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A Generic Impact-Scoring System Applied to Alien Mammals in Europe

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Abstract: *We present a generic scoring system that compares the impact of alien species among members of large taxonomic groups. This scoring can be used to identify the most harmful alien species so that conservation measures to ameliorate their negative effects can be prioritized. For all alien mammals in Europe, we assessed impact reports as completely as possible. Impact was classified as either environmental or economic. We subdivided each of these categories into five subcategories (environmental: impact through competition, predation, hybridization, transmission of disease, and herbivory; economic: impact on agriculture, livestock, forestry, human health, and infrastructure). We assigned all impact reports to one of these 10 categories. All categories had impact scores that ranged from zero (minimal) to five (maximal possible impact at a location). We summed all impact scores for a species to calculate "potential impact" scores. We obtained "actual impact" scores by multiplying potential impact scores by the percentage of area occupied by the respective species in Europe. Finally, we correlated species' ecological traits with the derived impact scores. Alien mammals from the orders Rodentia, Artiodactyla, and Carnivora caused the highest impact. In particular, the brown rat (*Rattus norvegicus*), muskrat (*Ondathra zibethicus*), and sika deer (*Cervus nippon*) had the highest overall scores. Species with a high potential environmental impact also had a strong potential economic impact. Potential impact also correlated with the distribution of a species in Europe. Ecological flexibility (measured as number of different habitats a species occupies) was strongly related to impact. The scoring system was robust to uncertainty in knowledge of impact and could be adjusted with weight scores to account for specific value systems of particular stakeholder groups (e.g., agronomists or environmentalists). Finally, the scoring system is easily applicable and adaptable to other taxonomic groups.*

Keywords: ecological impact, environmental impact, invasive species, mitigation, prioritization, species traits, stakeholders

Un Sistema Genérico de Clasificación de Impacto Aplicado a Mamíferos Introducidas en Europa

Resumen: *Presentamos un sistema genérico de clasificación que compara el impacto de especies introducidas entre los miembros de grupos taxonómicos. Esta clasificación puede ser utilizada para identificar a las especies introducidas más dañinas para poder priorizar las medidas de conservación para aminorar sus efectos negativos. Evaluamos los reportes de impacto para todos los mamíferos introducidos en Europa. El impacto fue clasificado como ambiental o económico. Subdividimos cada una de esas categorías en cinco categorías (ambiental: impacto mediante competencia, depredación, hibridación, transmisión de enfermedades y herbivoría; económico: impacto sobre la agricultura, ganado, silvicultura, salud humana e infraestructura). Asignamos todos los reportes de impacto a una de esas 10 categorías. Todas las categorías tuvieron valores de impacto entre cero (mínimo) y cinco (impacto máximo posible en una localidad). Sumamos todos los valores de impacto para una especie para calcular valores de "impacto potencial". Obtuvimos valores de "impacto actual" multiplicando los valores de impacto potencial por el porcentaje del área ocupada por las respectivas especies en Europa. Finalmente, correlacionamos los atributos ecológicos de las especies con los valores de impacto derivados. Mamíferos introducidos de los órdenes Rodentia, Artiodactyla y Carnivora causaron el mayor impacto. En particular,* Rattus norvegicus, Ondathra zibethicus *y* Cervus nippon *tuvieron los valores* *totales más altos. Especies con un alto potencial de impacto ambiental también tuvieron un fuerte potencial de impacto económico. El impacto potencial también se correlacionó con la distribución en Europa. La flexibilidad ecológica (medida como el número de hábitats diferentes que ocupa una especie) se correlacionó estrechamente con el impacto. El sistema de clasificación fue robusto ante la incertidumbre en el conocimiento del impacto y pudo ser ajustado con valores de ponderación para considerar sistemas de valores específicos de ciertos grupos de interés (e.g., agrónomos o ambientalistas). Finalmente, el sistema de clasificación es fácilmente aplicable y adaptable a otros grupos taxonómicos.*

Palabras Clave: atributos de las especies, especies invasoras, grupos de interés, impacto ambiental, impacto ecológico, mitigación, priorización

Introduction

Alien invasive species are a large threat to biodiversity (Mack et al. 2000; IUCN 2008), and the economic damage they cause exceeds 5% of the global gross product (Pimentel 2002). Although there is a general consensus that the overall negative effects of alien species have to be reduced, strategies on how to do this effectively with a limited budget and which species should be targeted first are controversial matters. One promising way to address the problem is to prioritize actions against alien species that cause the highest level of impact or to prevent species with a high impact potential from becoming established or spreading. Thus, what is needed is a method to quantify impact in a way that it can be compared among alien species within a taxonomic group. Furthermore, one would like to be able to predict the potential impact of species that are not yet established in order to target preventive measures against those with the highest impact potential.

It is obviously challenging to compare the damage caused by different species, such as the carnivorous American mink (*Neovison vison*) and the herbivorous sika deer (*Cervus nippon*), and even more challenging to compare damage among species belonging to different taxonomic groups, such as fishes and birds. In addition, our knowledge of the impact of a given species varies from anecdotal reports to experimental evidence. To overcome these obstacles a general system of impact categories is needed, which allows scoring and comparison of all potentially relevant types of environmental and economic impact caused by alien species. Such a system should be generic so as to allow cross-taxon comparisons, and it should be robust to compensate for some level of uncertainty and lack of knowledge.

We devised an impact-scoring system that for alien mammals in Europe includes all relevant impact categories that have been reported in the scientific literature. A similar approach—risk-assessment analysis—was used with alien vertebrates in Australia (Bomford 2003) and with alien plants in Europe (Pyšek & Richardson 2007). Here, however, we dealt with an impact analysis for an entire class of organisms on an entire continent in a complete assessment of actual impact data. We hypothesized that scoring impact within categories would allow quantification of impact and that species could be ranked according to their impact scores, which would enable prioritization of mitigation or eradication strategies. Such a system would allow recommendations on the most efficient application of the limited resources available for controlling alien species. A better understanding of the relationship between impact scores and species traits may provide a novel method with which to predict the potential impact of a new alien mammal species. Our scoring system is generally formulated and could easily be transferred to other taxonomic groups; thus, our approach represents a generic and important step away from anecdotal descriptions and case studies of the impacts of alien species to generalizations and predictions of these impacts.

Methods

From the 121 alien mammal species mentioned in the DAISIE (Delivering Alien Invasive Species Inventories for Europe) database (www.europe-aliens.org), we excluded those from our examination that did not have established self-sustaining populations in Europe and species introduced before the year 1500. We restricted our study to alien mammal species with a native distribution entirely outside Europe ("true aliens"), which yielded a final list of 34 alien mammal species. Species that are native to parts of Europe, but alien to other European parts and feral domesticated species can also cause considerable damage, but we did not include them in this study because these groups have invasion histories different from those of true aliens. Their different backgrounds may result in different types and levels of impact. It is also not straightforward to compare the impacts of true aliens and aliens that are native in parts of Europe because impacts in the latter group are restricted to a fraction of Europe. Thus, we believe it is better to treat aliens that are native to parts of Europe and feral species separately.

We used the same definition of Europe as in the Fauna Europaea (2004) (i.e., the European continent and its islands, including in the east Ukraine, Belarus, and the

European part of Russia). For the 34 true alien mammals in Europe, we conducted an intensive literature survey on their impact. First, we compiled the information provided by Mitchell-Jones et al. (1999) and Long (2003). Second, we included information from databases on invasive species, such as NOBANIS (North European and Baltic Network on Invasive Alien Species; www.nobanis.org) and the Global Invasive Species Database of the International Union for Conservation of Nature (IUCN 2008), and from databases on mammals in general (Myers et al. 2008). Third, we extracted records of their impact from the ISI Web of Knowledge, where we used the species names as search term. In total, we found 150 useful articles in scientific journals (see Supporting Information).

For the comparison among species, we classified impacts as either environmental or economic. Each of these classes was then further divided into five subcategories. Environmental impacts were classified according to their mechanisms as impact through competition, predation, hybridization, transmission of disease, or herbivory. Economic impact was subdivided according to receptor categories into impact on agriculture, livestock, forestry, human health, or infrastructure. We assigned all impact reports to one of these 10 categories.

For each category, impact values ranged from zero to five, for which zero was no impact known or detectable and five was the highest impact possible at a site. We formulated a verbal description for each impact level, which made the scaling process transparent and reproducible and would easily allow adaptations if new information were to become available (Supporting Information). These impact scores were the local impact the species had at a given site, but could also be considered as the maximum potential impact the species would have if it were to occur throughout Europe (i.e., potential impact). Assessment of the potential impact did not take into account current distribution of the species. Alien mammals in Europe presently occupy areas of very different size. For example, the brown rat (*Rattus norvegicus*) occurs in all European countries we considered and in 68.8% of all UTM grid cells, whereas Finlayson's squirrel (*Callosciurus finlaysonii*) is currently restricted to a few locations in Italy (one-UTM grid cell) (Mitchell-Jones et al. 1999). To consider distribution of the species in addition to their impact, we multiplied potential impact values by the percentage of UTM grid cells (about 50 × 50 km) the species occupies in Europe (species distributions from Mitchell-Jones et al. [1999]). The impact scores corrected for the area can be interpreted as the "actual impact" the species currently causes in Europe. We compared impacts among species by summing up scores of environmental and economic impacts. We did not weigh scores of subcategories, thus all subcategories were considered as of equal importance.

Each author scored all impacts for all mammal species independently; thus, three people independently assigned impact scores following the scoring scheme in Supporting Information. We used median scores for all analyses and presentations. Nevertheless, we also quantified deviations in scoring to test reproducibility of the scoring by different persons. To verify robustness of the conclusions drawn, we carried out all analyses with each author's individual scores and compared results to those obtained with the median scores.

Scoring of impacts also allowed us to test whether species causing a high impact, either environmental or economic, shared common traits. We therefore investigated whether species traits, which are in general considered to be related to invasion success in mammals, (Jeschke & Strayer 2006) are associated with their impact. First, we tested a number of general life-history traits (body size, fecundity, age at maturity, longevity, diet type [herbivorous vs. carnivorous/omnivorous]). Such traits usually code for a certain life style (Sakai et al. 2001), and we sought to determine whether certain life styles are associated with larger impacts. We used life-history and dietary data from Fiedler et al. (1967) and Long (2003). Ecological flexibility may also determine impact because species that can live under a variety of environmental circumstances may sustain higher population densities and occupy larger areas. We used the number of different habitat types in which a species can be found in its native range as proxy for ecological flexibility. Species' habitat descriptions (Long 2003) were translated into nine EUNIS level-1 habitat types (European Environment Agency; eunis.eea.europa.eu): coastal; inland surface waters; mires, bogs and fens; grasslands; heathland, scrub, and tundra; woodland and forest; inland unvegetated or sparsely vegetated habitats; agricultural, horticultural, and domestic habitats; and constructed, industrial, and other artificial habitats.

The factor that is probably most often believed to be the single most reliable predictor of impact is whether a species causes damage elsewhere outside its native range (Williamson 1999; Simberloff et al. 2002; Bomford 2003; Krivánek & Pyšek 2006). We investigated how records of damage elsewhere related to impact in Europe because of its wide use in risk assessments and to compare its predictive value with that of species' traits. In our analysis we used information on known damage caused outside Europe and outside a species' native range. Impact was quantified with the same scoring system as described previously.

We used linear mixed-effects models to analyze the relationship between species traits and impact in Europe (function lme in the statistical software R, version 2.7.1; R Development Core Team 2008). The dependent variables were environmental or economic impact scores, either as actual or as potential impact. Species traits were modeled as fixed effects. Because many species traits are proxies for the same phenomenon, they often correlate with each other leading to collinearity problems in model fitting

Table 1. Total impact scores for all alien mammals in Europe (detailed scores in Supporting Information).*

Order	Family	Species	Potential impact		Actual impact	
			environmental	economic	environmental	economic
Artiodactyla	Bovidae	*Ammotragus lervia*	8	6	0.013	0.01
		Bison bison	12	6	0.014	0.007
		Ovibos moschatus	4	1	0.01	0.002
		Ovis orientalis	7	5	0.942	0.673
	Cervidae	*Axis axis*	8	14	0.013	0.022
		Cervus canadensis	7	13	0.028	0.052
		Cervus nippon	14	17	0.581	0.706
		Dama dama	9	16	1.64	2.92
		Hydropotes inermis	2	3	0.01	0.014
		Muntiacus reevesi	11	14	0.259	0.330
		Odocoileus virginianus	7	9	0.204	0.262
Carnivora	Canidae	*Nyctereutes procyonoides*	10	6	2.19	1.31
	Herpestidae	*Herpestes auropunctatus*	6	5	0.012	0.01
	Mustelidae	*Neovison vison*	17	4	6.54	1.54
	Procyonidae	*Procyon lotor*	9	10	0.593	0.659
Chiroptera	Pteropodidae	*Rousettus aegyptiacus*	5	6	0.004	0.005
Diprotodontia	Macropodidae	*Macropus rufogriseus*	0	1	0	0.002
Insectivora	Erinaceidae	*Hemiechinus auritus*	1	1	0.001	0.001
Lagomorpha	Leporidae	*Lepus capensis*	2	7	0.005	0.017
		Sylvilagus floridanus	2	8	0.010	0.038
		Sylvilagus transitionalis	2	4	0.002	0.003
Rodentia	Castoridae	*Castor canadensis*	7	12	0.215	0.369
	Cricetidae	*Mesocricetus auratus*	2	6	0.001	0.002
		Ondatra zibethicus	14	14	4.93	4.93
	Echimyidae	*Myocastor coypus*	12	13	1.28	1.39
	Muridae	*Rattus norvegicus*	15	18	10.3	12.4
	Sciuridae	*Atlantoxerus getulus*	6	3	0.01	0.005
		Callosciurus erythraeus	4	6	0.002	0.002
		Callosciurus finlaysonii	5	11	0.002	0.004
		Funambulus pennanti	0	0	0	0
		Sciurus anomalus	0	1	0	0.002
		Sciurus carolinensis	17	7	0.794	0.327
		Tamias sibiricus	2	4	0.014	0.027
		Tamias striatus	1	1	< 0.001	< 0.001
Total			228	252	30.6	28.0

**Actual impact score is the potential impact score multiplied by the percent area of UTM grid cells the species occupies in Europe.*

(Graham 2006). For example, small-bodied alien mammals on average also have a shorter lifespan (linear regression: $p < 0.001$). Therefore, traits were only included singly in separate models. Because related species share many traits due to phylogenetic inheritance, species from the same taxonomic group are expected to cause similar impacts (Manchester & Bullock 2000). Therefore, the 34 species in our analysis cannot be considered statistically independent. We used the taxonomic hierarchy as random effect in our models (families nested within orders) to account for this nonindependence (Blackburn & Duncan 2001). Models were fitted by maximum likelihood.

Results

Reproducibility of the Scoring

From a total of 340 scores each author had to assign (34 species times 10 scores), all three of us agreed in 309 cases (91%), we had a maximum deviation of one score in 26 cases, a maximum deviation of two scores in four cases, and once a discrepancy of three scores. In all cases of discrepancy, two authors had the same score and one deviated. The impact scores we used for analyses were median scores (i.e., scores on which at least two authors agreed). We also carried out all analyses with scores of the different authors, but conclusions remained the same for all four data sets.

Potential Impact

The 34 alien mammal species in Europe are from seven orders and 15 families (Table 1). Members of the orders Carnivora, Artiodactyla, and Rodentia had on average the highest potential environmental impact (Fig. 1a), but this difference was not statistically significant among orders (analysis of variance: $p > 0.05$). The species scoring highest in potential environmental impact were the American mink (*Neovison vison*), gray squirrel (*Sciurus*

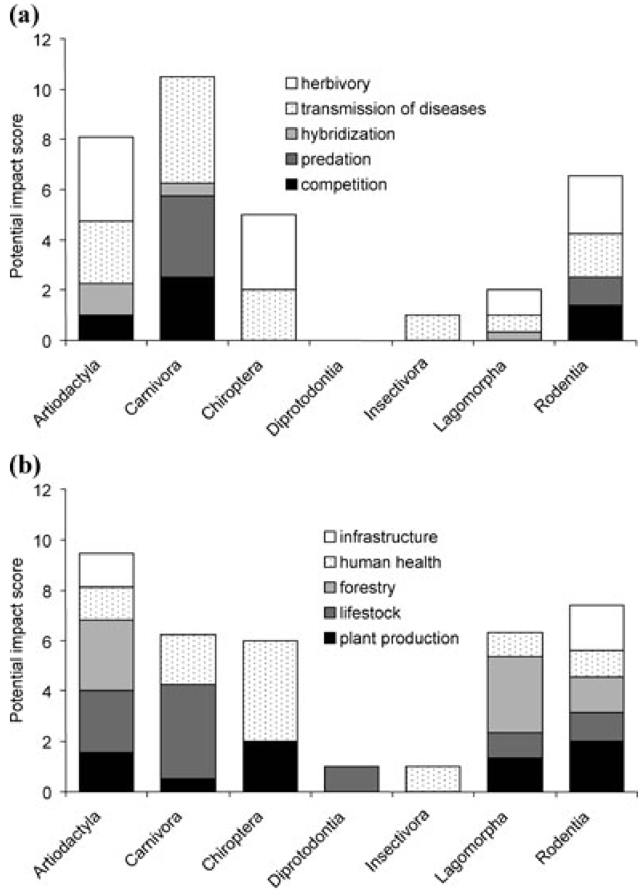

Figure 1. Average potential (a) environmental and (b) economic impact of alien mammals in Europe.

carolinensis), brown rat (*Rattus norvegicus*), sika deer (*Cervus nippon*), and muskrat (*Ondatra zibethicus*) (Table 1). Across orders, transmission of diseases and herbivory were the most important pathways of impact on local flora and fauna (linear mixed effects model with "species" as grouping factor: all $p < 0.003$; Fig. 1a; Supporting Information). The average potential impact on the economy was highest in Artiodactyla, but all other orders were causing considerable economic impact as well, except kangaroos (Diprotodontia) and Insectivora, each with only one species alien to Europe (Fig. 1b). Nevertheless, there were no statistically significant differences among orders (analysis of variance: $p > 0.05$). The species responsible for the highest potential economic impact were a rodent, the brown rat, and two artiodactyls, the sika deer and the fallow deer (*Dama dama*) (Table 1). Across orders, all economic categories were affected to about the same degree, and there was no conspicuous pattern for certain taxonomic orders to primarily affect one economic category (Fig. 1b). Species with a high potential environmental impact also showed a high potential economic impact (linear regression: economic impact = 0.6 ∗ environmental impact + 3.8, $R^2 = 0.31$, $p < 0.001$). Furthermore, species with high potential-impact scores also had a wider distribution (linear regression: environmental impact = 0.1 ∗ log(grid cells + 1) + 0.5, $R^2 = 0.54$, $p < 0.001$; economic impact = 0.1 ∗ log(grid cells + 1) + 0.7, $R^2 = 0.29$, $p = 0.001$). More widely distributed species also showed more ecological flexibility (linear regression: log(grid cells + 1) = 1.03 ∗ number of habitats + 1.63; $R^2 = 0.39$, $p < 0.001$).

We created risk maps by summing the potential impact scores from grid cells for all 34 alien species according to their European distribution (Mitchell-Jones et al. 1999). The highest environmental and economic impacts were concentrated in an area from the United Kingdom through Central Europe to the Czech Republic (Fig. 2).

Actual Impact

Based on current occupied area in Europe, again members of the order Carnivora had on average the highest actual environmental impact score, before rodents and artiodactyls (Fig. 3a); however, these differences were not significant (analysis of variance: $p > 0.05$). The brown rat, American mink, and muskrat, which already scored among the highest in potential environmental impact, had a wide distribution in Europe and thus also scored high in actual environmental impact (Table 1). In contrast, sika deer and gray squirrels, two species with a rather limited current distribution, had only moderate actual environmental impact scores, whereas raccoon dogs (*Nyctereutes procyonoides*), fallow deer, and nutria (*Myocastor coypus*) had rather high actual environmental impact scores due to their wide European distribution. Rodents had on average the highest actual economic impact score, with Carnivora ranking second and Artiodactyla third (Fig. 3b), but again we found no significant difference between orders (analysis of variance [ANOVA]: $p > 0.05$). Alien bats (Chiroptera), kangaroos (Diprotodontia), Insectivora, and Lagomorpha did not cause significant environmental or economic impacts at the European scale because of their currently limited distribution. The species with the highest actual economic scores were the brown rat and the muskrat (Table 1). Species from the order Carnivora and the family Bovidae were the only groups in which both the average potential and the actual environmental impact scores exceeded the economic scores (Table 1). All other taxonomic groups were characterized by higher economic than environmental impact scores. This effect was significant for potential impact differences (ANOVA: $p = 0.024$), but not for actual impact differences (ANOVA: $p > 0.05$).

Trait Analysis

Life-history traits and diet type were rather weak indicators of impact. Only fecundity (number of offspring per year) was positively correlated with actual environmental

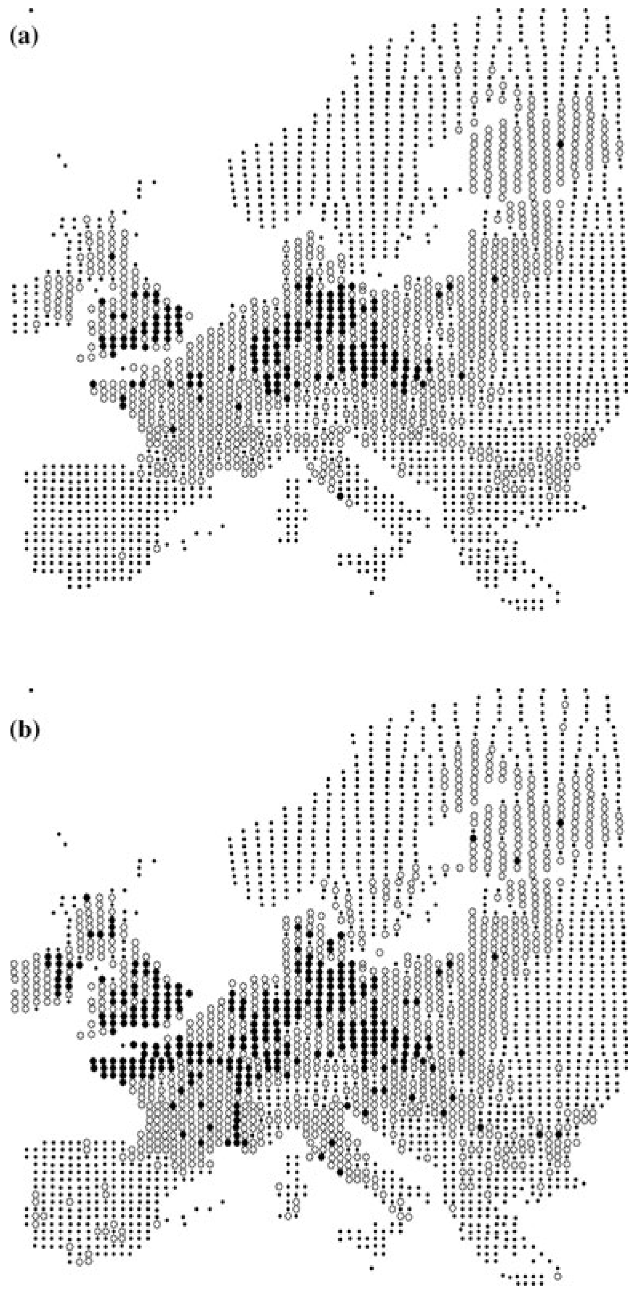

Figure 2. Distribution of the potential (a) environmental impact and (b) economic impact for 34 alien mammals in Europe. For each species the potential impact scores of each of the five environmental impact categories and each of the five economic impact categories were summed up for each grid cell in which the considered species is present. Next, the environmental impact scores of all 34 alien species were grid-wise summed up to one map, now showing total environmental impact. The same was done for economic impact. Finally, impact scores were replaced by symbols to visualize the grid-based distribution of impact over Europe with a dot for scores 0–29, an open circle (gray area) for scores 30–59, and a filled circle (black area) for scores ≥ 60.

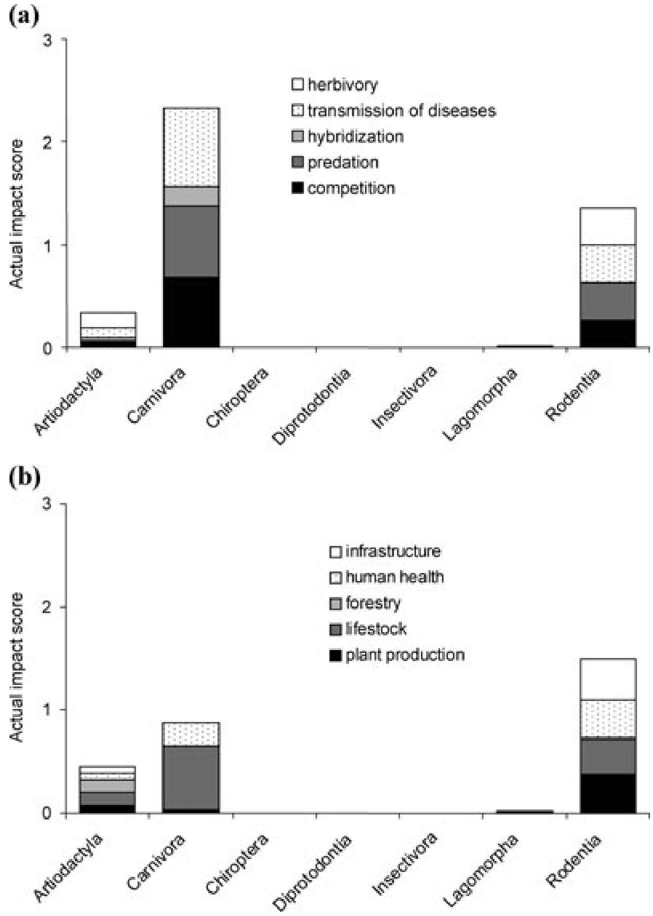

Figure 3. Average actual (a) environmental and (b) economic impact of alien mammals in Europe. Actual impact is the potential impact of a species multiplied by the percent area of the European continent the species currently occupies.

and economic impact, and species longevity was just significantly and positively correlated with potential economic impact (Table 2). The strong correlation between fecundity and actual impact was partly due to the fact that by far the most widely distributed species, the brown rat (1724 UTM grid cells; 1.8 times more than the second-most widely distributed species), was also the species with by far the highest fecundity (0.75 times more than the second highest species). When we removed the brown rat from the analysis, the correlation between fecundity and actual environmental impact vanished ($p = 0.53$), but remained significant between fecundity and actual economic impact ($p = 0.007$).

In contrast to life-history traits, ecological flexibility, defined as the number of habitats a species uses, was strongly and consistently related to all impact types investigated. Species capable of living in a large number of habitat types had higher impact scores, both potential and actual. The fact that a species caused damage

Table 2. Relationships between impact and traits of alien mammal species (univariate linear mixed effects models).*

	Body size	*Fecundity*	*Age at maturity*	*Longevity*	*Diet*	*Habitat generalism*	*Impact elsewhere*
df	18	18	17	17	18	16	18
Potential environmental impact	0.538	0.278	0.670	0.073	0.487	0.003	0.026
Actual environmental impact	0.599	0.002	0.961	0.953	0.265	< 0.001	0.008
Potential economic impact	0.910	0.198	0.442	0.048	0.591	0.032	0.008
Actual economic impact	0.762	<0.001	0.969	0.629	0.428	0.002	0.004

**Given are the degrees of freedom (df) and the error probabilities (*p *values) for the fixed effects of the models. Family nested within order was modeled as random effect (not shown) to remove the nonindependence of species due to hierarchical clustering.*

elsewhere outside its native range was also a strong and consistent predictor of impact in Europe. Information on age at maturity, longevity, and habitat use was not available for all species; therefore, models with different species traits were fitted on different data sets (Table 2, indicated by different degrees of freedom) and could not be compared directly with information criteria. Nevertheless, when we reduced the data set to those species for which all information was available ($n = 32$), models with ecological flexibility had lower Akaike information criteria (AIC) for potential ($\Delta AIC = 3.57$) and actual environmental impact ($\Delta AIC = 2.37$), whereas damage elsewhere predicted potential economic impact better ($\Delta AIC = 3.52$). Actual economic impact was predicted by both variables almost equally well ($\Delta AIC = 1.09$; all models 16 df).

Discussion

By considering all the information available on the environmental and economic impacts of alien mammals in Europe, we were able to derive rankings of species according to their relative impact. Moreover, impact was related to ecological flexibility of alien species. This is an interesting general finding for invasion ecology because it is to our knowledge the first rigorous statistical proof that impact in a large taxonomic group can be explained by a species trait. This finding may also be useful in practice to predict future damage of newly emerging alien species. At the heart of our scoring system is the categorization of impact into types that cover the entire spectrum of relevant potential impacts alien species can cause. We first discuss the potential and limitation of our scoring system for impact studies in general and then make some practical recommendations regarding alien mammals in Europe.

Scoring System

The 10 impact categories in our scoring system were evenly distributed among environmental and economic impact and were all assigned the same weight. The system is easily adaptable to other taxonomic groups or geographical areas; the same impact categories should apply to other alien animal groups as well, as long as they contain members of different trophic guilds. If the alien group of interest consists of members of only one trophic guild, at least the environmental impact scoring has to be adapted to account for the fact that one or more of the mechanisms through which environmental impacts can occur do not apply to the focal group. For example, when considering alien plants, impacts cannot occur through herbivory or predation. This is not problematic as long as all possible impacts are captured by the scoring. Maybe, for some groups of aliens, new impact categories would have to be added.

If hard data for a given impact category are lacking, our scoring system allows use of values based on expert opinion, which allows comparisons among species in the face of uncertainty. Moreover, levels of the impact within categories are defined broadly so that given a description of a species' impact, its scoring can be done with a high degree of consistency among scorers. Thus, our scoring system was rather robust to uncertainty in impact knowledge.

We only used currently known impacts (either assessed directly or estimated based on expert opinion) to calculate the overall impact. The impact scores thus represent a minimum impact value for each species. Mammals are estimated to have an average lag phase between establishment and spread of 50 years (Jeschke & Strayer 2005). For species that were only recently introduced to Europe or that have currently conquered only a small fraction of their potential range, the full extent of their impact may not yet be known. This applies, for example, to many aliens in the family Sciuridae and to the only bat so far established in Europe.

In the absence of objective scientific criteria to consider one impact category more important than another, we refrained from using selective weights. This is in contrast to other risk assessments of aliens (but see Olenin et al. 2007 for aquatic aliens). For example, in their analysis of the impact of alien bird and mammal pests, Smallwood and Salmon (1992) used a rating system that gave an overbalance to the impact on agriculture, whereas damage to natural resources was regarded as less relevant. A risk assessment for alien vertebrates in Australia (Bomford 2003) used a similar approach. In both cases, no

Table 3. Change in the distributional range by nine alien mammals between the publications *The Atlas of European Mammals* (Mitchell-Jones et al. 1999) and *Handbook of Alien Species in Europe* (DAISIE 2009).

Scientific name	*Common name*	*Change in number of grid cells occupied (%)*	*Area currently occupied in Europe (after DAISIE 2009) (%)*
Cervus nippon	sika deer	51	6
Nyctereutes procyonoides	raccoon dog	11	24
Neovison vison	American mink	36	52
Procyon lotor	raccoon	55	10
Ondatra zibethicus	muskrat	5	37
Myocastor coypus	nutria	53	16
Rattus norvegicus	brown rat	7	74
Sciurus carolinensis	gray squirrel	−5	4
Tamias sibiricus	Siberian chipmunk	76	1

scientifically based explanation was given for the decision to give agricultural impact a disproportionally high weight. The decision on relative impact weights is a social, not a scientific process. Different groups of stakeholders will consider different impact categories as more relevant than others. Our scoring system easily allows incorporating weights for scores. By comparing the outcome of scoring alien species with weights from different stakeholder groups, one can highlight communalities and differences in alien species ranking. Thus, our scoring system can help find solutions to a variety of social problems caused by the impact of alien species.

Prioritization

Our scoring system allows for ranking of the worst alien species according to their impact. These rankings can then be used to prioritize actions against them along with other criteria such as feasibility and cost of the action. Our list of high-priority alien mammals shows a large overlap with lists of the worst invasive species in Belgium (www.ias.biodiversity.be), Europe (www.europe-aliens.com), and worldwide (www.invasivespecies.net). Only the Belgium list applies published information on impacts to assign species to priority categories (black and watch lists); the other two are results of expert judgment. All species on the black list in Belgium had higher or equal scores in our scoring system than species on the watch list. On all three lists, species mentioned as the worst aliens also scored high in our scoring scheme. The large overlap between the lists and our scoring suggests that scoring accurately captures the opinion of many experts on alien mammals. Alien mammals that were targets for eradication campaigns in Europe (Genovesi 2005) always scored high in our scheme, with the brown rat being the species most often subjected to eradication campaigns. This shows that our scoring scheme seems to be in good agreement with eradication practice.

In combination with forecasts from species distribution models and knowledge on their rate of spread (such data are available for many alien species, for example, Grosholz 1996), our scoring system allows calculation of the actual impact of alien species. For example, updated distribution data since publication of *The Atlas of European Mammals* (Mitchell-Jones et al. 1999) are available for nine mammals considered among the worst aliens in Europe (DAISIE 2009). Although three species did not show large changes in their distribution during the 10 years between the two publications, five aliens expanded their range considerably (Table 3). It also becomes apparent from Table 3 that of the rapidly expanding species, the Siberian chipmunk (*Tamias sibiricus*) and the sika deer currently only occupy small areas in Europe, which indicates that immediate action is advisable to prevent rapid increase in damage caused by these harmful species. Both species occur in scattered populations, increasing the possibility of successful local control or eradication.

Species Traits

In the early phase of invasion, aliens do not show their full impact. Thus one would like to predict their potential or future impact based on species traits. In mammals alien to Europe, life-history traits do not seem to be reliable predictors of species impact. This is in accordance with earlier phases of the invasion process, where life-history traits also fail to explain significant parts of variation in mammal establishment success (Sol et al. 2008). Thus, there does not seem to be such a thing as a generic life-history strategy that makes mammal species successful invaders. Nevertheless, again as during the establishment phase (Sol et al. 2008), ecological flexibility was also strongly correlated with the impact score in mammals. Moreover, ecological flexibility was as good at predicting impact in Europe as the knowledge of impact the species caused in other parts of the world, which is often considered the only reliable predictor of impact (Williamson 1996). Nevertheless, "damage caused elsewhere" cannot be considered a species trait because it implies that impact of the species, which should be predicted by the model, has already been quantified at another location. Although knowledge on damage elsewhere may be helpful in predicting impact of known invaders in new areas, it cannot explain why species cause an impact. Finally, one should be aware that the impact of newly emerging alien species cannot be predicted by this variable at all. Thus, in mammals, information about ecological flexibility seems to be a useful predictor of impact.

The fact that the more widespread European aliens could be found in more habitats also indicates that ecological flexibility may be an important asset during the spread phase of an invasion. In general, being able to tolerate a wide range of environmental conditions seems to be a key characteristic of successful invaders across different taxonomic groups (Sakai et al. 2001; Daehler 2003; Richardson & Pyšek 2006). In practice, ecological flexibility as single criterion will probably not be precise enough to predict the final impact of a newly invading species with the accuracy that is desired by stakeholders. In the absence of better criteria, however, ecological flexibility can be useful as a first indication of whether an alien species may become problematic in the future.

Recommendation for Practice

Our calculated potential and actual impact values (Table 1) can be used for recommendations to the practitioner. The sika deer, muskrat, and brown rat yielded the highest values both for potential and for actual impact in environmental and economic terms. The American mink yielded high values for potential and actual environmental impact. This indicates that these species already cause considerable damage, and actions against them should be a priority. Two other taxonomic groups with currently only low actual but high potential impact values should be carefully observed: cervids and sciurids. Most of the seven cervid species in Table 1 have high potential environmental and economic impact scores. Due to their currently limited distribution in Europe, their actual impact is still low. Among the eight sciurid species in Table 1, at least two have a strong potential impact: Finlayson's squirrel on economy and the gray squirrel on the environment. In general, alien sciurids should be watched carefully; this seems to be an emerging potential high-impact group that is currently increasing due to releases from the pet trade (Hulme et al. 2008).

In general, mammals that caused high environmental damage also caused high economic damage. This information is useful for practice in two ways. First, it can be expected that species for which one impact type (environmental or economic) is well known, but the other has not been studied, will score similarly in both categories. Second, scoring similarly in both categories will help solve potential differences between stakeholder groups with different agendas (e.g., farmers and environmentalists) by allowing prioritization of aliens for countermeasures, because alien mammals will score either high or low for both groups. The positive relationship between distribution and potential impact of alien mammals can also be used to predict the potential impact of newly emerging alien species. Species that have a large potential European distribution (suitable habitats widespread in Europe; climatic niche matches climatic conditions in large parts of Europe) can be expected to have more severe local impacts.

Our scoring system for impact analysis of alien species offers a way for stakeholders and decision makers to prioritize the threat among alien species in a transparent manner, to invest wisely limited resources to prevent or eradicate alien species, and to mitigate their negative environmental and economic effects.

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Supporting Information

Literature list of published impacts analyzed in this study (Appendix S1); classification of impact categories (Appendix S2); and detailed impacts by species (Appendix S3) are available as part of the on-line article. The authors are responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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