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

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Summary

1. Alien species can change the recipient environment in various ways, and 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 the 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 prioritizing management efforts and effective allocation of resources. By applying the generic impact scoring system (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, and context dependence of impacts. This would also allow studies at lower taxonomic levels, and within-taxon analyses of functional groups and guilds.

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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; Powell, Chase & Knight 2011; Vilà *et al*. 2011; Pyšek *et al*. 2012), mammals (e.g. Nentwig, Kühnel & Bacher 2010), birds (e.g. Shirley & Kark 2009; Kumschick & Nentwig 2010; Kumschick, Bacher & Blackburn 2013; Evans *et al*. 2014) and other groups (e.g. Lovell, Stone & Fernandez 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 vary, but also to compare different groups of organisms (Nentwig, Kühnel & Bacher 2010; Kumschick, Bacher & Blackburn 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, Williams & Halloy 1999), to produce prohibited lists (e.g. Gederaas *et al*. 2012), for prioritization (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, Kühnel & Bacher (2010) and subsequently extended by Kumschick *et al*. (2012) has proven useful for comparing the impact of alien species between taxa (Kumschick & Nentwig 2010) and between native and invaded ranges (Kumschick *et al*. 2011); and for finding specific species traits associated with impact (Nentwig, Kühnel & Bacher 2010; Kumschick, Bacher & Blackburn 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 of 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. Kolar & Lodge 2001; Hayes & Barry 2008). 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, Williamson & Dalmazzone 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 traditional 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, Kühnel & Bacher 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 hybridization, impact is dependent on the presence or absence of a closely related species (e.g. Smith, Henderson & Robertson 2005).

The main aim of this study is to apply the GISS (Nentwig, Kühnel & Bacher 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 and 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 magnitudes. 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 prioritization and risk assessment (European Commission 2014).

Materials and 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 data base (www.europe-aliens.org; Pergl *et al.* 2012). This included 26 birds and 34 mammals (see also Kumschick & Nentwig 2010; Nentwig, Kühnel & Bacher 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 data base. A detailed list of species can be found in the Appendix S1 (Supporting information).

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 three 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, Kühnel & Bacher (2010), Kumschick & Nentwig (2010), Kumschick *et al.* (2011), Vaes-Petignat & Nentwig (2014) and Van der Veer & Nentwig (2014) or be obtained from the authors for plants (Z. Marková, M. Vilà, J. Pergl, W. Nentwig & P. Pyšek, unpublished data).

For all taxa, data on reported impacts were collected. For mammals and birds, information on impacts in Europe and other invaded ranges was kept separate 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 were 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 previously applied to mammals and birds (e.g. Kumschick & Nentwig 2010; Nentwig, Kühnel & Bacher 2010; Kumschick, Bacher & Blackburn 2013; Evans *et al.* 2014), and arthropods (Vaes-Petignat & Nentwig 2014) and with potential to be extended to many other taxa (Nentwig, Kühnel & Bacher 2010; Kumschick *et al.* 2012) was used. The GISS includes two impact classes, environmental and socio-economic, with six impact categories assigned to each group. Environmental impacts are classified as follows: (i) on plants or vegetation (e.g. through herbivory), (ii) on animals through predation or parasitism, (iii) through competition, (iv) transmission of diseases or parasites to native species, (v) hybridization and (vi) on ecosystems in general (e.g. through changes in nutrient cycling). Socio-economic impact consists of impacts (i) on agriculture, (ii) animal production, (iii) forestry, (iv) human health, (v) human infrastructure and administration, and (vi) 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, Kühnel & Bacher 2010; Kumschick & Nentwig 2011; see 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, that is 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 as fixed effect. 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, Vilà & Kühn 2008). Models were fitted with the lmer function in the package lme4 (version 0·999999-2; Bates, Maechler & Bolker 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; Pinheiro *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 impacts 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). For selecting random effects, models were fit by REML (Zuur *et al.* 2009).

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 (Fig. 1). Overall, mammals had the highest total impacts and fish the lowest (Fig. 1a). When considering environmental impact only, arthropods are having the lowest impact (Fig. 1b). For socio-economic impact

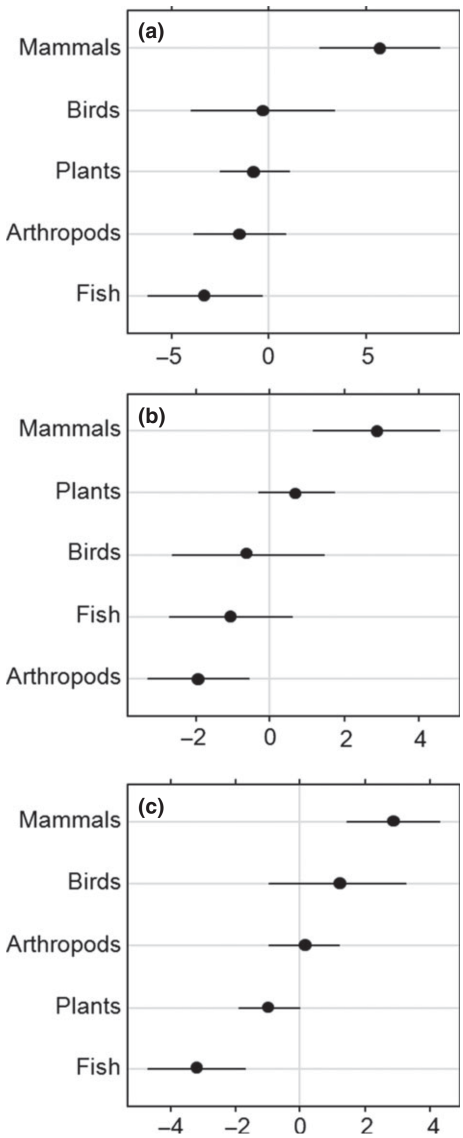

Fig. 1. Comparison of (a) total, (b) environmental and (c) socio-economic impact between taxa. Values on x-axes are the random effects of deviances (mean ± SD) in impacts of taxonomic groups from the common mean impact (set to zero) of the mixed effects model.

separately, mammals also had the highest impacts and plants and fish the lowest (Fig. 1c).

ENVIRONMENTAL VS. 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 = $0{\cdot}75 \pm 0{\cdot}07$; 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, that is 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 that 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 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 hybridization, 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 taxon 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 taxon to exert impact on 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 demonstrates 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

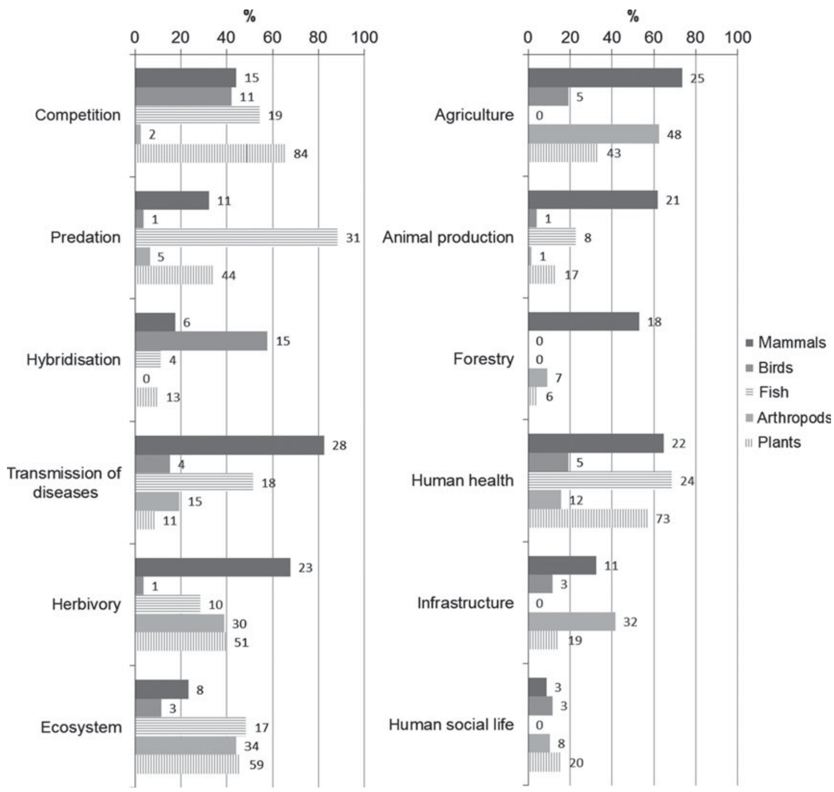

Fig. 2. Percentage of species per taxonomic group for which impact records were found in each impact category. The number at the head of each bar represents the number of species with impact records found (out of all assessed: mammals: 34; birds: 26; fish: 35; arthropods: 77; plants: 128).

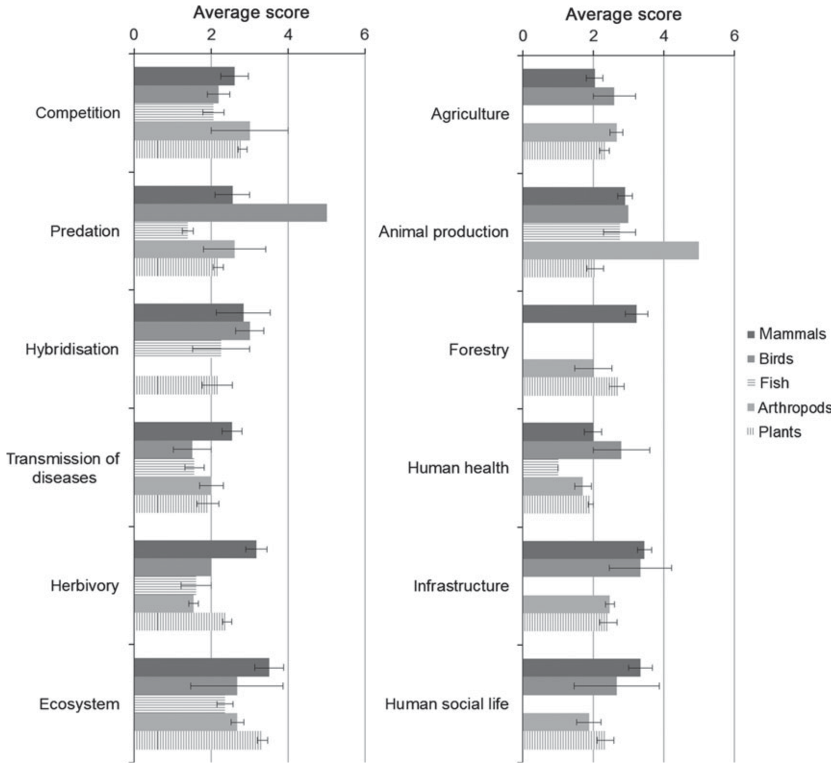

Fig. 3. Average scores (± SE of the mean) of impact per taxomonic group and impact category for species with impact scores >0 (i.e. the species for which at least one impact record was found in the respective impact category). If no error bar is shown, only one species was found to have impact in this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

Europe (impact elsewhere minus 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; 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, reveals the similarities and differences between the magnitude of environmental and socio-economic impacts associated with five major taxonomic groups as diverse as plants, vertebrates and invertebrates. First of all, we demonstrate 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 it is often necessary to assess alien species coming from distant taxonomic groups with a common procedure (e.g. Blackburn *et al.* 2014).

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 Organization (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 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 is high either on the environment or on socio-economy, 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 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 that 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 that is the second most frequently scored impact. The significance of this impact type for humans is usually neither 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 prioritization 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 is 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 or their per-capita impacts 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, that is 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.* 2015).

Our study does not only reveal patterns on available data, but it shows potential gaps concerning the knowledge of impacts 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. First, 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. This 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 are 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 a 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, Kühnel & Bacher 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 prioritizing alien species and listing processes (e.g. 'black lists', 100-worst-lists). Usually, available risk assessments, which are often required by policymakers 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 (EU Regulation 1143/2014) 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 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, we have a limited understanding of this variation in impact level, and the reasons that cause it. Future studies should aim to identify significant variations in alien species impacts, along with the mechanisms responsible for this variation. Such studies would further our understanding of 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, Bacher & Blackburn 2013). Future studies should therefore try to identify common traits across taxa that are responsible for the observed impacts that 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 be possible to incorporate such results in regional risk assessments and decision-making.

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Data accessibility

All data are available in the Supporting Information.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

- List of species and their environmental and socioeconomic impact.
- Generic impact scoring system (GISS).
- Socioeconomic vs. environmental impact.
- Impact in Europe vs. impact elsewhere.