Comparing impacts of alien plants and animals in Europe using a standard scoring system

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Running title Comparing impacts of alien plants and animals

Word count total 7687; summary 390; main text 5084; acknowledgements 123; references 1917; tables 0; figure legends 268

Number of tables 0

Number of figures 5

Number of references 57

Summary

1. Alien species can change the recipient environment in various ways, some of them cause considerable damage. Understanding such impacts is crucial to direct management actions. This study addresses the following questions: Is it possible to quantify impact across higher taxa in a comparative manner? Do impacts differ between taxonomic groups? How are environmental and socio-economic impacts related? Can impacts be predicted based on those in other regions?
2. To address these questions, we reviewed literature describing the impacts of 300 species from five major taxonomic groups: mammals, birds, fish, terrestrial arthropods and plants. To make very diverse impact measures comparable, we used the semi-quantitative generic impact scoring system (GISS) which describes environmental and socio-economic impacts using twelve categories. In each category, scores range from zero (no impact known or detectable) to five (the highest possible impact).
3. Using the same scoring system for taxa as diverse as invertebrates, vertebrates and plants, we found that overall, alien mammals in Europe have the highest impact, while fish have the lowest. Terrestrial arthropods were found to have the lowest environmental impact, while fish had relatively low socio-economic impact.
4. Overall, the magnitude of environmental and socio-economic impacts of individual alien species is highly correlated. However, at species level, major deviations are found.
5. For mammals and birds, the impacts in invaded ranges outside of Europe are broadly similar to those recorded for alien species within Europe, indicating that a consideration of the known impacts of a species in other regions can be generally useful when predicting the impacts of an alien species. However, it should be noted that this pattern is not consistent across all mammal and bird orders, and thus such information should be considered with caution.
6. *Synthesis and applications* Comparing the impacts of alien species across taxa is necessary for prioritising management efforts and effective allocation of resources. By applying the GISS to five major taxonomic groups, we provide the basis for a semi-quantitative cross-taxa listing process (e.g., “black lists” or 100-worst-lists). If more data are collated from different geographical regions and habitats using standard GISS protocols, risk assessments for alien species based on rigorous measures of impact could be improved by taking into account local variation in and context-dependence of impacts. This would also

allow studies at lower taxonomic levels and within-taxon analyses of functional groups and guilds.

Keywords risk assessment, impact assessment, bird, mammal, arthropod, vertebrate, invertebrate, generic impact scoring system, biological invasions, non-native species

Introduction

Biological invasions have received increasing attention within the last decades (e.g., Richardson & Pyšek 2008; Gurevitch *et al.* 2011), and important progress regarding our understanding of the impacts of alien species has been made (Pyšek & Richardson 2010), including the development of a framework by Parker *et al.* (1999). However, there is still considerable debate and uncertainty as to whether and how alien species impact their environment (e.g., Richardson & Ricciardi 2013). The lack of consensus as to the severity and significance of alien species impacts has been attributed to differences in human perceptions of invasions (Simberloff *et al.* 2013), and is also partly routed in the fact that various definitions are used to describe and quantify impacts (Jeschke *et al.* 2014). Recent reviews that frame classical invasion hypotheses within the context of impact (Ricciardi *et al.* 2013), as well as detailed research on specific taxonomic groups including plants (e.g., Levine *et al.* 2003; Gaertner *et al.* 2009; Vilà *et al.* 2011; Powell *et al.* 2011; Pyšek *et al.* 2012), mammals (e.g., Nentwig *et al.* 2010), birds (e.g., Shirley & Kark 2009; Kumschick & Nentwig 2010; Kumschick *et al.* 2013; Evans *et al.* 2014) and other groups (e.g., Lovell *et al.* 2006; Kenis *et al.* 2009; Vaes-Petignat & Nentwig 2014) have shed light on the magnitude and scope of impacts, as well as the underlying mechanisms.

A number of variables have been used to quantify impact (Hulme *et al.* 2013) and meta-analyses have quantified the magnitude of impacts for a few taxa only (e.g. for plants, Gaertner *et al.* 2009; Vilà *et al.* 2011). Unfortunately, most impact measures are not directly comparable among taxa, adding another level of complexity. In order to effectively prioritize management options, stakeholders affected by biological invasions need to be able to identify those species, among different taxa, that are likely to cause the most damage. Using scoring systems for impact provides the means to not only compare impacts where the quantity, quality and structure of data varies, but also to compare different groups of organisms

(Nentwig *et al.* 2010; Kumschick *et al.* 2013). A scoring system is no alternative to an empirical study directly measuring impact, but a tool to compare or rank variable data. Scoring systems have been used or suggested for the assessment of risk (e.g., Pheloung *et al.* 1999), to produce black lists (e.g., Gederaas *et al.* 2012), for prioritisation (e.g., Kumschick *et al.* 2012), and for policy development (e.g., Essl *et al.* 2011). The semi-quantitative generic impact scoring system (GISS) originally developed by Nentwig *et al.* (2010) and subsequently extended by Kumschick *et al.* (2012) has proven useful for comparing the impact of alien species between taxa (Kumschick & Nentwig 2010), between native and invaded ranges (Kumschick *et al.* 2011); and for finding specific species traits associated with impact (Nentwig *et al.* 2010; Kumschick *et al.* 2013; Evans *et al.* 2014). It has also been applied outside of Europe, namely for birds in Australia (Evans et al. 2014).

Risk assessment for alien species usually consists of the evaluation of likelihood of a species to be transported, to establish and to spread, as well as the risk for having impact (e.g., Leung *et al.* 2012; Kumschick & Richardson 2013). Predicting impact, however, has proven to be a challenge (Ricciardi *et al.* 2013). Often, invasion history (i.e., "impact elsewhere") has been used to predict impact. There is evidence that species which are invasive in one part of the planet are likely to become invasive in other parts of similar suitability when given the opportunity (e.g., Hayes & Barry 2008; Kolar & Lodge 2001). However, invasiveness does not necessarily equal impact (Ricciardi & Cohen 2007), and the degree to which the "elsewhere"-rule applies to impact has yet to be established (but see Ricciardi 2003, who developed a predictive model for the impact of zebra mussel *Dreissena polymorpha* based on impact elsewhere).

In most risk assessments for alien species, only environmental impacts are considered (Kumschick & Richardson 2013), even though many alien species are known to have substantial impacts on economy and human social life (e.g. Perrings *et al.* 2000; Binimelis *et al.* 2007; Vilà *et al.* 2010). For example, many of the harmful alien insects are crop pests

(Kenis *et al.* 2009), which do not necessarily pose harm to biodiversity or the environment, but to agricultural production, and thus economy. There is a long tradition and well developed system for pest risk assessments in plant protection aimed at economic issues (Kenis *et al.* 2012). For most taxa, the relationship between the magnitude of the environmental and economic impacts, remains unclear (but see Nentwig *et al*. 2010 for mammals).

For the management of biological invasions, it is important to identify the mechanisms through which alien species are impacting their surroundings, especially if certain ecosystems or ecosystem services are to be protected. An understanding of impact mechanisms can also shed light on how consistent an impact is likely to be over different regions. For example, if the main mechanism is hybridisation, impact is dependent on the presence or absence of a closely related species (e.g., Smith *et al.* 2005).

The main aim of this study is to apply the GISS (Nentwig *et al.* 2010; Kumschick *et al.* 2012) for various taxa in order to compare their impacts. We collated records of environmental and socio-economic impacts of five major taxonomic groups of alien species in Europe: mammals, birds, fish, terrestrial arthropods and plants. By using the same impact scoring system for all taxa we were able to compare several aspects of impact between taxa and functional groups within taxa. Specifically, we (i) unravel patterns related to different impact types, on the one hand looking at proportions of species per taxon having impact, and on the other hand comparing impact magnitude. Furthermore, (ii) we test how environmental and socio-economic impacts are related, and (iii) provide recommendations on whether "impact elsewhere" is as good a predictor of impact as "invasive elsewhere" has been shown to be for invasiveness (e.g., Hayes & Barry 2008). This study, therefore, does not only contribute to the debate on alien species impacts, but is also valuable for management prioritisation and risk assessment (European Commission 2014).

Methods

Species selection

We chose a total of 300 alien species introduced after the year 1500 with established (sensu Blackburn *et al.* 2011) populations in Europe, and native distribution ranges entirely outside of Europe from the updated DAISIE database (www.europe-aliens.org; Pergl *et al.* 2012). This included 26 birds and 34 mammals (see also Nentwig *et al.* 2010; Kumschick & Nentwig 2010), 35 fish (Van der Veer & Nentwig 2014), 77 terrestrial arthropods (Vaes-Petignat & Nentwig 2014) and 128 plants. For vertebrates, all species that satisfied the criteria were included, while for arthropods and plants the selection criteria were modified slightly because of the large numbers of alien species present in Europe. Only arthropods present in > 20 countries and plants in > 10 countries in Europe were selected from the DAISIE database. A detailed list of species can be found in the Supplementary Material Appendix S1.

Literature search on information about impact

As a first step, we searched the ISI Web of Knowledge for publications about impacts caused by these species, using their scientific species names as search terms. Furthermore, relevant primary literature on the specific taxa and information provided on websites (e.g., www.nobanis.org; www.europe-aliens.org), as well as literature cited therein, was used to compile all published information available on impacts of the 300 selected species. We also explored relevant grey literature encountered during the literature search. In total, over 1400 papers were screened, and 923 finally included in the impact assessments, which is on average around 3 papers per species. However, many sources contain information on more than one species, which increases the average number of papers included per species. Literature used for scoring can be found in Nentwig et al. (2010), Kumschick & Nentwig (2010), Kumschick et al. (2011), Vaes-Petignat & Nentwig (2014), Van der Veer & Nentwig

(2014), or be obtained from the authors for plants (Marková Z, Vilà M, Pergl J, Nentwig W & Pyšek P unpublished).

For all taxa, data on reported impacts were collected. For mammals and birds, information on impacts in Europe and other invaded ranges was kept separately and can therefore be compared. For the other taxonomic groups, the information on impact of many species was too scarce to allow a proper comparison of Europe with other invaded ranges; for these taxa impact data was pooled across all alien ranges. Additionally, for mammals, birds and arthropods, information on impact in the native range was available and also recorded separately (see also Kumschick *et al.* 2011).

Impact scoring with GISS

The semi-quantitative GISS applied to mammals and birds (e.g., Nentwig *et al.* 2010; Kumschick & Nentwig 2010; Kumschick *et al.* 2013; Evans *et al.* 2014), arthropods (Vaes-Petignat & Nentwig 2014), and with potential to be extended to many other taxa (Nentwig *et al.* 2010; Kumschick *et al.* 2012) was used. The GISS includes two impact groups, environmental and socio-economic, with six impact categories assigned to each group. Environmental impacts are classified as (1) on plants or vegetation (e.g., through herbivory), (2) on animals through predation or parasitism, (3) through competition, (4) transmission of diseases or parasites to native species, (5) hybridisation, and (6) on ecosystems in general (e.g., through changes in nutrient cycling). Socio-economic impact consists of impacts (1) on agriculture, (2) animal production, (3) forestry, (4) human health, (5) human infrastructure and administration, and (6) human social life (e.g., through noise disturbance). Within each of these 12 impact categories, impact is assessed using a semi-quantitative scale with six impact levels, ranging from zero (no impact known or detectable) to five (highest impact possible at a site). Each impact category and impact level is well defined and described in scenarios so as to avoid ambiguities between assessors as much as possible (Nentwig *et al.* 2010; Kumschick

& Nentwig 2011; see Supplementary Material Appendix S2 for a full version of the GISS). All impact records found in the literature were assigned a score according to the above described system, and therefore made comparable over categories, taxa, and regions.

We define impact for this study as any deviation in the state of a system due to the presence of an alien species. We include both environmental and socio-economic impacts in the assessment, but only deleterious impacts are considered, i.e. deleterious environmental impact (*sensu* Blackburn *et al.* 2014), and socio-economic impacts perceived as "damage" by humans (*cf.* Jeschke *et al.* 2014).

Zero values can mean two things in the scoring system, namely "no data available" and "no impact detectable" (Appendix S2). Therefore, we tested the two extreme cases: all zero values were defined as "no data available" in the first case, thereby assuming that all alien species cause impacts (overestimating true impacts), and in the second case, all zeros were defined as "no impact detectable", thereby implying that alien species with unknown impacts do not cause impacts (underestimating true impacts). The results did not differ qualitatively between these two methods, therefore we only show results with zero values defined as "no data available". This represents the precautionary approach towards alien species and is in line with the findings of Davidson & Hewitt (2014), who found that non-significant outcomes in impact studies are often discounted as "no impact", although low statistical power did not actually enable the identification of impacts.

The respective highest scores found per category and species were used for the analysis, and scores summed up per impact group (environmental and socio-economic; highest possible score per species and impact group was 30) and overall (total impact = environmental + socio-economic; highest possible score was 60).

Statistical analyses

In general, impact was modelled in a linear mixed effect framework with the impact score being the response variable and explanatory variables included either as random or fixed effects. The taxonomy was always incorporated as random effect, with families nested within orders nested within classes. Here we assume that impacts from species within the same group are correlated, while species from different taxa show no correlation (a variance component model). This accounts for non-independence of data due to the phylogenetic relatedness of the species (Sol *et al.* 2008). Models were fitted with the lmer function in the package lme4 (version 0.999999-2; Bates *et al.* 2013) in the statistical software R (version 3.0.1; R Core Team 2013). For model comparison, models were fitted by maximum likelihood (ML) while for the reported parameter estimates, models were fitted by restricted maximum likelihood (REML) to obtain unbiased estimates (Bolker *et al.* 2009).

To investigate differences in impact scores among taxa, we only included the taxonomy as random effects and allowed for an intercept as fixed effect. We verified that inclusion of random effects improved model fit (i.e., that taxa differ in their impact) compared to an equivalent model without random effects fitted by generalized least squares (function gls from the package nlme, version 3.1-113; Pineiro *et al.* 2013) by comparing their AICc values (Zuur *et al.* 2009). For the description of the differences of impacts (environmental, socio-economic, total) among taxa, we extracted the confidence intervals for the random effects for each taxonomic level.

To investigate if socio-economic impact is a predictor of environmental impact we fitted linear mixed models with environmental impact as response variable, socio-economic impact as fixed factor and taxonomy as random effects. We tested if the relationship between environmental and socio-economic impact differs between taxa by allowing the random effects to vary in slope and intercept. By fitting models with all possible combinations of random effects, we selected those taxonomic levels that best explained the data according to information theoretic criteria (ΔAICc; Burnham & Anderson 2002).

Finally, for birds and mammals we investigated whether impact in Europe differs in magnitude from the impact described for the species elsewhere. For this, we subtracted the impact score for Europe from the score for regions outside of Europe and tested if the difference deviated from zero, accounting for non-independence due to phylogenetic relatedness by including the taxonomy as random effects. This also enabled us to test for taxonomic differences. We considered only those species where a non-zero impact was reported for both categories to avoid bias due to misclassification of species with unknown impacts as "no impact".

Results

Taxonomic differences

We analysed impacts over the 12 impact categories across taxonomic groups by comparing their deviations from the mean impact as given by the confidence intervals of the random effects (Figure 1). Overall, mammals had the highest total impacts and fish the lowest (Fig. 1a). When considering environmental impact only, the ranking of taxa remained the same with the exception of arthropods having the lowest impact (Fig. 1b). For socio-economic impact separately, mammals also had the highest impacts and plants and fish the lowest (Fig. 1c).

Environmental versus socio-economic impact

The magnitude of impacts in the two main impact classes was overall highly correlated, with socio-economic impacts increasing faster than environmental impacts (common slope = 0.75±0.07; Supplementary Material Appendix S3). The relationship between socio-economic and environmental impacts was the same across all taxonomic groups; a model with taxon-specific slopes fitted considerably worse (ΔAIC = 12). However, patterns in magnitude of impacts differed among taxonomic groups, i.e. fish and plants always had on average higher environmental than socio-economic impacts while arthropods showed the reverse. Mammals and birds with low socio-economic impacts had higher environmental impacts, but those which scored high in socio-economic impacts had equally high or lower environmental impacts.

Categories of impact

The number and proportion of species found to have impacts in certain categories differs greatly between taxonomic groups (Fig. 2), indicating that the various types of impact mechanisms and type are taxon-specific. For example, the most common categories for mammals were transmission of diseases to native species and impacts on vegetation, but mammals were also more likely to have impacts on agriculture, forestry and animal production, as well as on human infrastructure, than most other taxa studied here. The main type of impact for birds was genetic pollution through hybridisation, which did not seem to be a significant impact in the other taxa studied. Most alien fish species caused impacts through predation, and together with mammals and plants, they were the leading taxa causing human health impacts. The main impact categories for arthropods were agricultural damage and impact on human infrastructure – both socio-economic impacts. The category with most impacting species for plants was competition, and they, together with mammals, were the only taxa to exert impact in all 12 categories.

In terms of the magnitude of impacts, higher taxa were much more similar to each other (Fig. 3), with the exception being mammals. Higher magnitudes were mainly attributable to mammals and their impacts on forestry, herbivory, and transmission of diseases to native species. Outliers show cases where an impact was recorded for only one species in a respective category (arthropods and animal production; birds and predation). This shows that even though for certain taxa impact is more likely in certain categories the magnitude is not expected to differ considerably among categories for most taxa.

Impact elsewhere

Across mammal and bird species, environmental impact in Europe was not significantly different from impact in areas where the same species were introduced outside of Europe (impact elsewhere – Europe = -1.3 ± 1.7 SE, t = 0.78, $P = 0.45$). There was no significant difference between mammals and birds in their environmental impact score in Europe and elsewhere (variance in random effects = 0.82; not shown). However, there was considerable variation within orders (variance in random effects = 9.80; Supplementary Material Appendix S4). Passeriform birds had slightly higher documented impacts outside of Europe, while rodents and anseriform birds scored higher within Europe. A comparable pattern was found for socio-economic impacts, but here the mammal order Carnivora had higher impacts outside of Europe, and anseriform birds within Europe.

Discussion

This study, for the first time, elaborates differences and similarities between five major taxonomic groups as different as plants, vertebrates and invertebrates with respect to the magnitude of their environmental and socio-economic impacts. First of all, we show that using the GISS allows comparison of impacts not only between different groups of vertebrates (e.g. Kumschick & Nentwig 2010) but also among taxa that come from different phyla and thus differ much more in functional groups and life strategies, like plants and animals. This is important, as legislation often does not distinguish between taxonomic groups, but pools all alien species together, whereas risk and impact assessment schemes used to date have largely been taxon-specific (Essl *et al.* 2011; Leung *et al.* 2012; Kumschick &

Richardson 2013). However, for management prioritization and listing purposes (e.g. black lists; Blackburn *et al.* 2014) it is often necessary to assess alien species coming from distant taxonomic groups with a common procedure.

Furthermore, different sectors (e.g., human, animal and plant health, agriculture, conservation etc.) have different priorities and therefore different risk and impact assessment procedures (Hulme 2013). Many risk assessments for alien species include mainly environmental impacts (Kumschick & Richardson 2013) whereas until recently, systems for plant health such as the pest risk assessment scheme of the European Plant Protection Organisation (EPPO 2011) mainly included socio-economic impacts (but see Kenis *et al.* 2012). The GISS includes both, and therefore allows comparisons of these two impact classes. We show that environmental and socio-economic impacts are generally correlated, not only concerning the number of species found with recorded impacts and the number of categories impacted on (Vilà *et al.* 2010), but also in the magnitude of impacts caused. Thus, if impact either on the environment or on socio-economy is high, the other is also likely to be high, and this seems to be generally the case for all taxa investigated. However, despite an overall correlation, taxa show distinct impact patterns with fish and plants always having on average higher environmental than socio-economic impacts while arthropods showing the reverse, and mammals and birds being in-between. Moreover, this does not mean that on a species level these two impacts are of the same magnitude. There are still some species which do not have documented environmental impacts but do have socio-economic impacts, namely two arthropods (*Ptinus tectus* and *Periplaneta americana*) and six plants (e.g., *Melia azedarach* and *Paspalum dilatatum*). The opposite is the case for a few birds (e.g., *Oxyura jamaicensis, Anser cygnoides* and *A. indicus*) and 13 plants (e.g., *Buddleja davidii, Carpobrotus edulis* and *C. acinaciformis*). Reasons for why some species do not show environmental impact may be that environmental impact is still not known or the species is rare in natural environments but reaches high abundances and impacts only in agricultural or urban systems; however this highlights the need for risk assessments to include both, environmental and socio-economic impacts if a complete picture of (potential) damage is to be drawn.

The significance of different impact categories clearly differs between taxonomic groups and reflects the different impact mechanisms and types of impacts caused by different taxa. Human health is the category where overall, most species were found to have an impact, and the mean percentage of species with documented impact per group is over 45% in this category. A possible explanation for this high number would be that since humans are most directly affected by this impact category, it is more likely to be reported. This category is followed by competition with native species which is the second most frequently scored impact. The significance of this impact type for humans is usually not obvious nor directly visible. However it is the most commonly studied species interaction mechanism for plants (Grime 2006). This seems to indicate that due to the wide literature search GISS requires and its broad scoring system, impact records found seem to be balanced according to actual importance rather than human perceived values (as far as possible).

We confirm the common belief that generally, impact in alien ranges elsewhere is similar to impact in the alien European range, at least for mammals and birds. This finding can be very useful for management and policy purposes because it enables the prioritisation of species before they become a problem in a new range. Nevertheless, this assumption is only useful if the species in question has an invasion history elsewhere. Furthermore, it is known that impact can be highly context dependent (Vilà *et al.* 2006; Hulme *et al.* 2013) and can therefore vary on temporal and spatial scales depending on the conditions. A good example are predators on islands, where due to the naïveté of the recipient community, invasions have driven species to extinction and extirpated whole communities, whereas impacts due to predation on the mainland are comparatively low (e.g., D'Antonio & Dudley 1995). This context dependency is also reflected in our study, where we show that this concordance differs between several bird and mammal orders. Not all orders show a strong dependency between impact elsewhere and impact in Europe. For example, passeriform birds like the common myna (*Acridotheres tristis*) tend to have higher environmental impact elsewhere than in Europe (Evans *et al.* 2014), while rodents tend towards the opposite pattern. Whether this pattern is related with differences in species abundances needs to be further investigated (Parker *et al.* 1999). Concerning socio-economic impacts, anseriform birds exhibit higher impact scores in Europe than elsewhere. This shows that it is important to be aware of the limitations of the use of "impact elsewhere" for the assessment of alien species risks, i.e., the context dependency and differences between taxa. More studies on context dependencies of impact should be performed to find out to what extent we can rely on information on a species' impact history elsewhere (Kumschick *et al.* accepted).

Our study does not only reveal patterns on available data, but it shows potential gaps concerning the knowledge of impact of alien species for the taxa studied. No record of impact was found for some taxa and categories. There are several potential reasons for these gaps. Firstly, it is possible that some taxa do not exert impact in all categories. Secondly, and impossible to disentangle with current knowledge from the first reason, some impact categories have yet to be widely studied for certain taxa, but could (and potentially do) occur (e.g., hybridization in arthropods, impact on human social life by fish). This is rather likely, since studies of alien species impacts have concentrated on highly damaging species (Hulme *et al.* 2013). This presents a potential limitation of the system, as it only takes into account documented impacts. It is however known that non-significant results do not necessarily mean "no impact" (Davidson & Hewitt 2014) and negative results are less likely to be published.

Thirdly, the respective taxa cannot show an impact in certain categories due to taxon-specific traits. For example, it is difficult (but not impossible) to imagine how fish could affect forestry or agriculture, mainly because fish are aquatic, and agricultural habitats in Europe are largely terrestrial. Even though some across-ecosystem impacts are well studied (e.g. Knight et al. 2005), there remain some potential situations that possibly have not been explored to their full extent. For instance, potential fish impacts in rice fields, fish affecting human social life with respect to angling activities, and impacts of birds on forestry due to certain nesting behaviour. Thus, it is likely that with further study of a broader range of alien species and habitats we can reduce existing knowledge gaps on the impacts of alien species, and impact scores will increase. We highly encourage more impact studies in currently understudied areas and for understudied species in order to increase our knowledge on alien species impacts, which will also increase effectiveness of management and reduce costs by allowing us to target the most harmful species.

In biological invasions, decisions should be made on the most detailed level possible, usually the species level with which invasiveness is most closely associated (Pyšek et al. 2009, 2010). Unfortunately, data is not always available on such a high taxonomic resolution and this lack of information is especially pronounced for the classification of impacts. In some situations information on a coarse taxonomic resolution is useful, for example, if there is a need to screen potentially invasive species that are not yet present in a region, or to regulate pathways by which the most harmful species are likely to be introduced (e.g. pet trade, horticulture). This is when knowing that, for example, mammals cause a higher impact of certain type than fish can prove crucial for efficient management. In this study, by rigorously comparing impacts for distinct groups defined at taxonomically high level we show that general principles can be outlined for such groups of aliens with respect to the impacts they cause. Such an approach is well in line with the new EC regulation on invasive alien species (European Commission 2014), mentioning explicitly that taxonomic groups with demonstrated impacts should be regulated and our study provides a good baseline for such decisions.

Conclusions

With this study we demonstrate that by using the GISS (derived from Nentwig *et al.* 2010; Kumschick *et al.* 2012) the magnitude of impact can be compared between taxonomic groups as different as plants, vertebrates and invertebrates. Having such a generally applicable system at hand is not only useful to make different impact categories comparable between, for example, the Canada goose (*Branta canadensis*) and prickly-pear cactus (*Opuntia spp.*), but it is largely needed to make informed policy and management decisions, and useful as a basis for prioritising of alien species and listing processes (e.g., “black lists”, 100-worst-lists). Usually, available risk assessments, which are often required by policy makers as a basis for decision making, are taxon-specific (Kumschick & Richardson 2013). However, national and international policies require prioritization of management across a broad range of higher taxa, and generally aim at protecting the recipient community, ecosystem and economy. As mentioned previously, the EU has recently adopted a new regulation on invasive alien species (European Commission 2014) in which it is explicitly stated that taxonomic groups can be banned: “As species within the same taxonomic group often have similar ecological requirements and may pose similar risks, the inclusion of taxonomic groups of species on the Union list should be allowed, where appropriate.” It should also be stressed that our approach can help building the “list of invasive alien species of Union concern”, which is going to be the most important management tool at the European level (Genovesi et al. 2014), for selecting potentially high-impact species not yet established in Europe according to their taxonomic affiliation. The GISS therefore provides a straightforward tool for management prioritization regardless of taxonomic affiliation, and it has already been suggested as a baseline for an IUCN black listing classification scheme for alien species (Blackburn *et al.* 2014). Furthermore, it is a very flexible system, for example, allowing for the weighting of different categories of impact if a specific management goal needs to be reached, as well as for stakeholder involvement (Kumschick *et al.* 2012).

Since this is the first analysis of impacts across taxa with a standardized protocol, the results should be interpreted with caution. Species of the same taxon level (e.g. phylum, class, order) may differ in their impacts, but currently our understanding is limited of where variation in impacts is high and for which reasons. Future studies should address in which taxa alien species vary a lot regarding their impacts and should aim at identifying the mechanisms responsible for the variation. This would help understanding the limits of our approach to predict impact by taxonomic affiliation. To achieve this, more species should be classified, allowing for higher taxonomic resolution of the analyses. This would also enable future analyses on functional groups or guilds within taxa. Moreover, taxonomic affiliation is often a surrogate for species traits that are proximately linked to the impact mechanism and magnitude (see e.g. Kumschick et al. 2013). Future studies should therefore try to identify common traits across taxa that are responsible for the observed impacts which would allow more precise predictions of harmful alien species.

Our study does not provide a direct test of applicability of GISS for specific environmental settings. However, we suggest that if data are collated by future studies using a standardized GISS protocol on impacts of the same species in different regions and habitats, to account for the context dependence of impacts of invasive species (Hulme et al. 2013), it will make it possible to incorporate such results in regional risk assessment and decision making.

Acknowledgements

We thank Elfi Kühnel for data collection and two reviewers for their comments. SK acknowledges financial support from the Swiss National Science Foundation, and the Drakenstein Trust through the DST-NRF Centre of Excellence for Invasion Biology. ZM, JP and PP were supported from long-term research development project no. RVO 67985939

(Academy of Sciences of the Czech Republic), Centre of Excellence PLADIAS no. 14-36079G, no. P504/11/1028 (Czech Science Foundation), and institutional resources of the Ministry of Education, Youth and Sports of the Czech Republic. PP also acknowledges support by the Praemium Academiae award from the Academy of Sciences of the Czech Republic, MV through the Severo Ochoa Program for Centres of Excellence in R+D+I (SEV-2012-0262). This research contributes to COST Actions TD1209 and ES1304.

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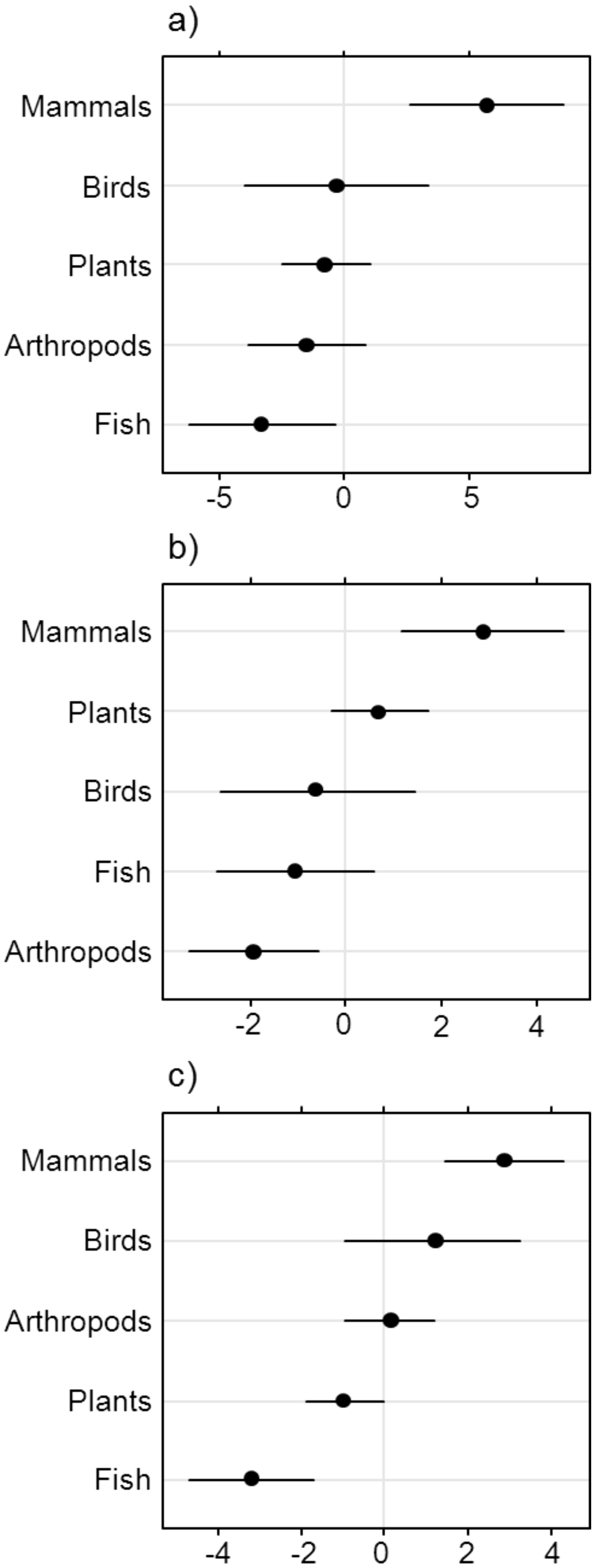


Figure 1: Comparison of a) total, b) environmental and c) socio-economic impact between taxa. Values on x-axes are the random effects of deviances (mean ± SD) in impacts of taxonomic groups from the common mean impact (set to zero) of the mixed effects model.

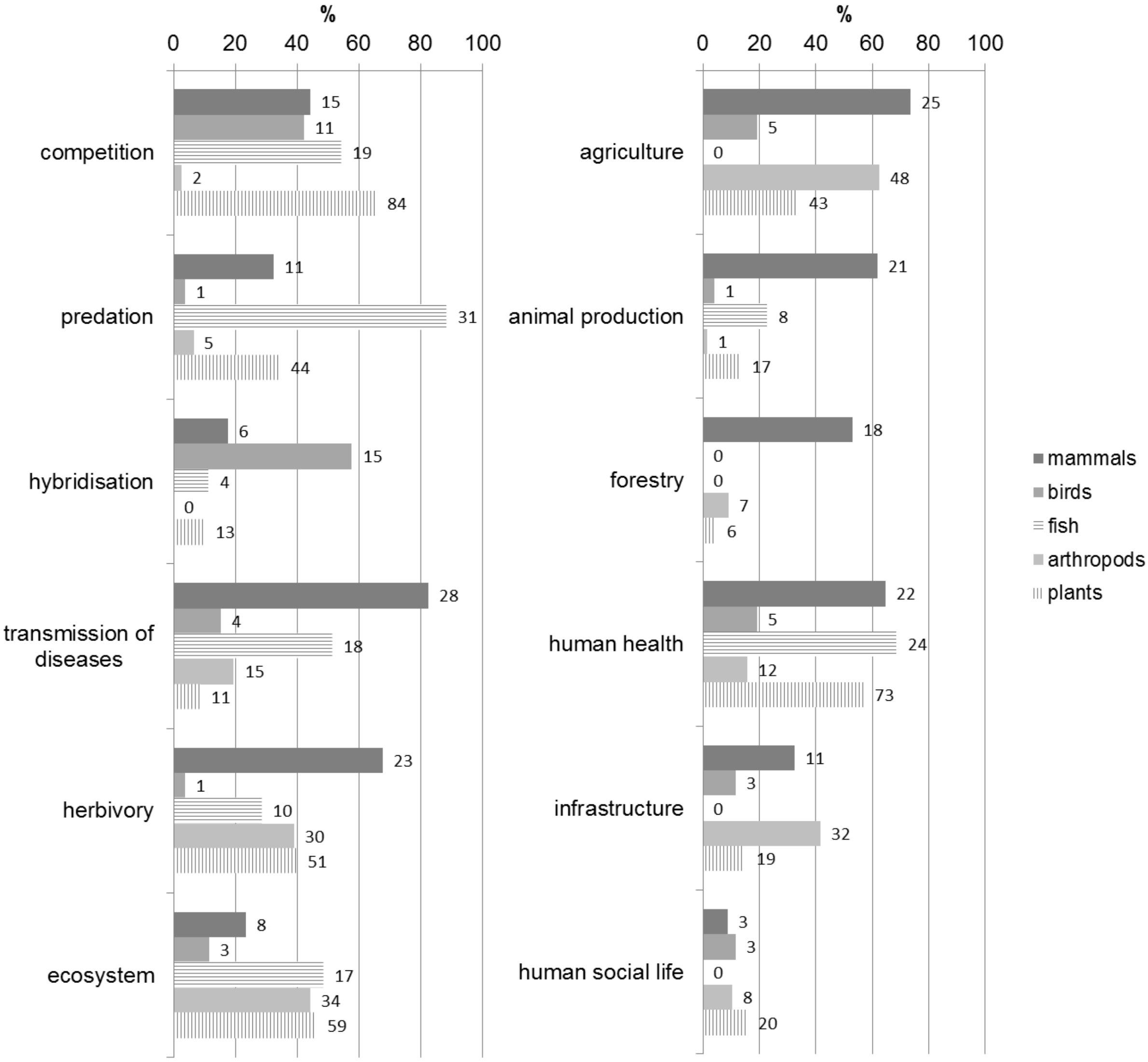


Figure 2: Percentage of species per higher taxon for which impact records were found in each impact category. The number at the head of each bar represents the number of species with impact records found (out of all assessed: mammals: 34; birds: 26; fish: 35; arthropods: 77; plants: 128).

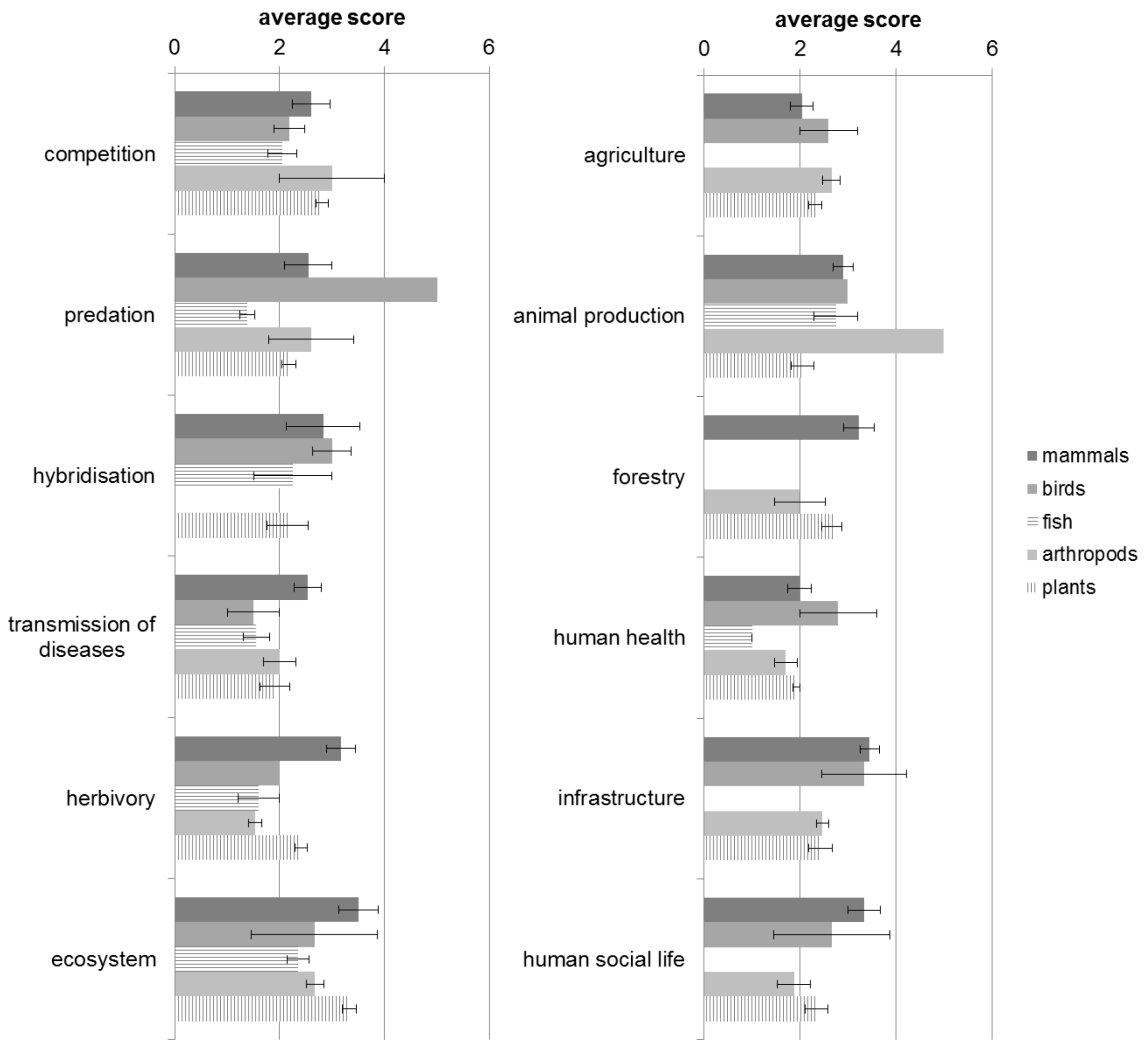


Figure 3: Average scores (± standard errors of the mean) of impact per higher taxon and impact category for species with impact scores > 0 (i.e., the species for which at least one impact record was found in the respective impact category). If no error bar is shown, only one species was found to have impact in this category.

Supplementary Material

Appendix S1: List of species and their environmental and socio-economic impact

		Impact score		
Species	**Taxon group**	**Environmental**	**Socio-economic**	**Total**
Rattus norvegicus	Mammals	19	19	38
Branta canadensis	Birds	17	21	38
Dama dama	Mammals	17	16	33
Cervus nippon	Mammals	16	17	33
Ondatra zibethicus	Mammals	18	14	32
Lantana camara	Plants	17	14	31
Acridotheres tristis	Birds	16	15	31
Varroa destructor	Arthropods	15	16	31
Muntiacus reevesi	Mammals	16	14	30
Eichhornia crassipes	Plants	16	13	29
Cervus canadensis	Mammals	15	14	29
Axis axis	Mammals	13	16	29
Sciurus carolinensis	Mammals	17	11	28
Myocastor coypus	Mammals	15	13	28
Neovison vison	Mammals	21	4	25
Castor canadensis	Mammals	13	12	25
Carassius auratus	Fish	19	5	24
Elodea canadensis	Plants	15	8	23
Procyon lotor	Mammals	9	14	23
Crassula helmsii	Plants	12	10	22
Anoplophora chinensis	Arthropods	8	14	22
Heracleum mantegazzianum	Plants	13	8	21
Fallopia japonica	Plants	12	9	21
Robinia pseudoacacia	Plants	11	9	20
Arundo donax	Plants	13	6	19
Hydrocotyle ranunculoides	Plants	13	6	19
Eucalyptus globulus	Plants	14	4	18
Ammotragus lervia	Mammals	12	6	18
Bison bison	Mammals	12	6	18
Ambrosia artemisiifolia	Plants	10	8	18
Herpestes auropunctatus	Mammals	9	9	18
Pseudorasbora parva	Fish	13	4	17
Senecio mikanioides	Plants	13	4	17
Solidago canadensis	Plants	13	4	17
Linepithema humile	Arthropods	12	5	17
Prunus serotina	Plants	12	5	17
Harmonia axyridis	Arthropods	9	8	17
Odocoileus virginianus	Mammals	8	9	17
Anoplophora glabripennis	Arthropods	7	10	17
Psittacula krameri	Birds	6	11	17
Callosciurus finlaysonii	Mammals	6	11	17
Eucalyptus camaldulensis	Plants	14	2	16
Tradescantia fluminensis	Plants	14	2	16
Ctenopharyngodon idella	Fish	12	4	16
Eleagnus angustifolia	Plants	11	5	16
Nyctereutes procyonoides	Mammals	10	6	16
Ambrosia trifida	Plants	10	6	16
Threskiornis aethiopicus	Birds	9	7	16
Frankliniella occidentalis	Arthropods	8	8	16

Species	Taxon group	Impact score		
		Environmental	Socio-economic	Total
Arctotheca calendula	Plants	7	9	16
Carpobrotus acinaciformis	Plants	15	0	15
Myriophyllum aquaticum	Plants	12	3	15
Acacia saligna	Plants	11	4	15
Cotula coronopifolia	Plants	11	4	15
Bemisia tabaci	Arthropods	8	7	15
Conyza canadensis	Plants	7	8	15
Carpobrotus edulis	Plants	14	0	14
Lupinus polyphyllus	Plants	11	3	14
Impatiens glandulifera	Plants	10	4	14
Lagarosiphon major	Plants	9	5	14
Oxalis pes-caprae	Plants	9	5	14
Aphis gossypii	Arthropods	8	6	14
Opuntia maxima	Plants	8	6	14
Tuta absoluta	Arthropods	5	9	14
Panonychus citri	Arthropods	3	11	14
Cyperus alternifolius	Plants	11	2	13
Rosa rugosa	Plants	10	3	13
Poecilia reticulata	Fish	9	4	13
Ailanthus altissima	Plants	9	4	13
Bidens frondosa	Plants	7	6	13
Paspalum distichum	Plants	7	6	13
Diabrotica virgifera	Arthropods	6	7	13
Callosciurus erythraeus	Mammals	5	8	13
Datura stramonium	Plants	5	8	13
Atlantoxerus getulus	Mammals	9	3	12
Amaranthus retroflexus	Plants	8	4	12
Fallopia x bohemica	Plants	8	4	12
Ovis orientalis	Mammals	7	5	12
Elodea nuttallii	Plants	6	6	12
Lepus capensis	Mammals	5	7	12
Aedes albopictus	Arthropods	4	8	12
Callosobruchus chinensis	Arthropods	4	8	12
Cyperus eragrostis	Plants	4	8	12
Ricinus communis	Plants	4	8	12
Buddleja davidii	Plants	11	0	11
Gambusia holbrooki	Fish	10	1	11
Salvelinus fontinalis	Fish	10	1	11
Acacia longifolia	Plants	9	2	11
Quercus rubra	Plants	9	2	11
Macrosiphum euphorbiae	Arthropods	6	5	11
Galinsoga parviflora	Plants	6	5	11
Rousettus aegyptiacus	Mammals	5	6	11
Grapholita molesta	Arthropods	4	7	11
Diaspidiotus perniciosus	Arthropods	4	7	11
Ceratitis capitata	Arthropods	4	7	11
Leptinotarsa decemlineata	Arthropods	4	7	11
Myiopsitta monachus	Birds	3	8	11
Sylvilagus floridanus	Mammals	3	8	11
Micropterus salmoides	Fish	9	1	10
Mimulus guttatus	Plants	9	1	10
Amelanchier spicata	Plants	8	2	10
Helianthus annuus	Plants	6	4	10
Acanthoscelides obtectus	Arthropods	5	5	10

Species	Taxon group	Impact score		
		Environmental	Socio-economic	Total
Liriomyza huidobrensis	Arthropods	5	5	10
Amorpha fruticosa	Plants	5	5	10
Heliothrips haemorrhoidalis	Arthropods	4	6	10
Bruchus pisorum	Arthropods	4	6	10
Eriosoma lanigerum	Arthropods	4	6	10
Sitophilus oryzae	Arthropods	3	7	10
Rhyzopertha dominica	Arthropods	2	8	10
Halophila stipulacea	Plants	9	0	9
Lepomis gibbosus	Fish	8	1	9
Ameiurus melas	Fish	8	1	9
Acacia dealbata	Plants	7	2	9
Solidago gigantea	Plants	7	2	9
Cairina moschata	Birds	6	3	9
Cygnus atratus	Birds	6	3	9
Cortaderia selloana	Plants	6	3	9
Amaranthus hybridus	Plants	5	4	9
Spodoptera littoralis	Arthropods	3	6	9
Helianthus tuberosus	Plants	3	6	9
Tamias sibiricus	Mammals	2	7	9
Oxyura jamaicensis	Birds	8	0	8
Aptenia cordifolia	Plants	8	0	8
Boussingaultia cordifolia	Plants	8	0	8
Impatiens parviflora	Plants	8	0	8
Pseudotsuga menziesii	Plants	8	0	8
Ameiurus nebulosus	Fish	7	1	8
Oncorhynchus mykiss	Fish	6	2	8
Oenothera biennis	Plants	5	3	8
Conyza bonariensis	Plants	4	4	8
Nicotiana glauca	Plants	4	4	8
Hyphantria cunea	Arthropods	3	5	8
Mesocricetus auratus	Mammals	2	6	8
Anser cygnoides	Birds	7	0	7
Caragana arborescens	Plants	7	0	7
Lonicera japonica	Plants	7	0	7
Populus x canadensis	Plants	7	0	7
Misgurnus anguillicaudatus	Fish	6	1	7
Gambusia affinis	Fish	6	1	7
Rosa multiflora	Plants	6	1	7
Pimephales promelas	Fish	5	2	7
Agave americana	Plants	5	2	7
Aster lanceolatus	Plants	5	2	7
Fallopia sachalinensis	Plants	5	2	7
Brevipalpus obovatus	Arthropods	4	3	7
Estrilda astrild	Birds	3	4	7
Conyza sumatrensis	Plants	3	4	7
Sitotroga cerealella	Arthropods	2	5	7
Saissetia oleae	Arthropods	2	5	7
Eleusine indica	Plants	2	5	7
Galinsoga quadriradiata	Plants	2	5	7
Gomphocarpus fruticosus	Plants	6	0	6
Anser caerulescens	Birds	5	1	6
Clarias gariepinus	Fish	5	1	6
Hypophthalmichthys molitrix	Fish	5	1	6
Hypophthalmichthys nobilis	Fish	5	1	6

Species	Taxon group	Impact score		
		Environmental	Socio-economic	Total
Perccottus glenii	Fish	5	1	6
Ictalurus punctatus	Fish	4	2	6
Fraxinus pennsylvanica	Plants	4	2	6
Acer negundo	Plants	3	3	6
Pseudococcus viburni	Arthropods	2	4	6
Oncorhynchus kisutch	Fish	2	4	6
Sylvilagus transitionalis	Mammals	2	4	6
Amaranthus muricatus	Plants	2	4	6
Monomorium pharaonis	Arthropods	1	5	6
Ptinus tectus	Arthropods	0	6	6
Periplaneta americana	Arthropods	0	6	6
Anser indicus	Birds	5	0	5
Syrmaticus reevesii	Birds	5	0	5
Ovibos moschatus	Mammals	4	1	5
Amaranthus caudatus	Plants	4	1	5
Tropaeolum majus	Plants	4	1	5
Aster novi-belgii	Plants	3	2	5
Sorghum bicolor	Plants	3	2	5
Parthenothrips dracaenae	Arthropods	2	3	5
Hydropotes inermis	Mammals	2	3	5
Ipomoea purpurea	Plants	2	3	5
Parthenocissus quinquefolia	Plants	1	4	5
Melia azedarach	Plants	0	5	5
Paspalum dilatatum	Plants	0	5	5
Chrysolophus pictus	Birds	4	0	4
Coturnix japonica	Birds	4	0	4
Phoenicopterus chilensis	Birds	4	0	4
Eschscholzia californica	Plants	4	0	4
Nosopsyllus fasciatus	Arthropods	3	1	4
Chaetosiphon fragaefolii	Arthropods	3	1	4
Aix galericulata	Birds	3	1	4
Zantedeschia aethiopica	Plants	3	1	4
Fallopia baldschuanica	Plants	2	2	4
Oxidus gracilis	Arthropods	1	3	4
Abutilon theophrasti	Plants	0	4	4
Amaranthus blitoides	Plants	0	4	4
Amaranthus deflexus	Plants	0	4	4
Panicum capillare	Plants	0	4	4
Estrilda troglodytes	Birds	3	0	3
Ictiobus cyprinellus	Fish	3	0	3
Culaea inconstans	Fish	3	0	3
Alcea rosea	Plants	3	0	3
Lysichiton americanus	Plants	3	0	3
Mirabilis jalapa	Plants	3	0	3
Pinus strobus	Plants	3	0	3
Rhopalosiphum maidis	Arthropods	2	1	3
Catostomus commersoni	Fish	2	1	3
Ictiobus bubalus	Fish	2	1	3
Oncorhynchus gorbuscha	Fish	2	1	3
Chromaphis juglandicola	Arthropods	1	2	3
Aspidiotus nerii	Arthropods	1	2	3
Obolodiplosis robiniae	Arthropods	1	2	3
Ambrosia coronopifolia	Plants	1	2	3
Solidago graminifolia	Plants	1	2	3

Species	Taxon group	Impact score		
		Environmental	Socio-economic	Total
Amaranthus hypochondriacus	Plants	0	3	3
Ipomoea indica	Plants	0	3	3
Stictocephala bisonia	Arthropods	2	0	2
Aix sponsa	Birds	2	0	2
Salvelinus namaycush	Fish	2	0	2
Umbra pygmaea	Fish	2	0	2
Chenopodium ambrosioides	Plants	2	0	2
Cornus sericea	Plants	2	0	2
Duchesnea indica	Plants	2	0	2
Epilobium ciliatum	Plants	2	0	2
Mahonia aquifolium	Plants	2	0	2
Macrosiphoniella sanborni	Arthropods	1	1	2
Myzus ornatus	Arthropods	1	1	2
Myzus varians	Arthropods	1	1	2
Bruchus rufimanus	Arthropods	1	1	2
Amandava amandava	Birds	1	1	2
Callipepla californica	Birds	1	1	2
Acipenser transmontanus	Fish	1	1	2
Odontesthes bonariensis	Fish	1	1	2
Hemichromis fasciatus	Fish	1	1	2
Liza haematocheila	Fish	1	1	2
Hemiechinus auritus	Mammals	1	1	2
Tamias striatus	Mammals	1	1	2
Lycopersicon esculentum	Plants	1	1	2
Phytolacca americana	Plants	1	1	2
Megastigmus spermotrophus	Arthropods	0	2	2
Omonadus floralis	Arthropods	0	2	2
Macropus rufogriseus	Mammals	0	2	2
Fagopyrum esculentum	Plants	0	2	2
Hordeum jubatum	Plants	0	2	2
Lepidium densiflorum	Plants	0	2	2
Lepidium sativum	Plants	0	2	2
Persicaria wallichii	Plants	0	2	2
Rudbeckia laciniata	Plants	0	2	2
Solanum sodomaeum	Plants	0	2	2
Symphoricarpos albus	Plants	0	2	2
Encarsia formosa	Arthropods	1	0	1
Aphytis mytilaspidis	Arthropods	1	0	1
Myzus ascalonicus	Arthropods	1	0	1
Panaphis juglandis	Arthropods	1	0	1
Alectoris barbara	Birds	1	0	1
Micropercops cinctus	Fish	1	0	1
Aloe vera	Plants	1	0	1
Echinocystis lobata	Plants	1	0	1
Oenothera glazioviana	Plants	1	0	1
Hypoponera punctatissima	Arthropods	0	1	1
Aphis spiraephaga	Arthropods	0	1	1
Rhodobium porosum	Arthropods	0	1	1
Coccus hesperidum	Arthropods	0	1	1
Carpophilus marginellus	Arthropods	0	1	1
Glischrochilus quadrisignatus	Arthropods	0	1	1
Urophorus humeralis	Arthropods	0	1	1
Sciurus anomalus	Mammals	0	1	1
Amaranthus crispus	Plants	0	1	1

		Impact score		
Species	**Taxon group**	**Environmental**	**Socio-economic**	**Total**
Nicandra physalodes	Plants	0	1	1
Solanum tuberosum	Plants	0	1	1
Lamyctes emarginatus	Arthropods	0	0	0
Tinea translucens	Arthropods	0	0	0
Copidosoma floridanum	Arthropods	0	0	0
Leptomastix dactylopii	Arthropods	0	0	0
Acyrthosiphon caraganae	Arthropods	0	0	0
Neomyzus circumflexus	Arthropods	0	0	0
Rhopalosiphum insertum	Arthropods	0	0	0
Uroleucon erigeronense	Arthropods	0	0	0
Pulvinaria hydrangeae	Arthropods	0	0	0
Megaselia gregaria	Arthropods	0	0	0
Stricticomus tobias	Arthropods	0	0	0
Trechicus nigriceps	Arthropods	0	0	0
Caenoscelis subdeplanata	Arthropods	0	0	0
Cartodere nodifer	Arthropods	0	0	0
Carpophilus bifenestratus	Arthropods	0	0	0
Carpophilus nepos	Arthropods	0	0	0
Philonthus rectangulus	Arthropods	0	0	0
Colinus virginianus	Birds	0	0	0
Francolinus erckelii	Birds	0	0	0
Meleagris gallopavo	Birds	0	0	0
Perdix dauurica	Birds	0	0	0
Oryzias sinensis	Fish	0	0	0
Ictiobus niger	Fish	0	0	0
Hemichromis letourneauxi	Fish	0	0	0
Funambulus pennanti	Mammals	0	0	0
Citrullus lanatus	Plants	0	0	0
Elaeagnus commutata	Plants	0	0	0
Juncus tenuis	Plants	0	0	0
Phacelia tanacetifolia	Plants	0	0	0
Physocarpus opulifolius	Plants	0	0	0
Solanum cornutum	Plants	0	0	0
Sorbaria sorbifolia	Plants	0	0	0
Spiraea chamaedryfolia	Plants	0	0	0

Appendix S2: Generic Impact Scoring System (GISS)

Detailed description of impact categories. An updated Excel version is available from the authors on request.

1 Environmental impacts

1.1 Impacts on plants or vegetation

Impacts concerns single or a few plant species (e.g., by changes in reproduction, survival, growth, abundance). In case of plants, impact may consist of allelopathy or the release of plant exudates such as oxygen or salt. In case of animals impact include herbivory, grazing, bark stripping, antler rubbing, feeding on algae, or uprooting of aquatic macrophytes. It includes restrictions in establishment, pollination, or seed dispersal of native species. Impacts range from population decline to population loss and it includes also minor changes in the food web.

0 No impacts known or detectable.

1 Minor impacts, in the range of native species, only locally or on abundant species.

2 Minor impacts, in the range of native species, not only locally or on abundant species.

3 Medium impacts, large-scale, several species concerned, relevant decline (this includes decrease in species richness or diversity).

4 Major small-scale destruction of the vegetation, decrease of species of concern.

5 Major large-scale destruction of the vegetation, threat to species of concern, including local extinctions.

1.2 Impacts on animals through predation or parasitism

Impacts may concern single animal species or a guild, e.g., through predation, parasitation, or intoxication of eggs, juveniles or adults, measurable for example as changes in reproduction, survival, growth, or abundance. When the alien species is a plant, the impact can be due to a change in food availability or palatability (e.g. fruits, forage or flowers affecting pollinators), and the uptake of secondary plant compounds or toxic compounds by animals. This impact may act on different levels, ranging from population decline to population loss and it includes also minor changes in the food web.

0 No impacts known or detectable.
1 Minor impacts, in the range of native species, only locally or on abundant species.
2 Minor impacts, in the range of native species, not only locally or on abundant species.
3 Medium impacts, large-scale, several species concerned, relevant decline (this includes decrease in species richness or diversity).
4 Major small-scale impacts on target species, decrease of species of concern.
5 Major large-scale impacts on target species, threat to species of concern, including local extinctions.

1.3 Impacts on species through competition

Impacts may concern single species, a group or a community, e.g., by competition for nutrients, food, water, space or other resources, including competition for pollinators which might affect plant fecundity (i.e. fruit or set set). Often, the alien species outcompetes native species due to higher reproduction, resistance or longevity. In the beginning, this impact may be inconspicuous and only recognizable as slow change in species abundance which finally may lead to the disappearance of a native species. It includes behavioural changes in outcompeted species and ranges from population decline to population loss.

0 No impacts known or detectable.

1 Minor impacts, in the range of native species, only locally or on abundant species.

2 Minor impacts, in the range of native species, not only locally or on abundant species.

3 Medium impacts, large-scale, several species concerned, relevant decline.

4 Major small-scale impacts on target species, decrease of species of concern.

5 Major large-scale impacts on target species, threat to species of concern, including local extinctions.

1.4 Impacts through transmission of diseases or parasites to native species

Host or alternate host for diseases (viruses, fungi, protozoans or other pathogens) or parasites, impact on native species by transmission of diseases or parasites.

0 No impacts known or detectable.

1 Occasional transmission to native species. No impacts on native species detectable.

2 Occasional transmission to native species. Only minor impacts on native species detectable.

3 Regular transmission to native species. Minor population decline in native species.

4 Transmission to native species and/or species of concern, decline of these species but no extinction.

5 Transmission to native species and/or species of concern, serious decline of these species and/or local extinction.

1.5 Impacts through hybridization

Impacts through hybridization with native species, usually closely related, leading to a loss of reproduction possibility, sterile or fertile hybrid offspring, gradual loss of the genetic identity of a species, and/or disappearance of a native species, i.e. local extinction.

0 No impacts known or detectable.
1 Hybridization possible in ornamental breeding or captivity, but not or only rarely in the wild.
2 Hybridization common in the wild, no hybrid offspring, constraints to normal reproduction.
3 Hybridization common, with sterile offspring.
4 Hybridization common with fertile offspring, growing hybrid populations.
5 Hybridization common with fertile offspring, predominant hybrid populations, increasing loss of the genetic identity of a native species, local extinction of the native species.

1.6 Impacts on ecosystems

Impacts on characteristic properties of an ecosystem, its nutritional status (e.g., changes in nutrient pools and fluxes, which may be caused by nitrogen-fixating symbionts, increased turbidity or pollution), modification of soil properties (e.g., soil moisture, pH, C/N ratio, salinity, eutrophication), and disturbance regimes (vegetation flammability, changes in erosion or soil compacting), changes in ecosystem services (e.g., pollination or decomposition). Impact on ecosystems includes modification of successional processes. Such habitat modifications may lead to reduced suitability (e.g. shelter) for other species, thus causing their disappearance. Impacts also include the need for applying pesticides which due to their low selectivity have side-effects on non-target organisms.

0 No impacts known or detectable.

1 Minor impacts, only locally, only few species affected.

2 Minor impacts, not only locally, e.g., impact on a particular ecosystem parameter.

3 Medium impacts, large-scale, damage of sites of conservation importance, relevant ecosystem modifications, impact on several ecosystem properties, pesticide applications needed, relevant changes in species composition.

4 Major small-scale effects, damage of sites of conservation importance, changes in soil properties, major changes in ecosystem services, decrease of species of concern.

5 Major large-scale effects, damage of sites of conservation importance, changes in disturbance regimes, threat to species of concern, including local extinctions.

2. Socio-economic impacts

2.1 Impacts on agricultural production

Impacts through damage to crops or plantations, but also to horticultural and stored products. Impacts include competition with weeds, direct feeding damage (from feeding traces which reduce marketability to complete production loss) but also reduced accessibility, usability or marketability through contamination. Impacts include the need for applying pesticides which involve additional costs, also by reducing market quality. Impacts usually lead to an economic loss.

0 No impacts known or detectable.

1 Minor impacts, in the range of native species, only locally, negligible economic loss.

2 Minor impacts, in the range of native species, but more wide-spread, minor economic loss.

3 Medium impacts, large-scale or frequently, pesticide application necessary, medium economic loss.

4 Major impacts with high damage, often occurring or with high probability, major economic loss

5 Major impacts with complete destruction and economic loss.

2.2 Impacts on animal production

Impacts through competition with livestock, transmission of diseases or parasites to livestock and predation of livestock. Intoxication of livestock through changes in food palatability, secondary plant compounds or toxins, weakening or injuring livestock, e.g., by stinging or biting. Also impacts on livestock environment such as pollution by droppings on farmland which domestic stock are then reluctant to graze. Hybridization with livestock. Impacts include the need for applying pesticides which involve additional costs, also by reducing market quality. Impacts usually lead to an economic loss.

0 No impacts known or detectable.

1 Minor impacts, in the range of native species, only locally, negligible economic loss.

2 Minor impacts, in the range of native species, but more wide-spread, minor economic loss.

3 Medium impacts, large-scale or frequently, pesticide application necessary, medium economic loss.

4 Major impacts with high damage, often occurring or with high probability, major economic loss

5 Major impacts with complete destruction and economic loss.

2.3 Impacts on forestry production

Impacts on forests or forest products through plant competition, parasitism, diseases, herbivory, effects on tree or forest growth and on seed dispersal. Impacts may affect forest regeneration through browsing on young trees, bark gnawing or stripping and antler rubbing. Damage includes felling trees, defoliating them for nesting material or causing floods. Impacts include the need for applying pesticides which involve additional costs, also by reducing market quality. Impacts usually lead to an economic loss.

0 No impacts known or detectable.

1 Minor impacts, in the range of native species, only locally, negligible economic loss.

2 Minor impacts, in the range of native species, but more wide-spread, minor economic loss.

3 Medium impacts, effects on forest regeneration, large-scale or frequently, pesticide application necessary, medium economic loss.

4 Major impacts with high damage, often occurring or with high probability, major economic loss

5 Major impacts with complete destruction and economic loss.

2.4 Impacts on human infrastructure and administration

Impacts include damage to human infrastructure, such as roads and other traffic infrastructure, buildings, damps, docks, fences, electricity cables (e.g., by gnawing or nesting on them) or through pollution (e.g., by droppings). Impacts through root growth, plant cover in open water bodies or digging activities on watersides, roadside embankments and buildings may affect flood defense systems, traffic infrastructure or stability of buidlings. Impacts may affect human safety and cause traffic accidents. Impacts include the need for applying pesticides, their development costs and further registration or administration costs, as well as costs for research and control. Impacts usually lead to an economic loss.

0 No impacts known or detectable.
1 Minor impacts, in the range of native species, only locally, negligible economic loss.
2 Minor impacts, in the range of native species, but more wide-spread, minor economic loss.
3 Medium impacts, large-scale or frequently, pesticide application necessary, medium economic loss.
4 Major impacts with high damage, often occurring or with high probability, major economic loss.
5 Major impacts with complete destruction and economic loss.

2.5 Impacts on human health

Injuries (e.g., bites, stings, scratches, rashes), transmission of diseases and parasites to humans, bioaccumulation of noxious substances, health hazard due to contamination with pathogens or parasites (e.g., of water, soil, food, or by feces or droppings), as well as secondary plant compounds, toxins or allergen substances such as pollen. Impacts include the need for applying pesticides which due to their low selectivity and/or residues may have side-effects on humans. Via health costs, impacts usually lead to economic costs.

0 No impacts known or detectable.
1 Minor impacts, in the range of native species, only locally, negligible economic costs.

2 Minor impacts, in the range of native species, but more wide-spread, minor economic costs.

3 Medium impacts, large-scale or frequently, pesticide application necessary, medium economic costs.

4 Major impacts with high damage, often occurring or with high probability, but rarely fatal, major economic costs.

5 Major impacts, fatal issues, high economic costs.

2.6 Impacts on human social life

Noise disturbance, pollution of recreational areas (water bodies, rural parks, golf courses or city parks), including fouling, eutrophication, damage by trampling and overgrazing, restrictions in accessibility (e.g. by thorns, other injuring structures, successional processes, or recent pesticide application) to habitats or a landscapes of recreational value. Restrictions or loss of recreational activities.

0 No impacts known or detectable.

1 Minor impacts, in the range of native species, only locally, negligible economic loss.

2 Minor impacts, in the range of native species, but more wide-spread, minor economic loss.

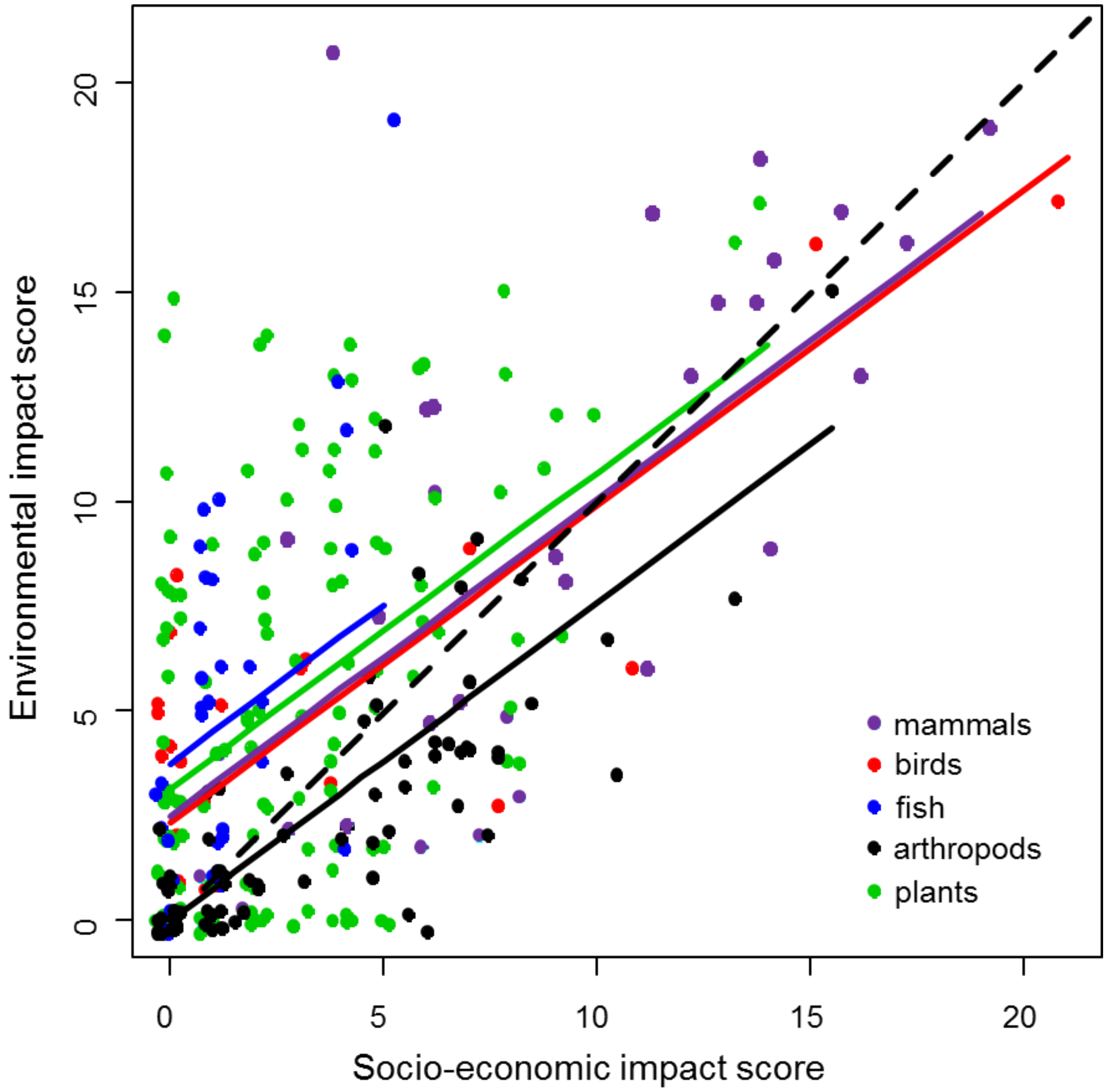
3 Medium impacts, large-scale or frequently, pesticide application necessary, medium economic loss.

4 Major impacts with high damage, often occurring or with high probability, recreational value of a location strongly affected, major economic loss.

5 Major impacts with complete destruction and loss of recreational value, major economic loss.

Appendix S3: Socio-economic versus environmental impact

Dashed is the unity line and marks where socio-economic equals environmental impact. Data points were jittered for better visibility. The plot is based on data assuming that no information about impact means that the species does not have a measurable impact, but a plot excluding all cases where either environmental or socio-economic impact was unknown or zero gives qualitatively similar results (not shown).



Appendix S4: Impact in Europe versus impact elsewhere.

Difference between a) environmental and b) socio-economic impact elsewhere (introduced range outside Europe) and Europe for mammal (blank squares) and bird (black circles) orders taking into account phylogenetic relatedness as random factor. Values on x-axes below zero show higher impact within Europe, and positive values higher impact outside Europe.