final list contained 49 species, including 17 Ponto-Caspian species, 14 marine and 35 freshwater macroinvertebrates, including 12 of the "100 of the worst" invaders according to DAISIE (2014).

The Generic Impact Scoring System (GISS) divides impact into two major classes of impact: environmental and socio-economic (Kumschick and Nentwig 2010; Nentwig et al. 2010; Vaes-Petignat and Nentwig 2014), all impacts considered are negative, as is usual in impact assessments. Each class contains six impact categories (Table 1). Impacts were scored according to five intensity levels from level 1 (minor impact) to level 5 (major impact). Impact level 5 corresponds to an impact which makes the species candidates for a black list (*sensu* Blackburn et al. 2014). An impact level of 0 was assigned where no impact is known (i.e. no evidence found in the literature) or detectable. Therefore, each species could attain a maximum score of 60 impact points and a minimum of 0 impact points (= 12 impact categories ×5 intensity levels). Each impact category is extensively described in the GISS questionnaire (see supplementary data) and this makes assigning a score relatively easy.

Table 1. The two classes and 12 impact categories used in the Generic Impact Scoring System (GISS). Full descriptions can be found in the GISS questionnaire (see Appendix 2).

1. Environmental impacts
1.1 Impacts on plants or vegetation through herbivory
1.2 Impacts on animals through predation or parasitism
1.3 Impacts on other species through competition
1.4 Impacts through transmission of diseases or parasites to native species
1.5 Impacts through hybridization
1.6 Impacts on ecosystems
2. Socio-economic impacts
2.1 Impacts on agricultural production
2.2 Impacts on animal production
2.3 Impacts on forestry production
2.4 Impacts on human infrastructure and administration
2.5 Impacts on human health
2.6 Impacts on human social life

GISS relies on published scientific information. These publications were found through literature searches using ISI Web of Knowledge and Google Scholar with "Species name" AND "Main category focus" as a search string. For example, with the killer shrimp, *Dikerogammarus villosus* (Sowinsky, 1894), impacts were searched using "*Dikerogammarus villosus*" AND "predation" as a search string. Short search strings proved to be more useful than the original category names to capture as large a body of information as possible. We used the following terms: vegetation, plants, herbivory, predation, parasitism, competition, disease transfer, hybridization, ecosystem, ecosystem impacts, ecosystem damage, agriculture, agricultural production, animal production, fisheries, forestry production, forest, human infrastructure, legislation, boating, fishing, recreation and human health. This search was repeated for each of the 49 species. The average number of references used per species, excluding those with zero impact scores, was 4.9 (165 references/34 scoring species) (Appendix 1).

After each such literature search, we scored a given species according to the GISS questionnaire. When we were unsure of an impact level, the higher impact value was chosen, as a precaution to ensure the potential impact was not under-estimated. The GISS assesses the maximal impact an invasive species can exert if distributed over all suitable habitats of the area of assessment (here Europe as defined). This "potential impact" (Nentwig et al. 2010) is the usual basis for impact assessments which at the end allows multi-species or cross-taxa comparisons. A chi-squared test was carried out using R version 3.0.2 testing for any statistical difference between the impacts generated by species originating from different areas (R core Development Team 2013).

Results

The 49 invertebrate species we scored comprised of Annelida (2 species), Arthropoda (24 species), Cnidaria (3 species), Ctenophora (1 species), Entoprocta (1 species), Mollusca (14 species), Nematoda (1 species) and Platyhelminthes (3 species) and belong to 20 orders and 36 families. These species obtained 286 impact points in total (Table S1) in 10 of the 12 impact categories (see Table 1). Within phyla, the Arthropoda and Mollusca accounted for 78% of total species (Figure 3) and 87% of total impact score (Figure 3). Within orders, the Decapoda, Neotaenioglossa, Veneroida and Amphipoda accounted for 53% of total species (Figure 4) and 72% of total impact score (Figure 4), indicating that these species have a higher impact. Overall, 76% of total impacts were from freshwater species (73% of species) with 34% of total impact from marine species (23% of species).

From the 286 total impact points obtained (Figure 1), 210 impact points were given for environmental (73%) and 76 for socio-economic (27%) impact. Within the six environmental categories (Table 1), invasive aquatic macroinvertebrates had the greatest impact on the ecosystem (25%), followed by predation (18%) and competition (14%) (Figure 2). Only the narrow-clawed crayfish, *Astacus leptodactylus* (Eschscholtz, 1823), had impact points caused by hybridization (Figure 2). Within the six socio-economic categories (Table 1), invasive aquatic macroinvertebrates had the greatest impact on animal production (9%) and human infrastructure and administration (8%) (Figure 2).

The area of origin showed that the Ponto-Caspian region accounted for the most species by number (Figure 5). The Americas donated the second highest number of species (Figure 5). Asia donated the third highest species number (Figure 5). However, there was no significant statistical difference in the impacts of species from the Ponto-Caspian, Asia or the Americas (χ^2=1.04, df=2, P=0.59).

Eleven species have an impact score of 10 or greater impact points (high impact species); five

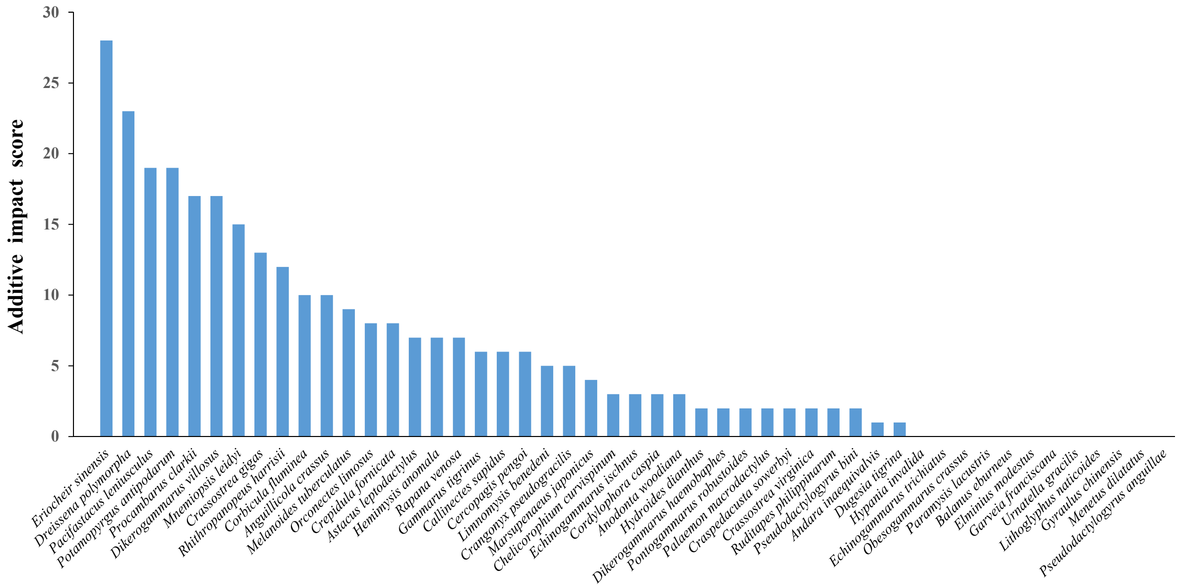

Figure 1. All 286 impact points distributed among individual species. Scores from environmental and socio-economic impact categories have been pooled.

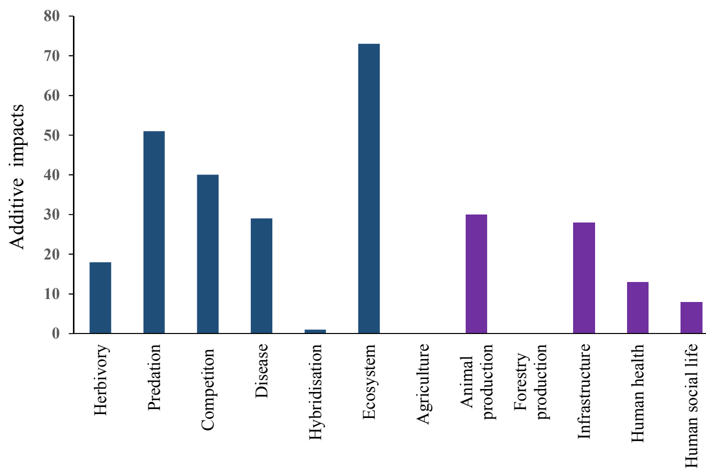

Figure 2. Additive impacts distributed among impact categories for aquatic alien macroinvertebrates in Europe in each of the 12 impact scoring categories, dark blue are environmental impacts and purple are socio-economic impacts.

arthropods (the Chinese mitten crab, *Eriocheir sinensis*, the signal crayfish, *Pacifastacus leniusculus*, the red swamp crayfish, *Procambarus clarkii* (Girard, 1852), Harris' mud crab, *Rhithropanopeus harrisii* (Gould, 1841), and the killer shrimp, *Dikerogammarus villosus*), four molluscs (the zebra mussel, *Dreissena polymorpha*, the New Zealand mud snail, *Potamopyrgus antipodarum* (Gray, 1843), the Pacific oyster, *Crassostrea gigas* (Thunberg, 1793), and the Asian clam, *Corbicula fluminea* (Müller, 1774)), one ctenophore (the warty comb jelly, *Mnemiopsis leidyi* (Agassiz, 1865) and one nematode (the swim bladder nematode, *Anguillicola crassus* (Kuwahara, Niimi and Hagaki, 1974)). All eleven species have environmental and socio-economic impacts (Table S1). Of these eleven species, seven have an impact score of 5 in one or more categories of impact which qualifies them as black list candidates (Blackburn et al. 2014). These species and associated categories were: the Chinese mitten crab, *Eriocheir sinensis* (ecosystems), the zebra mussel, *Dreissena polymorpha*

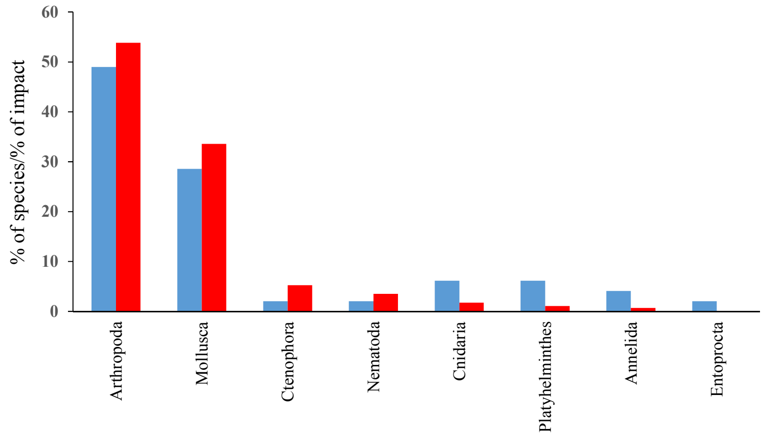

Figure 3. Percentage of species that belong to each phylum of aquatic alien invertebrate invaders (in blue) and the percentage of the impact points generated by each phylum of aquatic alien invertebrate invaders (in red).

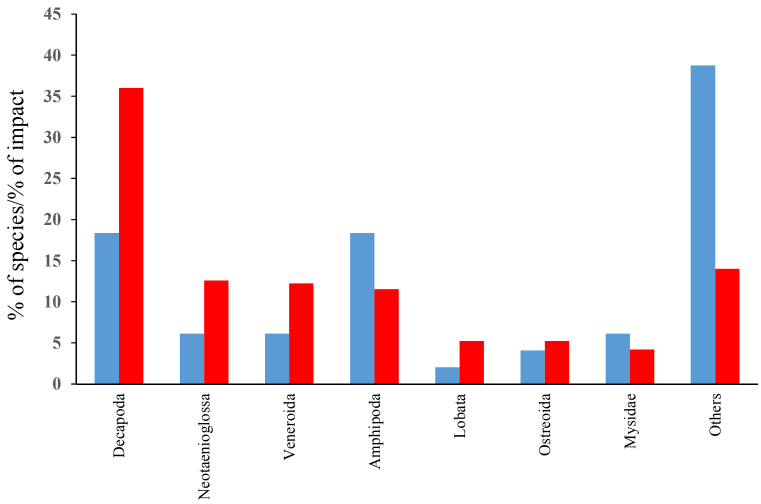

Figure 4. Percentage of species that belong to each order of aquatic alien invertebrate invaders (in blue) and the percentage of the impact points generated by each of the most numerous orders of aquatic alien invertebrate invaders (in red).

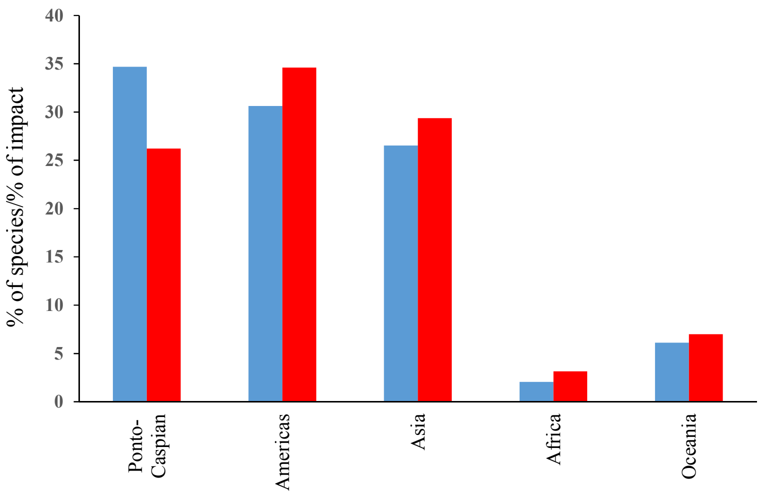

Figure 5. Percentage of aquatic alien invertebrate invader species that originate from each donor region (in blue) and the percentage of the impact points generated by species from each donor region (in red).

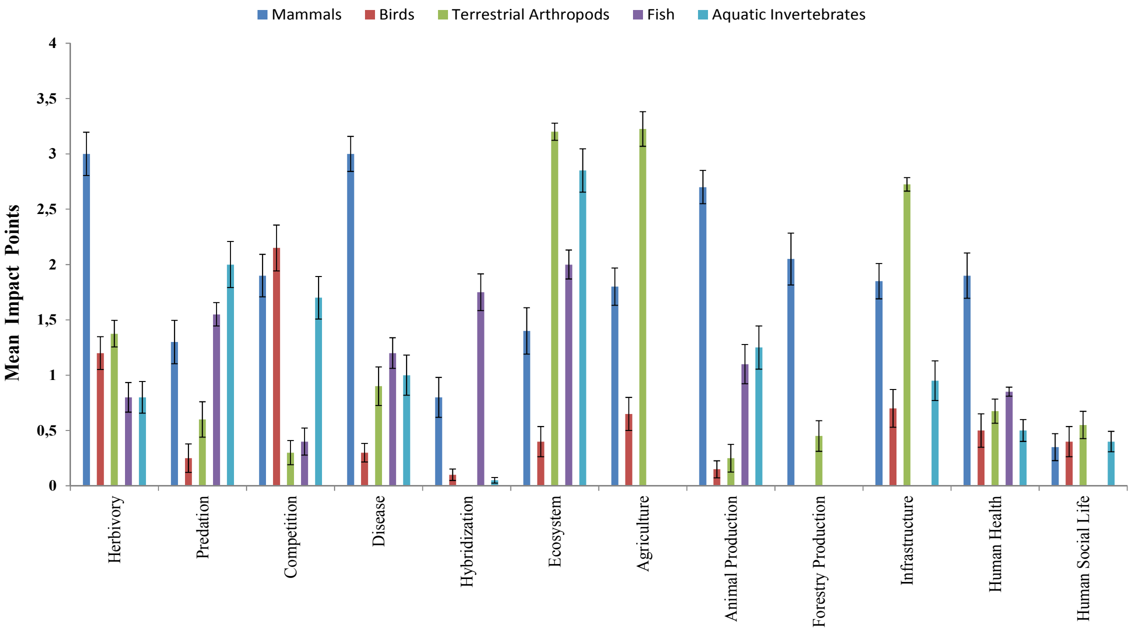

Figure 6. Mean impact and standard error of the top 20 scoring mammals, birds, terrestrial arthropods, fish and aquatic invertebrate invaders in Europe for the different categories of environmental and socio-economic impact (see text for details).

(ecosystems and human infrastructure and administration), the New Zealand mudsnail, *Potamopyrgus antipodarum* (ecosystems and animal production), the signal crayfish, *Pacifastacus leniusculus* (transmission of diseases or parasites), the killer shrimp, *Dikerogammarus villosus* (predation), the Pacific oyster, *Crassostrea gigas* (ecosystems), the swim bladder nematode, *Anguillicola crassus* (predation and animal production) (Table S1). Twelve species have no known impact (Table S1).

We compared our mean top twenty impact scores for aquatic macroinvertebrates with those for mammals (Nentwig et al. 2010), birds (Kumschick and Nentwig 2010), terrestrial arthropods (Vaes-Petignat and Nentwig 2014) and fish (Van der Veer and Nentwig 2014).

Overall, regardless of taxa, the highest mean impacts within the environmental categories were on ecosystems (2.9), through predation or parasitism (2.0) and through competition with native species (1.7) (Figure 6). The highest mean impacts within the socio-economic categories were on animal production (1.3) and on human infrastructure and administration (1.0) (Figure 6). Aquatic macroinvertebrates had the highest mean impact through predation (2.0) compared with mammals (1.3), birds (0.3), terrestrial arthropods (0.6) and fish (1.6) (Figure 6). Impacts through competition were higher in mammals (1.9) and birds (2.2) than in aquatic macroinvertebrates (1.7), terrestrial arthropods (0.3) and fish (0.4) (Figure 6). Impacts on the ecosystem were highest in terrestrial arthropods (3.2), aquatic macroinvertebrates (2.9) and fish (2.0), and were lower in mammals (1.4) and birds (0.4) (Figure 6). Impacts on animal production were greatest in mammals (2.7), aquatic macroinvertebrates (1.3) and fish (1.1) with lower impacts in terrestrial arthropods (0.3) and birds (0.2) (Figure 6). Impacts on human social life were low, with all values below 0.6 (Figure 6).

Discussion

Using the Generic Impact Scoring System (GISS) adapted from Nentwig et al. (2010), we scored aquatic alien invertebrate invaders in Europe that have a native distribution entirely outside the continent, with the exception of species from the Ponto-Caspian region. Impacts of aquatic invertebrate invaders are concentrated in the environmental category, with significant impacts on the related categories of ecosystem, predation and competition. Invasive species are known disruptors of native food webs and ecosystems, with aquatic invertebrate invaders in particular recognised for their disruptive tendencies in native systems (Paolucci et al. 2013; Dick et al. 2013). Impacts on animal production were all on fisheries production, in particular the swim bladder nematode, *Anguillicola crassus*, having devastating impacts on eel fisheries (Barus and Moravec 1999). Serious impacts were also found on riverbank stability due to high Chinese mitten crab, *Eriocheir sinensis*, abundance (Rudnick et al. 2003). Due to its general applicability to all taxa, GISS asks questions which do not exclusively relate to aquatic macroinvertebrates. So, unsurprisingly, agricultural and forestry stands were unaffected by aquatic invaders as they cannot directly access these systems in Europe. However, this does not exclude such a possibility in general, since inundated forests or rice fields would allow access of macroinvertebrates to such habitats.

Arthropoda and Mollusca are phyla that are successful aquatic invaders of Europe, having overcome abiotic and biotic barriers to become established, spread and produce damaging impacts (Karatayev et al. 1998; Dick and Platvoet 2000; Lucy et al. 2012). Indeed, the success of many of these species may provoke the question as to how they cause such levels of damage to native European communities. The most successful species of aquatic invaders often display higher resource consumption than native trophic analogues and are affected to a lesser degree by native higher predators, allowing these species to be successful invaders and propagate impacts through communities (Dick et al. 2013; Lucy et al. 2013; Alexander et al. 2014; Barrios-O'Neill et al. 2014; Laverty et al. 2015). Within the orders of aquatic macroinvertebrates, the Decapoda, Amphipoda (both arthropods), Neotaenioglossa and Veneroida (both molluscs) produced the greatest impacts, indicating that these orders contain successful invaders able to utilise resources with greater efficiency than natives or spread diseases to which native species have no immunity. The impacts produced were varied between arthropods and molluscs due to different feeding ecology between the groups (Wisenden and Bailey 1995; Frésard and Boncoeur 2006; Bollache et al. 2008; Filipová et al. 2013).

The area of origin of Europe's most damaging aquatic invertebrate invaders is important if invasive species legislation (EU Regulation No. 1143/2014) is to be effectively implemented, particularly because of their pathways of introduction. For example, ballast water and canalization are two major human mediated drivers and pathways of aquatic invasion (Tittizer 1996; MacIsaac et al. 2002). The Ponto-Caspian region is recognised as an aquatic invader donor "hotspot" and has become a major donor since the canalization of its tributaries has allowed the species to spread from the region along rivers and to reach ports that trade heavily with North America (Ricciardi and MacIsaac 2000; Harka and Bíró 2007; Bollache et al. 2008). Due to the long history of trade between Europe, Asia and the Americas, these regions are important to Europe in terms of aquatic invertebrate invader impact (Gallardo et al. 2013). We have found no significant differences between the impact scores generated by species from all three regions (Ponto-Caspian, Asia and the Americas). The fact that these Ponto-Caspian species have a devastating influence in European river systems underlines the former biogeographical separation of this area from the other European river systems (Dick and Platvoet 2000). Asian and American invaders are transported through shipping and then may spread throughout canals, across waterways and cause similar levels of impact as the Ponto-Caspian species, or impact and spread through the marine environment around ports. Connecting waterways by shipping traffic ensures high propagule pressure for both marine and freshwater invaders. This points to the ignorance of the architects of the canals with respect to the importance of separated biogeographical regions for biodiversity, the impact of alien species and the danger canals pose pathways for invasive species and the importance of controlling ballast water and hull fouling, a problem that was ignored for many years (Leppäkoski et al. 2002; Chan et al. 2012).

Eight of the eleven species that have impacts of 10 impact points or greater are recorded on the "100 of the worst list", while the New Zealand mudsnail, *Potamopyrgus antipodarum* and the signal crayfish, *Pacifastacus leniusculus* are not on the DAISIE list despite having impacts higher than all of the others except the Chinese mitten crab, *Eriocheir sinensis* and the zebra mussel, *Dreissena polymorpha*. This is due to the fact that the DAISIE list was created only with expert estimates and not with a comparative impact scoring system as we have done here. We propose to reanalyse the DAISIE list, in the future in collaboration with the EU COST programme e.g., with GISS, to provide a quantitatively justified list. Also, there are twelve species on our list with no known impacts, in all of the cases in this study this is due to lack of information on impact, rather than due to a lack of impact. These species should thus be researched in more depth, specifically in the field, to allow accurate prediction of impacts and to resolve the type of impact that can be expected from species with impact assessment lacking in the literature.

The mean impact of alien invasive aquatic macroinvertebrates is highest with regard to predation and in particular with regard to predatory arthropods (Dick and Platvoet 2000; Bollache et al. 2008), including predation by omnivorous species, among all the taxonomic groups and second only to terrestrial arthropods with regard to disruptive ecosystem impacts. These categories are linked as increased predation causes disruption of food webs and therefore wider community level impacts (Kelly et al. 2006; Dick et al. 2013). However, when reviewing the literature it was evident that the main research focus so far was on the environmental impacts of aquatic invaders, while data on the socio-economic impacts of this group are less available, thus more research is required in order to better inform policy makers and stakeholders about all of the possible impacts of this group.

Many of the categories and species assessed using GISS are assigned a zero impact score due to either lack of impact or lack of information on impact, this highlights a broader challenge for GISS and other risk assessment schemes (e.g. Ojaveer and Kotta 2015). GISS assigns zero scores based on both lack of impact and lack of information because no conclusion can be drawn about impact in either case and attempting to assign a score other than zero would introduce bias; although Hewitt et al. (2011) assigned high impact scores to species when information is lacking in the literature as a precautionary measure, this is not compatible with the current GISS method (Nentwig et al. 2010; Kumschick and Nentwig 2010; Vaes-Petignat and Nentwig 2014). Ojaveer et al. (2015) assigned species with a lack of information into the high category, instead of the low category contained in their assessment scheme in contrast to GISS. In all cases in this current study, zero scores were assigned due to a lack of information on impact, rather than to proven cases of no impact. However, in a broader context, zero scores assigned where no impacts have been detected are shown to be influenced by statistical testing without the necessary power to detect significance, leading to higher Type II error rates than Type I error rates (Davidson and Hewitt 2014). Thus, the false acceptance of the null hypothesis more often than the false acceptance of the alternative hypothesis likely decreases the risk of damaging invaders being targeted with management or preventative measures (Davidson and Hewitt 2014). It is outside the remit of this study, but future risk assessments could include power analysis of the studies, from the literature, reviewed when assigning impact scores to categories as suggested by Davidson and Hewitt (2014). Thus, we argue that GISS is justified in assigning a zero score where information or impact is lacking. However, the broader problem of below power statistical tests and unequal weighting, in terms of number of studies, in the literature for each individual invasive aquatic macroinvertebrate species are a concern for impact assessments, management and prevention of future damaging impacts caused by these invasive species.

In conclusion, the GISS system has been shown as appropriate at both evaluating the impacts of aquatic alien invertebrate invaders and identifying areas of impact that are understudied in the literature. Although no individual species reached the impact score of 30 as previously seen with mammals, birds and terrestrial arthropods (Nentwig et al. 2010; Kumschick and Nentwig 2010; Vaes-Petignat and Nentwig 2014), the mean impacts were comparatively significant. This highlights the usefulness of a comparative assessment to evaluate invasive species impacts and aid management decisions in a comparative manner across impact types and taxa.

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The following supplementary material is available for this article:

Table S1. Impact scores in each category of both environmental and socio-economic impact and the combined total score for each of the 49 aquatic invertebrate species.

Appendix 1. Reference list of literature used to assign species scores.

Appendix 2. Definitions of impact levels for aquatic macroinvertebrates.

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