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„The Global Invasive Species Database: what is covered, and where are the gaps? "

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Abstract

Invasive alien species cause ecological and economic impacts across the globe. The data availability on the extent of impacts of biological invasions world-wide has greatly improved in the last years, particularly due to the compilation of large databases, such as the Global Invasive Species Database (GISD). However, it is still unclear which geographic and taxonomic patterns prevail in the magnitude of impacts, and where the most important data gaps can be encountered. In this study, we assessed the information content of the GISD in the context of environmental and socio-economic impacts recorded for alien species, analysing the global status quo and trends of biological invasions. We found that recorded impacts of alien species on the environment dominate over impacts on socio-economy, especially in mainland regions compared to islands. This dominance of environmental impacts was hold largely true across zonobiomes and taxonomic groups responsible for them.

To conclude, we argue that the information on impacts in the GISD is currently highly uneven in terms of global geographic distribution. Thus, there is an urgent need to expand the GISD, in particular to cover regions and taxonomic groups that are currently underrepresented. Such an expansion of the GISD will ensure that it will become a truly global and cross-taxonomic database on alien species that may be ideally suited for addressing a suite of alien species research and management questions.

Keywords: biological invasions, conservation, distribution, environment, impacts, invasive alien species, socio-economy

Zusammenfassung

Invasive gebietsfremde Arten verursachen ökologische und ökonomische Auswirkungen auf der ganzen Welt. Die Datenverfügbarkeit zum Ausmaß der Auswirkungen von biologischen Invasionen weltweit hat sich in den letzten Jahren stark verbessert. Vor allem durch die Erstellung von großen Datenbanken, wie der Global Invasive Species-Datenbank (GISD). Es ist jedoch noch unklar, wie sich diese Auswirkungen geographisch, klimatisch und taxonomisch verteilen, welche Faktoren die Größe dieser Einflüsse beeinflussen, und wo die wichtigsten Datenlücken gefunden werden können.

In dieser Studie untersuchten wir den Informationsgehalt der GISD im Zusammenhang mit den ökologischen und sozioökonomischen Auswirkungen für bereits erfasste gebietsfremde Arten, indem wir den globalen Status quo und die Trends biologischer Invasionen analysierten.

Wir fanden heraus, dass die erfassten Auswirkungen von gebietsfremden Arten auf die Umwelt, im Vergleich mit Auswirkungen auf die Sozioökonomie, dominieren. Dies gilt speziell für Regionen, die auf kontinentalen Festländern liegen, im Vergleich zu Inseln. Diese Dominanz der Umweltauswirkungen zeigte sich einheitlich in den verschiedenen Zonobiomen und taxonomischen Gruppen. Abschließend diskutieren wir, dass die Informationen über die Auswirkungen von invasiven gebietsfremden Arten im Hinblick auf die globale geografische Abdeckung in der GISD derzeit sehr ungleichmäßig sind. Wir identifizierten dabei die wichtigsten Datenlücken in der GISD.

Es besteht ein dringender Bedarf, die Daten im GISD zu erweitern, besonders um Regionen und taxonomische Gruppen abzudecken, die derzeit unterrepräsentiert sind. Durch eine solche Erweiterung des GISD würde sichergestellt, dass diese Datenbank tatsächlich eine globale und taxonomisch umfassende Datenbank über gebietsfremde

Arten wird, die zur Adressierung einer Reihe von Fragestellungen zu gebietsfremden Arten und deren Management ideal geeignet ist.

Schlüsselwörter: biologische Invasionen, Erhaltung, Verteilung, Umwelt, Auswirkungen, invasive gebietsfremde Arten, Sozioökonomie

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Introduction

The increase in socio-economic activity associated with globalization has facilitated the anthropogenic movement of species beyond natural biogeographic barriers (Kettunen et al. 2008; Essl et al. 2011, Seebens at al. 2015). The number of species involved in this process is steadily increasing (Tittensor et al. 2014), with few signs of saturation (Essl et al. 2011; van Kleunen et al. 2015). Several studies have shown that key drivers underlying biological invasions are international trade and transport (Levine & D'Antonio, 2003; Hulme et al. 2009; Sharma et al. 2010; Essl et al. 2011; Seebens et al. 2015), most likely because of their influence on propagule pressure (Westphal et al. 2008).

Once alien species have established and spread they may cause several types of detrimental impacts on the environment, on humans and socio-economy. While only a small proportion of alien species succeeds to become invasive (Keller et al. 2011), the scale of their impacts may nevertheless be substantial (Pimentel et al. 2001; Blackburn et al. 2014; Essl et al. 2015a; Schindler et al. 2015). Impacts of alien species are highly context-dependent (Vilà et al. 2011; Kumschick et al. 2012; Pyšek et al., 2012), i.e. the impacts of the same species may vary widely depending on the habitat, the climate, and the interaction with resident biota (Ricciardi et al. 2013; Blackburn et al. 2014; Kumschick et al. 2015). Further, there is evidence that impacts fluctuate in both linear and non-linear manner with population density of the invasive alien species (Jackson et al. 2015). Alien species might also cause positive environmental or socio-economic impacts (Schlaepfer et al. 2011), as they may provide certain resources for native species (Muñoz and Cavieres, 2008) or ecosystem services supporting human well-being (Schlaepfer et al. 2011).

Data availability on the extent and impacts of biological invasions world-wide has greatly improved in the last years, particularly due to the compilation of large databases (e.g.

Capinha et al. 2015, van Kleunen et al. 2015, Dyer et al. 2016). In this context, the Global Invasive Species Database (GISD) is of particular relevance as it contains data on the distribution of alien species of a wide range of taxonomic groups, as well as information on years of first record, introduction pathways and the impacts they cause. Thus, the GISD has become a highly important source for assessing biological invasions and has served as source for calculating global trends on alien species accumulation and impacts (Tittensor et al. 2014). However, it remains unclear to which extent even large databases on biological invasions such as the GISD are truly global by providing a balanced geographical and taxonomic coverage on alien species (Pyšek et al. 2012).

Here, we use the GISD for analysing the status quo and patterns of biological invasions, and to identify gaps in coverage. More specifically, we asked the following questions (1) What is the global coverage and distribution of the data in the GISD? (2) What is the distribution of socio-economic and environmental impacts of invasive alien species as documented in the GISD across climatic zones and biogeographic regions (e.g. continents; islands vs. mainland regions)? (3) Which types of impacts prevail, how are the different kinds of impacts distributed, and are socio-economic and environmental impacts correlated? (4) Which invasive alien species are causing the most wide-spread impacts (i.e. numbers of regions with documented impacts)? (5) Do species of different taxonomic groups (plants, vertebrates, invertebrates) differ in the likelihood that they cause any impacts at all, and between the kinds of impacts they cause? (6) Which pathways are preferably used by the invasive alien species that are causing impacts? (7) Which environmental, biogeographic and socio-economic factors influence the spatial distribution of impacts?

Material and Methods

Alien species data: the GISD database

This study is based on the data of the Global Invasive Species Database (GISD), which has a focus on alien species that have negative impacts on biodiversity or human activities (ISSG, 2015). The GISD comprises records of > 10,000 alien species and a total of > 45,000 records from 121 regions (countries, islands) (Figure 1). The database contains only one entry per species and region. The alien species data of the GISD have been provided by a wide range of data contributors, mostly from national databases. Coverage of countries is assumed to be highly variable (Pagad et al. 2014). For this study, we checked the data for duplicate entries and a few records were removed. We classified countries as island or as being located on mainland and assigned them to continents and to climatically defined regions (zonobiomes sensu Walter & Breckle 1991).

Alien species in the GISD database were designated as invasive (or not invasive) following the concept of invasiveness of the CBD (2002) (= alien species with detrimental impacts on the environment or on human livelihoods) and according to evidence-based criteria based on information provided in the original data sources. For 2708 records from 67 countries, impacts were provided and in total 1667 species were covered by these records. For analyses, we classified these to impacts on the environment (including impacts on ecosystems and species) and socio-economic impacts. In the GISD, for 2009 records (covering 45 countries and 1311 species) the pathways of introduction were provided, for 711 of these records also impacts were specified.

For a subset of records (n=10,545 records; 65 countries; 4404 species), information of the year of first record within the country was also available. Some entries only contained information on time periods of first record. In this cases, we used maximum residence time (i.e. the target species was recorded after this year) and minimum residence time (i.e.

the target species was recorded before this year) and calculated the mean value for analyses. For those records with an exact year of first record, this year was used. Records with intervals >50 years where excluded from the analyses.

Analyses

We used the full data set of the GISD to give an overview on the alien species data coverage of this database. For the analyses of alien species impacts, we restricted the data set to the 2708 records from 67 countries that record impacts. For analyses of geographic differences of the distribution of environmental and socio-economic impacts, we grouped records to continents. Similarly, for analyses of the distribution of impacts across climatic zones we assigned the countries to zonobiomes and we assessed if the region was an island or located on a continent. Further, for analysing the distribution of impacts across taxonomic groups, we grouped the data to families and broad taxonomic units (plants, animals, fungi, bacteria).

For environmental and biogeographic variables, zonobiomes, continents and island/mainland relationships were included as explanatory variables in the analyses. Data on zonobiomes, country size and boundaries were taken from Olson et al. (2004).

We used multivariate analyses to examine the relationship between environmental, biogeographic and socio-economic predictor variables and the number of alien species having environmental or socio-economic impacts in a region.

Ordinary least squares regressions were used to analyse the influence on the spatial distribution of alien species with environmental and socio-economic impacts of a suite of predictors such as per capita GDP, human population density, Human Development Index (HDI), benefits index for biodiversity of the Global Environment Facility (GEF) and the number of alien species per country that cause impacts. These predictor variables integrate multiple environmental, climatic and socio-economic pressures. In particular, socio-economic variables have been shown to closely relate to propagule pressure and anthropogenic disturbances that facilitate biological invasions (Westphal et al. 2008; Essl et al. 2011). Data on per capita GDP were retrieved from the International Monetary Fund (2015). As for some countries the 2014 data were available only as estimates, we used data from 2013 for the analysis. HDI and human population density were obtained from the United Nations Development Programme (2014).

All statistical analyses were carried out in PAST (Palaeontological Statistics) software for scientific data analysis (Hammer et al. 2001).

Results

The global coverage of the GISD

The full data set of GISD includes data from 121 countries (Figure 1). While all taxonomic groups are considered, the majority of the records are for plants (>38,000 records; 85%). The remaining taxonomic structure of the records within the GISD reveals that invertebrates (3644; 8%), fish (1332; 3%), mammals (720; 1.6%) and birds (549; 1.2%) represent only a moderate fraction of the data. (Figure 2; Appendix 1 Table 1-2). It is important to note that there are substantial differences in the coverage of the full GISD data between continents. Alien species records have a higher coverage of regions in the continents Oceania (78%), North America (incl. the Caribbean) (68%), and Europe (63%). Only 19% of the total countries of Africa are covered by the database. In terms of number of records, Europe contributes 34% of total records and the Americas together 24%. In contrast, Africa reports only 7% of the total records.

In the subset of records with first year of introduction (n=10,539 records; 65 countries; 4404 species), Europe presents 80% of the data. Norway, Czech Republic, Germany, Italy, Lithuania, and Portugal recorded half of all the entries listed with introduction period globally. In respect of the other continents, the data corresponded predominantly to one or two countries. The year 1500 is the recorded first date of introduction for as much as 2000 records, this date is related to the major exchange of species after the European colonization and trade with the Americas. This early date of introduction was reported abundantly in several European countries with Bulgaria, Germany, Italy, Liechtenstein, and Malta almost 90% of their records provided this date of introduction. This clearly is an artefact on the original data source used here, i.e. data from the DAISIE-project (www.europe-aliens.org). The subset of data is with reported year of first record reduced to 1,135 records (52 countries; 813 species) when considering recorded impacts (Figure 3).

The distribution of socio-economic and environmental impacts of alien species in the GISD

In total, there are 2064 alien species records with environmental impacts and 649 records with socio-economic impacts in the GISD. We found substantial gaps in the distribution of countries that have recorded any type of impact produced by alien species (Figure 4). From the 2708 records with impacts, South America (27 %), North America (25 %) and Europe (25%) reported the highest proportions of alien species with impacts, respectively (Appendix 1 Tables 3, 4). From this, the majority of recorded impacts came from a few countries, i.e. Argentina, Brazil, Cuba, and Norway account for 39% of all impacts recorded (n=1060).

In total, 62% of environmental impacts were documented in countries located on continental landmasses, and 38% on islands. Socio-economic impacts are reported to 71%

in mainland regions and to 29% on islands (Figure 5). Given that islands add up to only 35% of all records within the GISD (n=15,715), impacts of alien species are more frequently reported from islands (41%) compared to continental countries (59%) (Appendix 1 Table 5).

For islands, 64% of the environmental impact records are presented by only three countries (Japan, Cuba, Ireland), whereas for mainland regions, Argentina, Brazil and Norway present 54% of the data. Socio-economics impacts follow similar distribution with 65% of the impact data is recorded in Japan, Ireland and Santa Lucia for island territories and Argentina, Brazil and Bolivia with 39% of the records for mainland countries.

Environmental impacts are distributed mainly in tropical (22%), subtropical savanna (20%) and nemoral zonobiomes (Figure 6). Many of the impacts in tropical and subtropical regions are produced by perennial grasses, leguminous shrubs and trees (e.g. *Leucaena leucocephala*) and aquatic vascular plants (e.g. *Eichhornia crassipes*). In the nemoral zonobiome, the most impacting species are herbaceous vascular plants of the Asteraceae, shrub and herbaceous plants of the Rosaceae and freshwater fishes.

One-fourth of all registered impacts correspond to those associated with socio-economic impacts. These impacts have a similar distribution across zonobiomes as have environmental impacts, but the proportion of impacts caused by animals is higher. Socio-economic impacts are mostly recorded in tropical (19%) and subtropical (17%) regions with additional representation in countries covering several zonobiomes (Argentina, China, Mexico, South Africa). In the latter countries, species belonging to composite vascular herbaceous plants, freshwater fish and perennial grasses are those reporting most records of impact. In tropical and subtropical zonobiomes, socio-economic impacts are recorded for leguminous shrubs and trees, perennial grasses, rodents and insects. These impacts are predominantly recorded on mainland territories of these tropical and subtropical zonobiomes, nevertheless, an important number of records are reported for islands in warm temperate regions (e.g. Japan).

Invasive alien species causing the most wide-spread impacts

The alien species with the most widely reported environmental impact were *Eichhornia crassipes* (n=20), *Rattus rattus* (n=15), *Elodea canadensis* (n=15), *Capra hircus* (n=14), and *Sus scrofa* (n=13). The highest numbers of socio-economic impacts have been recorded by *Eichhornia crassipes* (n=16), *Elodea canadensis* (n=13), *Mus musculus* (n=9), *Rattus rattus* (n=8), and *Columba livia* (n=6) (Appendix 1 Table 6). The aquatic vascular plant *Eichhornia crassipes* that accounts for the higher number of records can be found across 6 different zonobiomes, ranging from tropical to nemoral. On a higher taxonomic level, six families with 791 alien species contain a third of the taxa producing impacts. The vascular plant families Poaceae, Asteraceae (both 9%) and Fabaceae (7%) contain the highest numbers of species with environmental and socio-economic impacts in GISD (Table 1). On islands, animal species have a somewhat higher contribution to impacts compared to plant species, although plant species still produce the majority of recorded impacts (Figure 7, Table 2).

There are 335 cases of alien species that were recorded to have impacts both on the environmental and socio-economy, with 33% of the cases occurring in South America. Species such as *Eichhornia crassipes, Elodea canadensis, Rattus rattus* and *Arundo donax* were on a global scale usually recorded to produce both types of impacts.

Pathways of introduction

There are almost 30 different pathways of introductions recorded in the GISD. From those, ornamental purposes and horticulture, aquaculture/aquarium, interconnected waterways and agriculture accumulate to 64% of the records with descriptions of pathways (n=1279) (Table 3). Environmental impacts are given for a total of 580 records associated mainly to pathways such as ornamental purposes and horticulture (31%), aquaculture/aquarium (13%), and agriculture (10%).

A large percentage (80%) of the records of alien species with pathways and impacts documented have resulted from intentional releases (Table 4). This is particularly true for animals, which are introduced for various purposes including aquaculture and aquariums, ornamental purposes, recreation and fishing.

Environmental, biogeographic and socio-economic factors that influence the spatial distribution of alien species with impacts in the GISD

The statistical analysis showed no significance to the effect of continents versus islands, climatic regimes (zonobiomes) or taxonomic affiliation on the distribution of alien species number with recorded impacts (Table 5).

On the contrary, the ordinary least squares regression analysis (Table 6, Appendix 2) revealed statistically significant correlations between the number of alien species with recorded impact and three of our selected indexes. For a total of 63 countries, per capita GDP presented weak positive relationship to number of alien species ($r = 0.252$; $p<0.05$). Also for the regression of the Human Development index and the number of alien species producing impact we found a weak, but significant positive correlation ($r=0.305$; $p<0.05$; $n=55$). Countries that present HDI values higher than 0.7 account for more than 90% of recorded impacts.

This positive correlation was also observed between the GEF benefits index for biodiversity and the number of alien species causing impacts ($r=0.303$; $p<0.05$). This index highly significantly explained the number of alien species recorded in the GISD including those that presented no record of impact ($r= 0.349$; $p< 0.01$; $n= 70$). Additionally, it was the only index capable to stablish a relationships with species with socio-economic impact records ($r= 0.406$; $p< 0.01$; $n= 39$). Separately none of the selected indexes presented a statistically significant relation to the distribution of those species associated with environmental impacts records (Appendix 3).

Human population density was not a significant predictor of the number of alien species with recorded impacts ($r= -0.071$; $p= 0.58$; $n= 63$) .

Discussion

Geographic and taxonomic coverage and gaps in the GISD

The GISD was designed to provide a resource for essential information on the global distribution of alien species and the impacts they cause, including information needed for early warning purposes (Poorter et al. 2005). It covers all taxonomic groups from micro-organisms to animals and plants in all ecosystems (ISSG, 2015). However, although the GISD has indeed become an extensive and highly valuable data source for biological invasions, regional biases are present in the dataset. Regions of the world with high botanical and zoological research intensity such as Europe and the Americas (Meyer et al. 2015) are well represented in the GISD. On the contrary, continents such as Africa and Asia present only a third of their countries providing any recorded alien species.

Previous studies have shown that the financial resources for research (Wilson et al. 2007) and the socio-economic status of a region (Pyšek et al. 2008) influence both the documentation and the level of biological invasions. As the GISD is dependent on the provision of regional information, we argue that regions like Africa and Asia, with a lower socio-economic development status, are underrepresented in the GISD database (cf. McGeoch et al. 2010).

Certainly, the focus on documenting alien species with severe impacts may cause biases. The most prevalent taxonomic group covered by the GISD are plants, representing 85% of the total data. Crall et al. (2006) argue that alien plant species research efforts may be driven primarily by economic reasons, as a consequence of their associated greater economic losses, their direct observation and record; as well as their greater percentage in the total alien species pool relative to other taxa (Pimentel et al. 2001).

The distribution of socio-economic and environmental impacts in the GISD

We found that recorded impacts of alien species on the environment dominate over impacts on socio-economy, especially on mainland regions. This might be related to a strong underrepresentation of interdisciplinary socio-economic research in invasion science (Vaz et al. in prep.) Many countries are aware of the ecological effects of biological invasions and that the provision of ecosystem services may be negatively affected, however, they have failed to translate this into adequate invasive alien species policies (Reaser 2007, Van Wilgen et al. 2001).

Considering their climatic distribution, higher numbers of recorded impacts are located in tropical and subtropical savanna regions. Tropical ecosystems such as islands and disturbed forest in mainland are areas more vulnerable to impacts (Denslow, 2003). It was traditionally believed that high species richness in continental tropical forests made them less susceptible to invasion by alien plants and animals (Peters, 2001; Friedley et al. 2007). However, climate change, habitat fragmentation, land use-change, fires and many other disturbances derived from human activities are transforming the stability of these ecosystems (Carson et al. 2008). Thus, the proportions and numbers of invasive species in the tropics are increasing (Peters, 2001). Some of the most recorded species correspond to the Poaceae family, representing alien perennial grasses that are becoming widespread in American tropical and subtropical savannas, where both environmental and socio-economic impacts are recorded. Some of these species were intentionally selected and introduced for high forage and their seed production potential (Foxcroft et al. 2010).

The role of pathways for introducing alien species causing negative impacts in the GISD

Identifying the pathways of introductions of alien species represents an important step in the prevention and management of biological invasions (Essl et al. 2015b). Invasive alien species usually reach new regions via human trade and transport (Hulme et al. 2009, Sharma et al. 2010; Seebens et al. 2015). Accidental introductions do occur during the course of these economic activities (Hellmann et al. 2008). Species are introduced for a variety of reasons and within the GISD there are almost 30 different pathways of introductions (e.g., aquaculture, biocontrol, sport fishing, horticulture, agriculture) (Table 3).

The documented negative impacts in the GISD are strongly shaped by alien species that have been introduced intentionally. The introduction of species for ornamental purposes is the most important pathways for invasive alien species in the GISD. The horticulture industry plays an important role for plant invasions by selling, transporting, and cultivating alien species (Niemiera & Von Holle, 2009). Other economic activities facilitating pathways of introduction are those aiming to provide food for humans (aquaculture and agriculture). The demand for food production will continue to increase along with human population growth (Erb et al. 2016). Thus, these industries will most likely increase their production and expand to new areas with the consequent transport of new alien species.

Almost one third of the records (n=711) including pathways of introductions report environmental or socio-economic impacts, of which impacts on the environment are more frequent. Environmental impacts as a consequence of intentional species introductions, follow practically the same pathways mentioned above. An important subset of records is represented by terrestrial plant species introduced as ornamentals and species released from aquaculture and aquatic ornamental culture. Socio-economic impacts have been reported mainly for intentionally introduced aquatic species.

Identifying pathways and types of introductions can improve the management of invasive alien species by reducing colonization pressure (Lockwood et al. 2009). Once pathways are identified, several precautionary measures can be implemented such as risk assessments for intentional introductions, where target species must meet some criteria to demonstrate the likelihood of low impact (Ruiz & Carlton, 2003), increasing public awareness, improving measures of early detection and policy enforcement by limiting the unintentional transfers of known vectors (Pyšek & Richardson, 2010).

Environmental, biogeographic and socio-economic factors that influence the spatial distribution of alien species with impacts in the GISD

Although statistically significant, a weak positive correlation was revealed in the analysis between the number of alien species producing impact and 63 countries with per capita GDP. Measures of Gross Domestic Product (GDP) per capita can be considered to be drivers of forces such as propagule pressure or ecological disturbance which facilitates the establishment and spread of alien species (Taylor & Irwin, 2004; Essl et al. 2011). This positive feedback between the degree of wealth and invasions can be explain by the large trade volumes associated to developed regions with a high gross domestic product (Pyšek et al. 2008). Previous findings in the number of established alien species has significantly correlated with the import value of a country (Levine & D'Antonio, 2003; Westphal et al. 2008; Seebens et al. 2015). Those regions are the ones receiving the most alien species as intentional or unintentional commodities of their trade.

The same relationship was found for the regression with the Human Development index and the number of alien species producing impact with a weak, but significant positive correlation. The Human Development Index (HDI) is a United Nations estimation of the quality of life according to GDP, standard of basic education ('alphabetisation') and life expectancy (Vilà & Pujadas, 2001). According to McGeoch et al. (2010) development status of a country is likely to be associated with investment in research and data collection and hence the amount of documented alien species. In our analysis, the majority of recorded impacts are presented by countries whose HDI scores are high. The inclusion of higher standards of education representing a higher HDI is suggested by Lotz & Allen (2013) as a chance to include in those countries better decisions concerning the environment and therefore, present solutions to the impacts generated by the introduction of alien species.

We also found significant correlation between the numbers of alien species (presenting or not records of impacts) and the GEF benefits index for biodiversity. This index provides a measure of "biodiversity potential" at the country level, considering the complexity of different ecological components (Pandey, 2006), where countries like Brazil (GEF =100) present major biodiversity resources and high potential as a country to generate significant global environmental benefits. However, under our findings, countries with higher biodiversity potential also present higher pressures, due to the presence of alien species and this positive correlation.

The large scale of our analysis and the lack of more detailed information on geographical location of the impacts, does not allow us to correlate the presence/absence of the species impacts with other descriptors of invasion distribution such as disturbed habitats or the degree of land change. Davis et al. (2000) proposed that most invasive alien species occur primarily in disturbed habitats, which sometimes support a high diversity of invasive alien species due to reduced competition. Alterations of habitat types, disturbance regimes and rapid changes of species composition driven by land-use changes could affect future regional trends in alien species invasions which are mainly determined by their habitat types (Chytrý et al. 2012).

Making the GISD a truly global database on alien species: what is needed?

While the GISD database is the most comprehensive cross-taxonomic global database on alien species distributions and the impacts they cause and has thus been used for a range of analyses (e.g. Westphal et al. 2008; Faulkner et al. 2014; Tittensor et al. 2014; Essl et al. 2015b), our study shows that it nevertheless suffers from substantial geographic and taxonomic gaps. For instance, Europe, Asia and Oceania report approximately 70% of the alien species records in the GISD. Further, information on impacts is available for a small share of records. By only considering the recorded impacts, there has been a loss of 94% of the record data on the analysis presented in this study. In contrast to the total information, impact data are given mainly for the Americas and Europe (75%), i.e. continents with particularly high research intensity on biological invasions (Pyšek et al. 2008). Oceania and Africa are the continents presenting the highest gaps in terms of impacts, where 99 % and 96% of records do not specify any impact. The majority of countries world-wide are currently not presented in the GISD database with data that report impacts of alien species. In practical terms, understanding why there are records with no information on impacts is important. Alien species without recorded impact leads to the assumption that there is actually no impact of this species in this country. However, impacts may also be unknown or simply not reported.

The lack of integrated standards to determine an impact might contribute to the incompleteness of impact records in the dataset for many countries. Several authors have presented concerns on the difficulty of providing sets of parameters to base an objective quantification and ranking of impacts (Parker et al. 1999; Pyšek & Richardson 2010; Blackburn et al. 2014; Kumschick et al. 2015).

To conclude, we argue that the information on impacts in the GISD is currently highly uneven in terms of global geographic distribution. The completeness of data for a comprehensive invasive alien species database is essential for rapid assessments, validating predictive models or searching for patterns of distribution (Ricciardi et al. 2000). The availability of taxonomic, geographic, and temporal global data is critical to provide decision-makers with the information needed for alien species policy and management. Thus, there is an urgent need to expand the GISD, in particular to cover regions and taxonomic groups that are currently underrepresented. Such an expansion of the GISD will ensure that it will become a truly global and cross-taxonomic database on alien species that may be ideally suited for addressing a suite of alien species research and management questions.

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Figures and tables

Figures

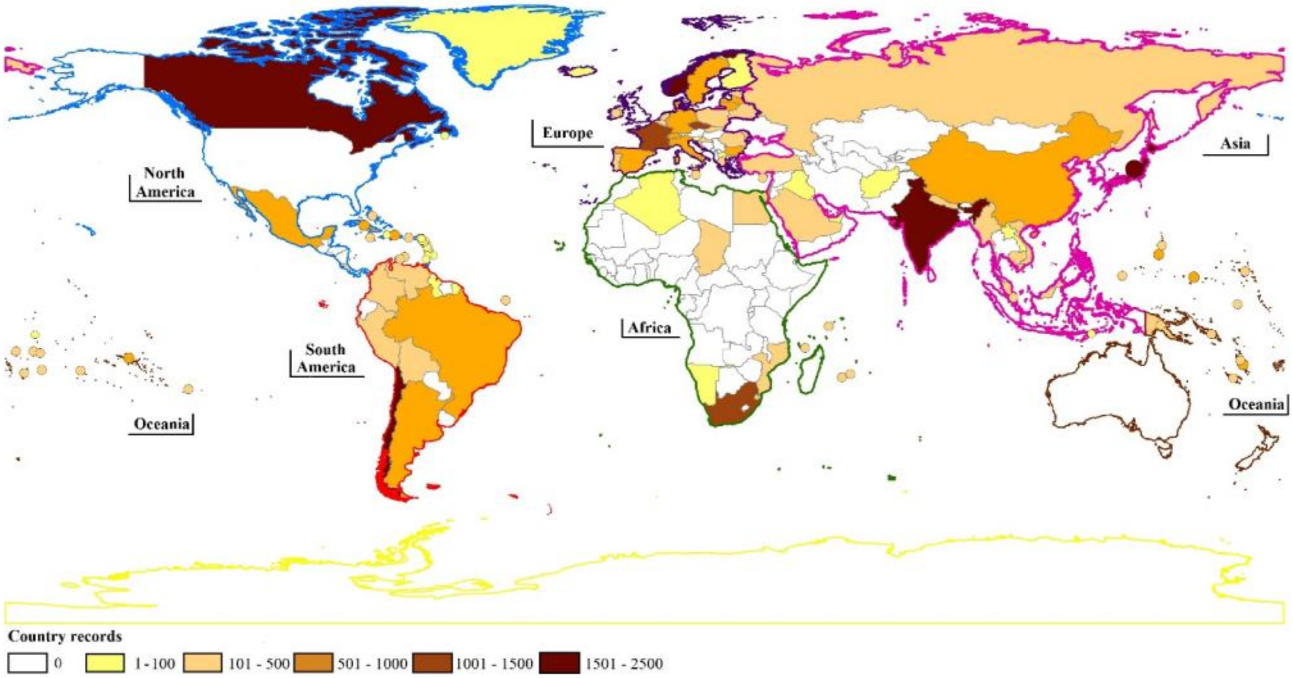

Fig. 1. The distribution of alien species records in the GISD. The numbers represent the number of alien species recorded per region.

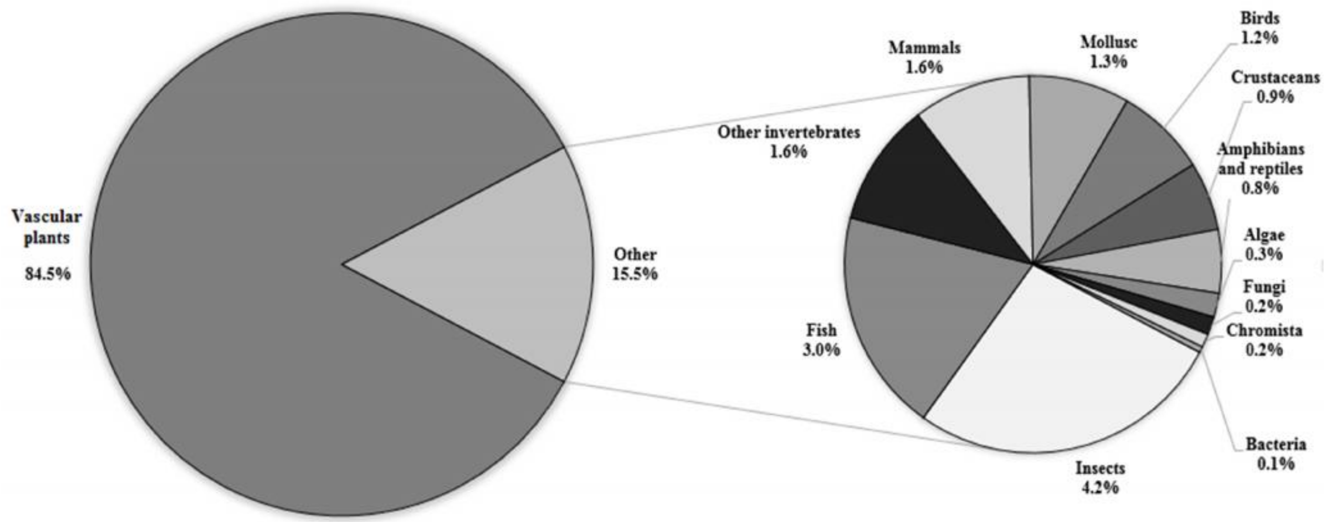

Fig. 2. Taxonomic structure of records (n = 45267) of alien species within the GISD.

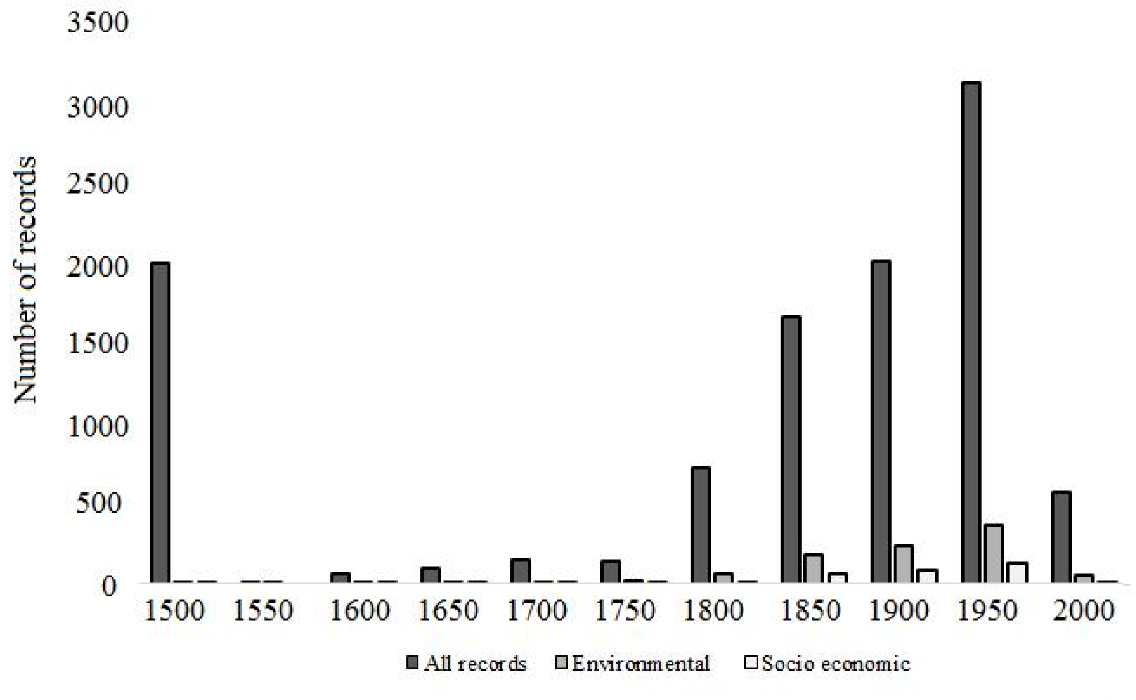

Fig. 3. Frequency distribution of records with introduction date within the GISD. All records with introduction period (dark grey), records with given environmental impact (light grey) and socio-economic impact (white).

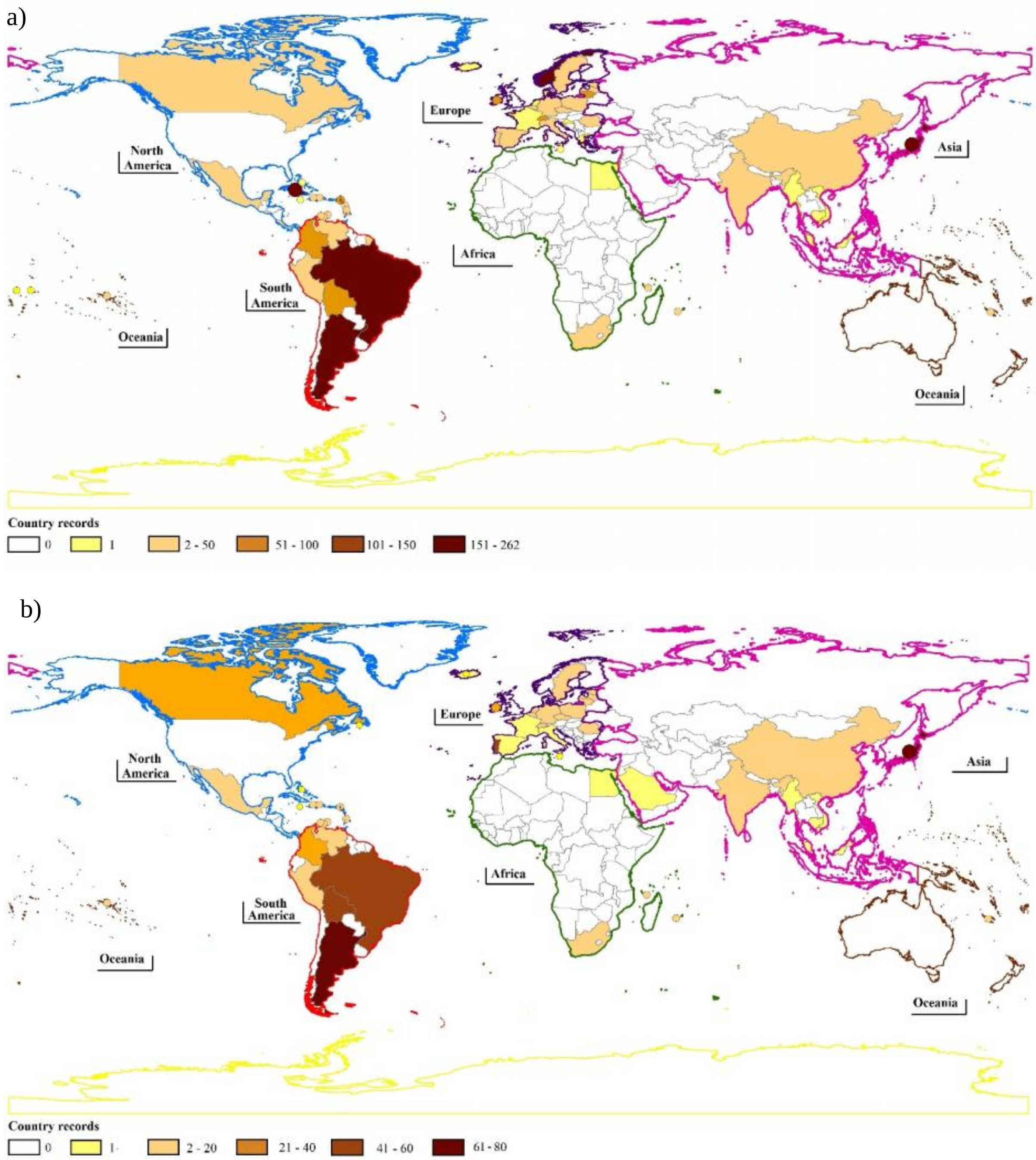

Fig. 4. The distribution of recorded (a) environmental and (b) socio-economic impacts of alien species in the GISD in countries of the world.

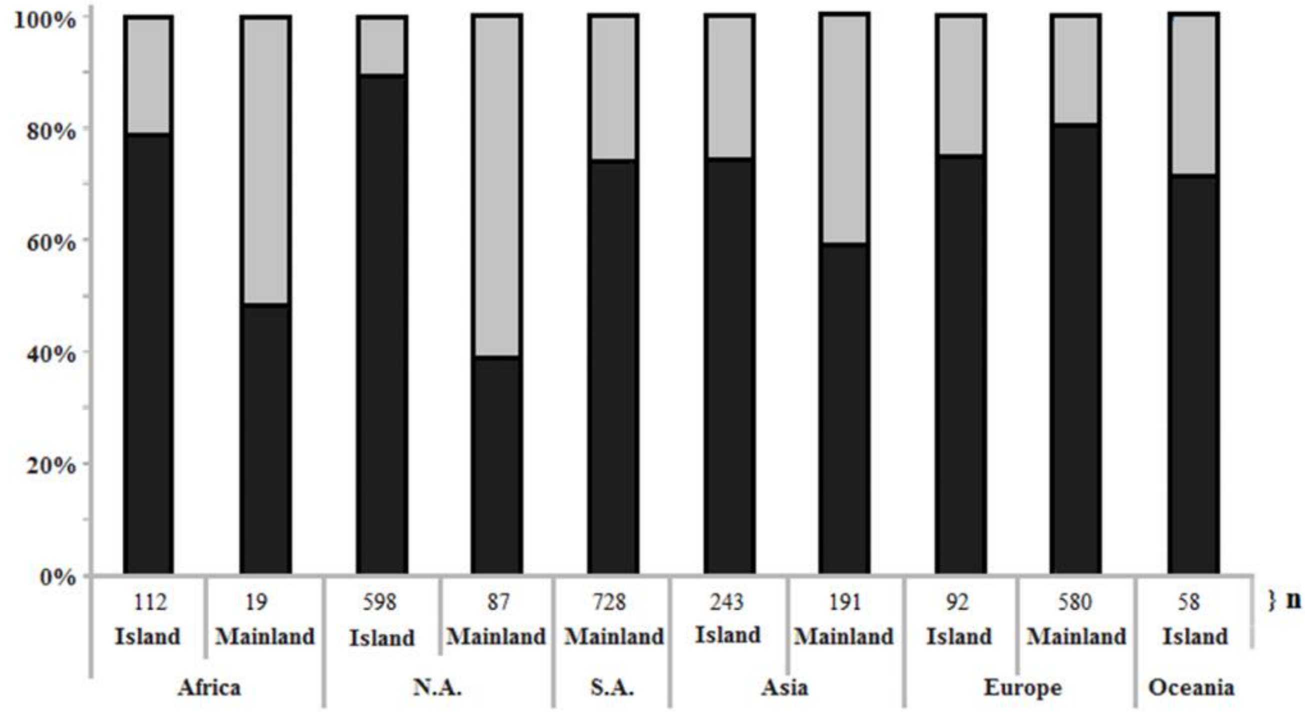

Fig. 5. Distribution of records with recorded socio-economic (light grey) and environmental (dark grey) impacts of alien species in the GISD on different continents.

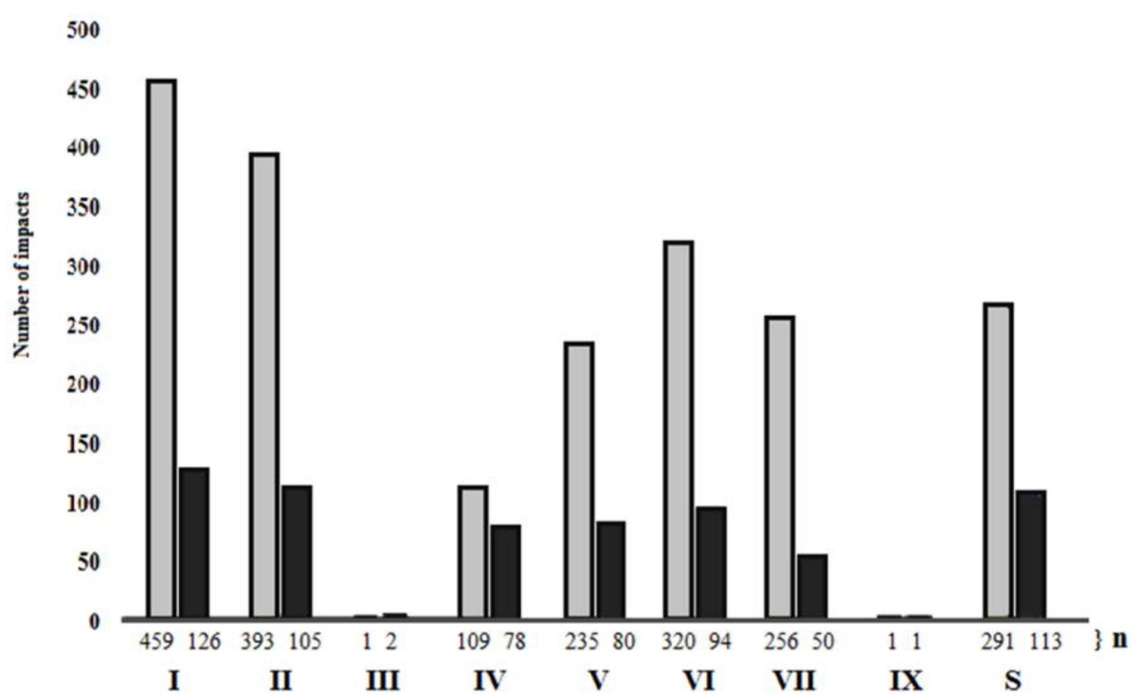

Fig. 6. The distribution of environmental (light grey) and socio-economic (dark grey) impacts of alien species in the GISD across major climatic regimes (zonobiomes sensu Walter & Breckle 1991). Legend: I: Tropical humid; II: Subtropical savanna; III: Subtropical arid; IV: Mediterranean; V: Laurophyllous; VI: Nemoral; VII: Continental; VIII: Boreal; IX: Arctic, S: Several.

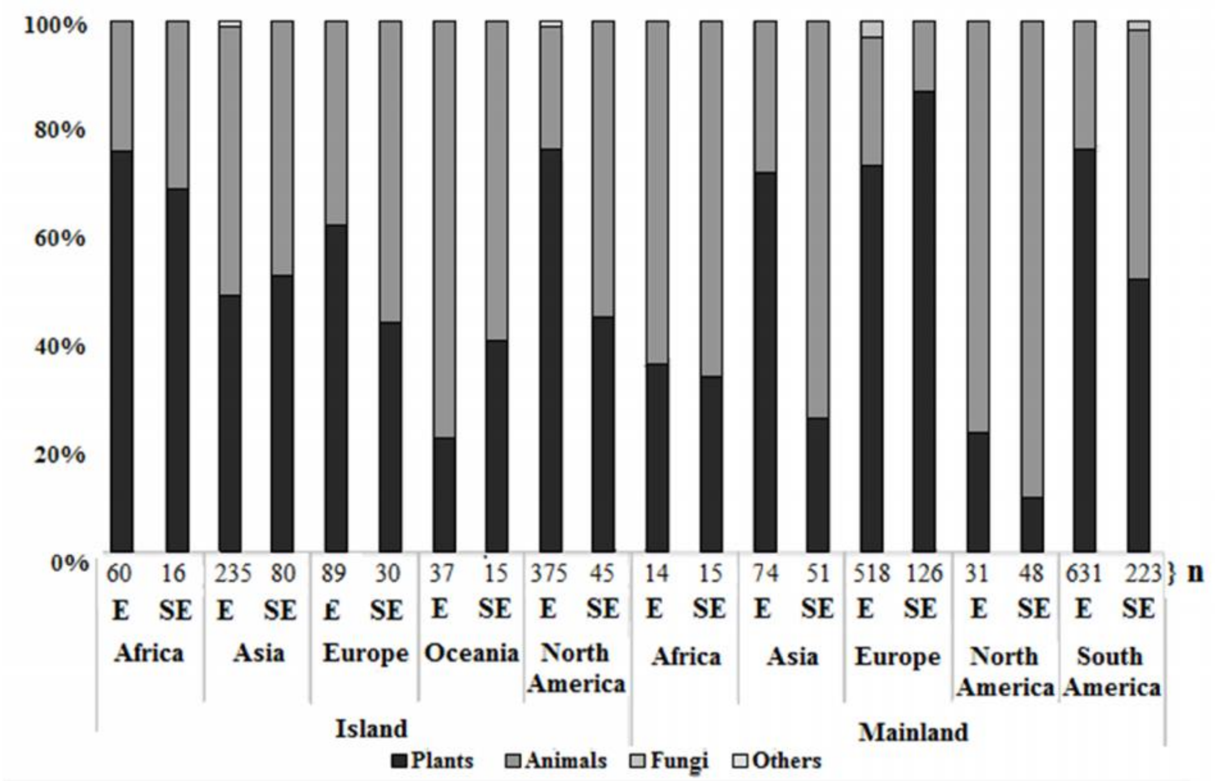

Fig. 7. The distribution of environmental (E) and socio-economic (SE) impacts of alien species in the GISD to taxonomic groups on islands vs. mainland regions and on different continents.

Tables

Table 1. The top 10 families with the highest number of environmental and socio-economic impacts of alien species in the GISD shown separately for different continents. Red font denotes animal families, green font plant families. The number of species for which impacts are recorded are given in brackets.

Africa			North America			South America			Asia			Europe			Oceania		
Family	Record (n°)	Sp. (n°)	Family	Record (n°)	Sp. (n°)	Family	Record (n°)	Sp. (n°)	Family	Record (n°)	Sp. (n°)	Family	Record (n°)	Sp. (n°)	Family	Record (n°)	Sp. (n°)
Fabaceae	9	(8)	Poaceae	89	(63)	Poaceae	87	(64)	Asteraceae	41	(38)	Asteraceae	68	(47)	Formicidae	8	(6)
Gekkonidae	6	(4)	Fabaceae	59	(46)	Asteraceae	71	(43)	Encyrtidae	27	(27)	Rosaceae	60	(48)	Muridae	5	(3)
Muridae	5	(3)	Asteraceae	23	(18)	Fabaceae	58	(36)	Fabaceae	19	(18)	Fabaceae	32	(24)	Bovidae	5	(3)
Cichlidae	5	(5)	Muridae	21	(3)	Brassicaceae	20	(14)	Poaceae	15	(15)	Poaceae	25	(20)	Sturnidae	3	(1)
Myrtaceae	5	(3)	Scorpaenidae	17	(2)	Caryophyllaceae	18	(14)	Cyprinidae	11	(11)	Apiaceae	24	(16)	Fabaceae	3	(3)
Formicidae	5	(5)	Convolvulaceae	15	(14)	Polygonaceae	16	(9)	Thripidae	9	(8)	Cyprinidae	22	(16)	Suidae	2	(1)
Pontederiaceae	4	(2)	Malvaceae	14	(13)	Plantaginaceae	14	(9)	Eulophidae	6	(6)	Hydrocharitaceae	21	(5)	Richardidae	2	(1)
Poaceae	4	(4)	Apocynaceae	12	(5)	Pinaceae	14	(9)	Pontederiaceae	6	(1)	Brassicaceae	20	(16)	Poaceae	2	(2)
Asteraceae	4	(4)	Lamiaceae	11	(11)	Rosaceae	14	(13)	Penaeidae	5	(4)	Polygonaceae	17	(10)	Culicidae	2	(2)
Culicidae	4	(3)	Araceae	11	(8)	Muridae	12	(4)	Solanaceae	5	(4)	Pinaceae	16	(9)	Centrarchidae	1	(1)

Table 2. Families that harbour alien species that cause the most wide-spread impacts in the GISD. Numbers represent species-region records. Red font denotes animal families, green font plant families. E: Environmental impact; SE: Socio-economic impact. Missing values on the total sum correspond to not defined types of impacts. Not matching sums correspond to records presenting both environmental and socio-economic impact.

Island				Mainland			
Family	E	SE	Total	Family	E	SE	Total
Poaceae	81	14	105	Asteraceae	122	32	144
Fabaceae	58	5	79	Poaceae	103	33	117
Asteraceae	48	19	64	Fabaceae	97	23	101
Muridae	23	10	37	Rosaceae	66	0	67
Convolvulaceae	17	0	19	Brassicaceae	36	13	41
Bovidae	17	0	18	Cyprinidae	26	15	37
Malvaceae	12	3	17	Apiaceae	27	10	32
Araceae	11	0	15	Pinaceae	29	0	29
Cyprinidae	13	4	14	Polygonaceae	27	0	29
Hydrocharitaceae	12	0	12	Salmonidae	21	9	23
Pontederiaceae	0	5	10	Hydrocharitaceae	0	15	19
Cervidae	0	4	7	Muridae	0	13	14
Richardidae	0	4	4	Pontederiaceae	0	12	14
Achatinidae	0	3	3				

Table 3. Pathways of introduction in the GISD database for alien species causing environmental and socio-economic impacts and for species that have no impacts recorded. Numbers represent species-region records. Missing values on the total sum correspond to not defined types of impacts. Not matching sums correspond to records presenting both environmental and socio-economic impact.

	Type of Impact			
Pathway	Environmental	Socio-economic	No impact record	Total
Ornamental and horticulture	180	65	243	453
Aquaculture/aquarium	77	40	275	387
Interconnected waterways	0	0	226	248
Agriculture	57	22	129	191
Recreation	28	21	51	84
Sport fishing/ fishing	25	3	46	75
Pet trade	23	6	49	72
Seed contaminant	13	6	55	69
Biocontrol	19	3	29	57
Boat transport	9	11	30	48
Forestry	18	6	21	40
Ballast water	18	3	19	39
Trade of goods	14	5	17	36
Landscape improvement	6	2	26	32

Pathway	Type of Impact			
	Environmental	Socio-economic	No impact record	Total
Transport	13	6	12	26
Escape from captivity	19	8	5	24
Food	14	5	8	22
For herbal or medicinal use	4	2	18	22
Neighbouring countries	3	1	13	16
Fur	13	3	2	15
Erosion control	14	1	0	14
Released	5	1	9	14
Research	4	0	5	9
Restoration	1	0	6	7
Botanical gardens	2	1	1	3
Gardens	0	2	1	3
Other use	1	0	1	2
Natural dispersal	0	0	1	1
Total	580	221	1298	2009

Table 4. Modes of introduction (intentional, unintentional, unknown) for alien species in the GISD database with no recorded impacts and with recorded impacts.

	All alien species		Alien species with impacts	
	No of data	% total	Number of environmental impacts	Number of socio-economic impacts
Intentional	545	27.1%	457	171
Unintentional	157	7.8%	119	47
Unknown	1307	65.1%	4	5
Total	2009		580	223

Table 5. PERMANOVA results of comparisons in the number of recorded impacts on different geographical distribution (Island/Mainland – I/M), climatic areas (Zonobiomes) and Continents

Source	N° of species impact record			
	df	MS	F	*p* -value
I/M	1	0,136	1,42E-05	0,994
Zonobiome	7	6896,4	0,719	0,138
Continent	4	885,8	0,096	0,947
I/M x Zonobiome	7	-44213	-4,607	0,305
I/M x Continent	4	-73979	-8,0439	0,366

I/M = Island/Mainland; n=64

PERMANOVA results of comparisons in the number of species producing impacts on different geographical distribution (Island/Mainland – I/M) and taxonomic affiliation

Source	N° of species impact record			
	df	MS	F	*p* -value
I/M	1	32,7	0,014	0,906
Kingdom	3	2238,8	0,961	0,414
I/M x Kingdom	3	221,0	0,095	0,963

I/M = Island/Mainland; n=64

Table 6. Ordinary Least Squares regresions of environmental and socio-econmomic predictors on the number of alien species in a country that cause environmental and socio-economic impacts in the GISD compared to the total number of alien species per country. Legend: n = number of countries with index values and alien species number information.

		n	p-value	R	R2
All records	GDP x Sp. n° (log-log)	115	0.266	0.104	0.01
	HDI x Sp. n° (log)	102	0.018*	0.232	0.05
	Pop. Density x Sp. n° (log-log)	115	0.941	-0.006	4.71x-05
	GEF x Sp. n°	70	0.003**	0.349	0.122
All impact records	GDP x Sp. n° (log-log)	63	0.046*	0.252	0.063
	HDI x Sp. n° (log)	55	0.023*	0.305	0.093
	Pop. Density x Sp. n° (log-log)	63	0.58	-0.071	0.005
	GEF x Sp. n°	45	0.042*	0.303	0.092
Environmental impact records	GDP x Sp. n° (log-log)	60	0.14	0.193	0.037
	HDI x Sp. n° (log)	54	0.054	0.264	0.07
	Pop. Density x Sp. n° (log-log)	61	0.157	-0.184	0.034
	GEF x Sp. n°	44	0.078	0.268	0.072
Socioeconomic impact records	GDP x Sp. n° (log-log)	53	0.392	0.12	0.014
	HDI x Sp. n° (log)	48	0.22	0.18	0.032
	Pop. Density x Sp. n° (log-log)	54	0.326	-0.136	0.018
	GEF x Sp. n°	39	0.01**	0.406	0.165

Significance levels: *** p ≤ 0.001, ** p ≤ 0.01, * p ≤0.05.

Appendix 1

The GISD (as of 2012-06-01) includes 45,267 records of alien species from 121 regions (countries or islands). These belong to 10,710 species from 1212 families.

Table 1. The geographic distribution and taxonomic affiliation of records of alien species in the GISD.

	Africa	North America	South America	Asia	Europe	Oceania	Total	% Total records
Vascular plants	2917	5039	3362	5717	14139	6985	38159	84.3
Algae	11	23	20	33	44	12	143	0.3
Fungi	4	16	12	10	58	8	108	0.2
Chromista	4	15	23	12	21	6	81	0.2
Bryophyta		4		1	29		34	0.1
Marchantiophyta				1	10		11	0.0
Fish	69	274	321	386	127	155	1332	2.9
Mammals	82	165	122	78	97	162	706	1.6
Birds	64	133	76	88	104	80	545	1.2
Amphibians and reptiles	51	149	52	60	15	53	380	0.8
Insects	56	205	223	647	494	269	1894	4.2
Mollusc	24	79	72	263	103	62	603	1.3
Crustaceans	18	68	105	92	104	23	410	0.9
Other invertebrates	14	212	168	168	143	32	737	1.6
Bacteria	2	4	15	6	2	6	35	0.1
Protozoa		27	11	22	2		62	0.1
Total records	3316	6413	4582	7584	15492	7853	45240	
% Total records	7.3	14.2	10.1	16.8	34.2	17.4		

Table 2. The numbers of alien species of different taxonomic groups included in the GISD and their geographic distribution.

	Africa	North America	South America	Asia	Europe	Oceania	Total N° species	% Total
Vascular plants	1664	2285	1984	3047	3485	1279	7385	69.1
Fungi	4	8	7	7	57	1	78	0.7
Algae	10	18	15	20	17	3	58	0.5
Bryophyta		4		1	4		8	0.1
Marchantiophyta				1	3		3	0.0
Chromista	4	12	16	10	15	2	43	0.4
Birds	42	62	44	68	78	25	217	2.0
Fish	42	151	177	272	63	56	507	4.7
Mammals	50	43	43	41	52	19	133	1.2
Amphibians and reptiles	36	59	28	44	10	11	139	1.3
Insects	39	144	116	533	438	53	1044	9.8
Crustaceans	14	56	73	76	71	12	215	2.0
Molluscs	20	58	39	212	66	19	318	3.0
Other invertebrates	14	179	121	154	116	12	475	4.4
Bacteria	2	4	5	4	2	2	10	0.1
Protozoa		26	5	20	2		50	0.5
Total	1941	3109	2673	4510	4479	1494	10683	

Table 3. The geographic distribution and taxonomic affiliation of alien species with recorded impacts in the GISD.

	Africa	North America	South America	Asia	Europe	Oceania	Total records	% Total records
Vascular plants	58	465	521	168	466	15	1693	62.5
Fungi		3	2		13		18	0.7
Algae				2	12		14	0.5
Chromista		1	2		8		11	0.4
Bryophyta					1		1	0.0
Fish	17	66	35	45	46	2	211	7.8
Mammals	16	55	56	32	22	16	197	7.3
Amphibians and reptiles	12	33	11	20	5	2	83	3.1
Birds	7	15	18	14	9	7	70	2.6
Insects	12	15	24	84	20	15	170	6.3
Molluscs	6	18	24	38	28	1	115	4.2
Crustaceans	3	4	15	14	25		61	2.3
Other invertebrates		10	19	16	17		62	2.3
Bacteria			1				1	0.0
Total record impact	131	685	728	434	672	58	2708	
% Total record impact	4.8	25.3	26.9	16.0	24.8	2.1		

Table 4. The numbers of alien species of different taxonomic groups included in the GISD and their geographic distribution.

	Africa	North America	South America	Asia	Europe	Oceania	N° species	% Total
Vascular plants	49	364	372	152	336	15	1085	65.01
Fungi		2	2		13		17	1.02
Algae				2	4		6	0.36
Chromista		1	2		7		8	0.48
Bryophyta			1		1		1	0.06
Fish	13	42	23	44	31	2	111	6.65
Mammals	12	18	25	30	16	11	56	3.36
Amphibians and reptiles	9	16	8	18	4	2	47	2.82
Birds	5	9	8	13	8	5	39	2.34
Insects	11	12	16	81	18	12	130	4.37
Molluscs	5	13	16	37	21	1	73	7.79
Crustaceans	3	3	12	12	22		44	2.64
Other invertebrates		2	18	15	16		50	3
Bacteria			1				1	0.06
Total	107	482	503	405	497	48	1669	

Table 5. Distribution of records of alien species in the GISD across zonobiomes and for islands versus mainland regions.

Impact distribution	Africa	North America	South America	Asia	Europe	Oceania	Total
Zonobiome							
I	29	174	358	1		22	459
II	84	456	108	7		36	416
III	1			1			1
IV				167	67		109
V				243			235
VI					357		320
VIII		41			247		256
IX					1		1
S	17	14	262	15			267
Island	112	598		243	92	58	1103
Mainland	19	87	728	191	580		1605

Table 6. The most wide-spread alien species with documented impacts in the GISD. Shown are the distributions of impacts (numbers represent regions with impact in mainland regions vs. islands, and zonobiomes). a) Most wide-spread species with environmental impact records. b) Most wide-spread species with socio-economic impact records. Red font denotes animal families, green font plant families.

a) Environmental impacts		Island						Mainland							Total
Species	Family	I	II	IV	V	VI	IX	I	II	III	IV	VI	VIII	several	
Eichhornia crassipes	Pontederiaceae		6		1			4	4	1	2	1		1	20
Rattus rattus	Muridae	6	5		1	1		1	1						15
Elodea canadensis	Hydrocharitaceae		1			1					3	7	2	1	15
Capra hircus	Bovidae	5	5		1			2	1						14
Sus scrofa	Suidae	2	3		1	1		3	1				1	1	13
Canis lupus	Canidae	3	5		1			2	1					1	13
Leucaena leucocephala	Fabaceae	4	5		1			1	1						12
Oncorhynchus mykiss	Salmonidae		1		1			2	1			2	2	1	10
Trachemys scripta	Emydidae				1	1		3	1		1	1		1	9
Rattus norvegicus	Muridae	3	1		1	1		2	1						9

b) Socio-economic impacts		Island					Mainland							Total
Species	Family	I	II	IV	V	VI	I	II	III	IV	VI	VIII	several	
Eichhornia crassipes	Pontederiaceae		4		1		3	4	1	1	1		1	16
Elodea canadensis	Hydrocharitaceae					1				3	7	1	1	13
Mus musculus	Muridae	2	3				3	1						9
Rattus rattus	Muridae	2	3				2	1						8
Columba livia	Columbidae	1					3	1					1	6
Lepus europaeus	Leporidae		1				3	1						5
Arundo donax	Poaceae		2							1	1		1	5
Macrobrachium rosenbergii	Palaemonidae		1				1						3	5
Apis mellifera	Apidae	1					2						2	5
Cyprinus carpio	Cyprinidae					1					1	1	2	5
Passer domesticus	Passeridae		1				3						1	5

Appendix 2.

Correlations of univariate Ordinary Least Squares (OLS) regressions of predictor variables and the total number of alien species per country in the GISD and the number of alien species that cause environmental or socio-economic impacts.

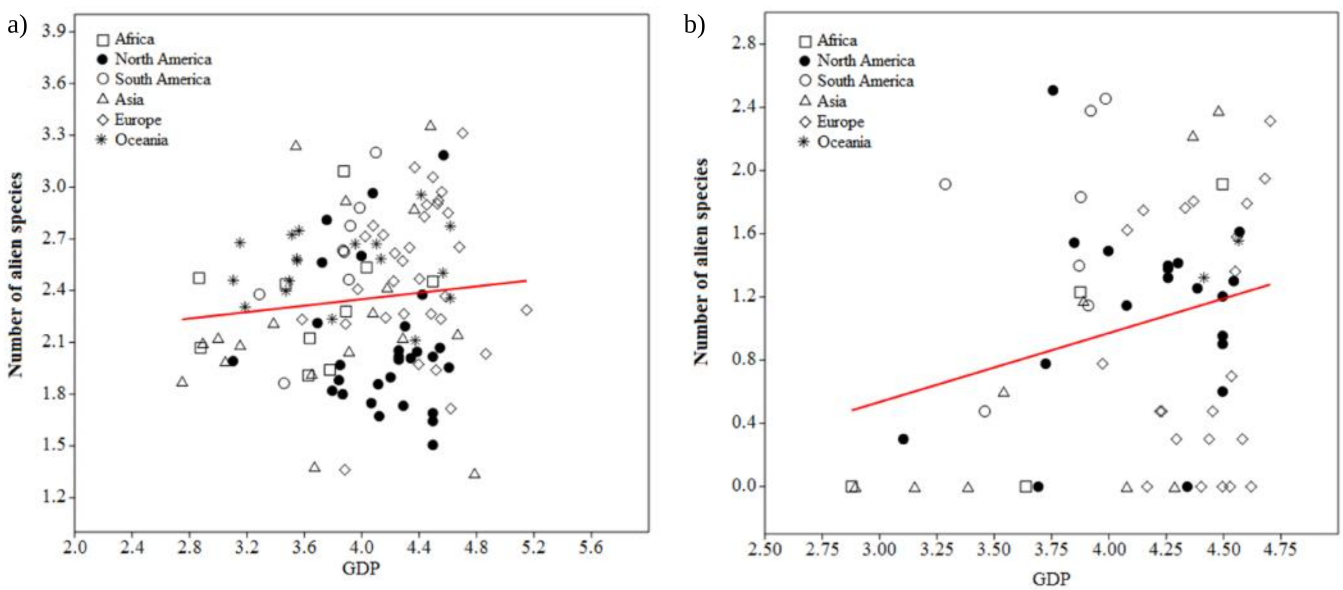

Fig 1. Gross Domestic Product correlations of univariate OLS regressions. a) Total country-record. b) Total country-record with impact registered.

	n	p-value	r	r2
GDP x Sp. n°	115	0.266	0.104	0.01
GDP x Sp. n° /impact	63	0.046*	0.252	0.063

Significance levels: *** p ≤ 0.001, ** p ≤ 0.01, * p ≤0.05.

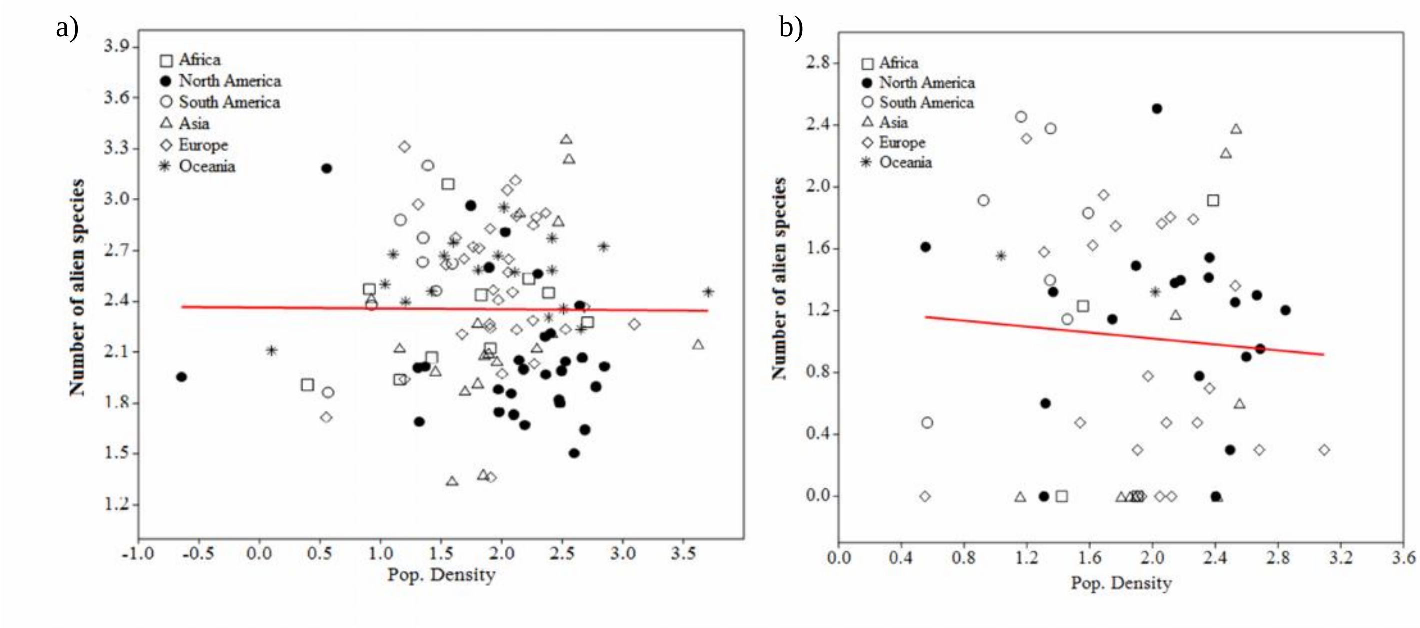

Fig 2. Population density correlations of univariate OLS regressions. a) Total country-record. b) Total country-record with impact registered.

	n	p-value	r	r2
Pop. Density x Sp. n°	115	0.941	-0.006	4.71x-05
Pop. Density x Sp. n° /impact	63	0.58	-0.071	0.005

Significance levels: *** p ≤ 0.001, ** p ≤ 0.01, * p ≤0.05.

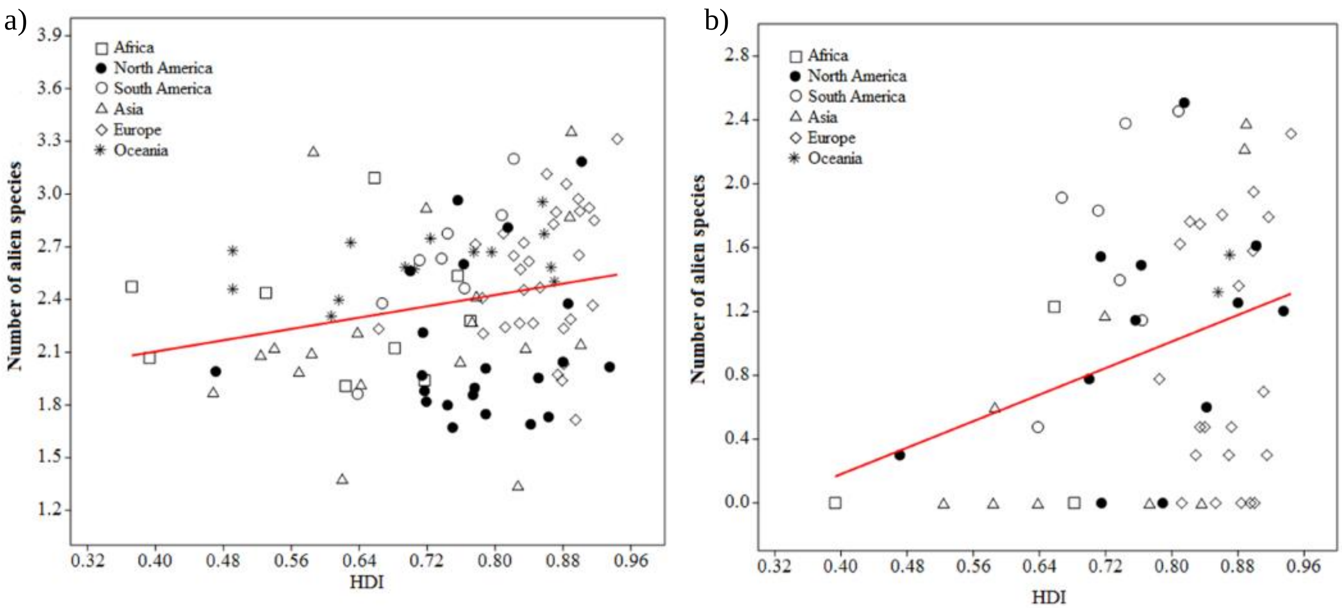

Fig 3. Human Development Index correlations of univariate OLS regressions. a) Total country-record. b) Total country-record with impact registered.

	n	p-value	r	r2
HDI x Sp. n°	102	0.018*	0.232	0.05
HDI x Sp. n° /impact	55	0.023*	0.305	0.093

Significance levels: *** p ≤ 0.001, ** p ≤ 0.01, * p ≤0.05.

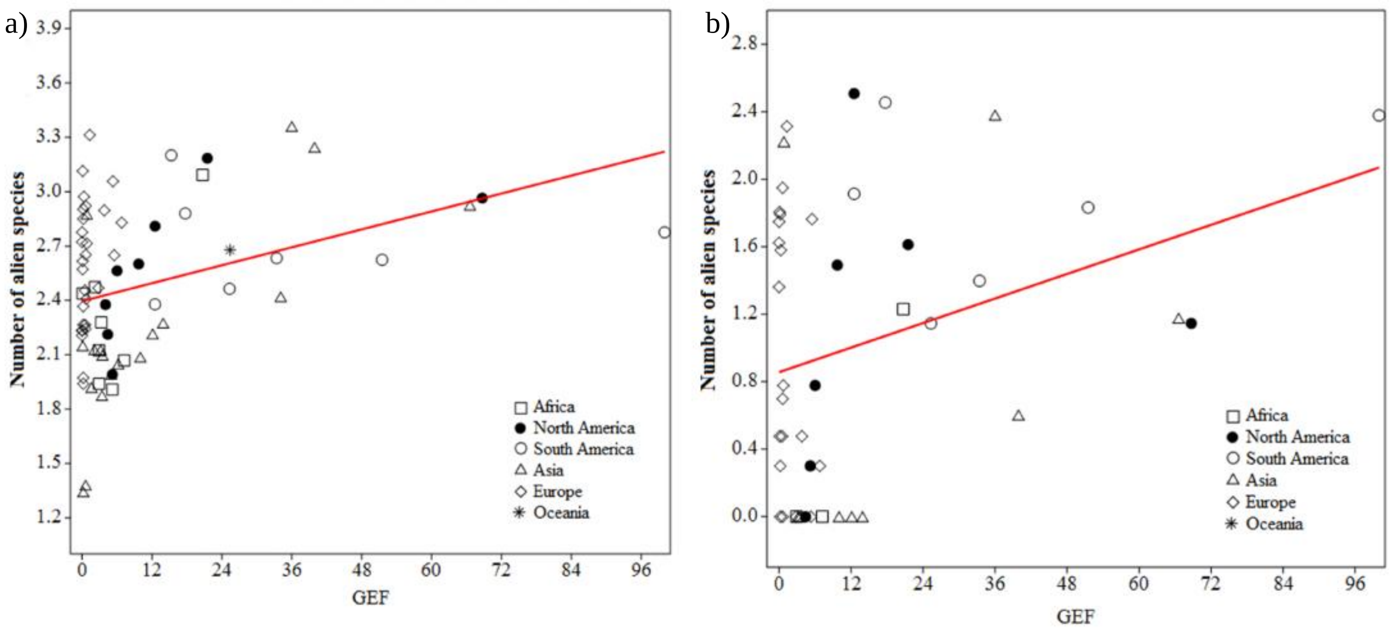

Fig 4. Global Environmental Facility benefits index for biodiversity correlations of univariate OLS regressions. a) Total country-record. b) Total country-record with impact registered.

	n	p-value	r	r2
GEF x Sp. n°	70	0.003**	0.349	0.122
GEF x Sp. n°/ impact	45	0.042*	0.303	0.092

Significance levels: *** p ≤ 0.001, ** p ≤ 0.01, * p ≤0.05.

Appendix 3.

Correlations of univariate Ordinary Least Squares (OLS) regressions of predictor variables and the number of alien species that cause environmental impacts in the GISD and the number of alien species that cause socio-economic impacts.

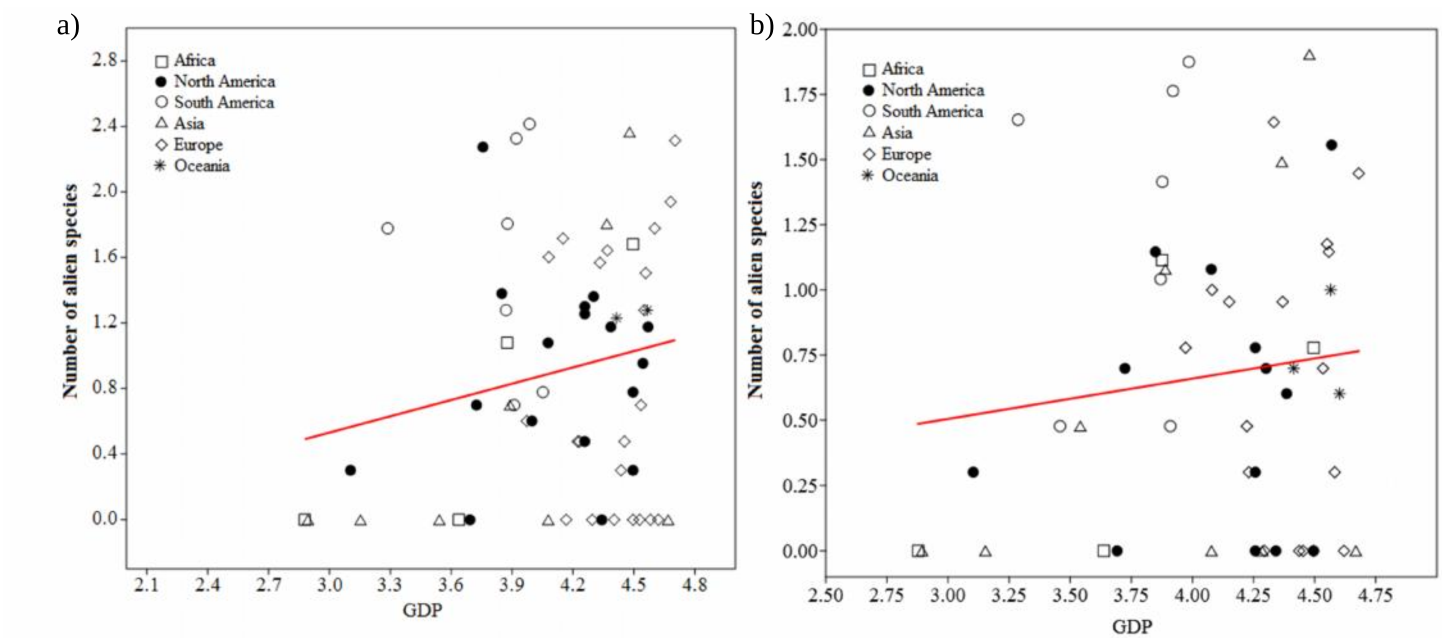

Fig 1. Gross Domestic Product correlations of univariate OLS regressions. a) Environmental impact record. b) Socio-economic impact record.

	n	p-value	r	r2
GDP x Sp. n°/Environmental	60	0.14	0.192	0.037
GDP x Sp. n°/Socio-economic	53	0.392	0.12	0.014

Significance levels: *** $p \leq 0.001$, ** $p \leq 0.01$, * $p \leq 0.05$.

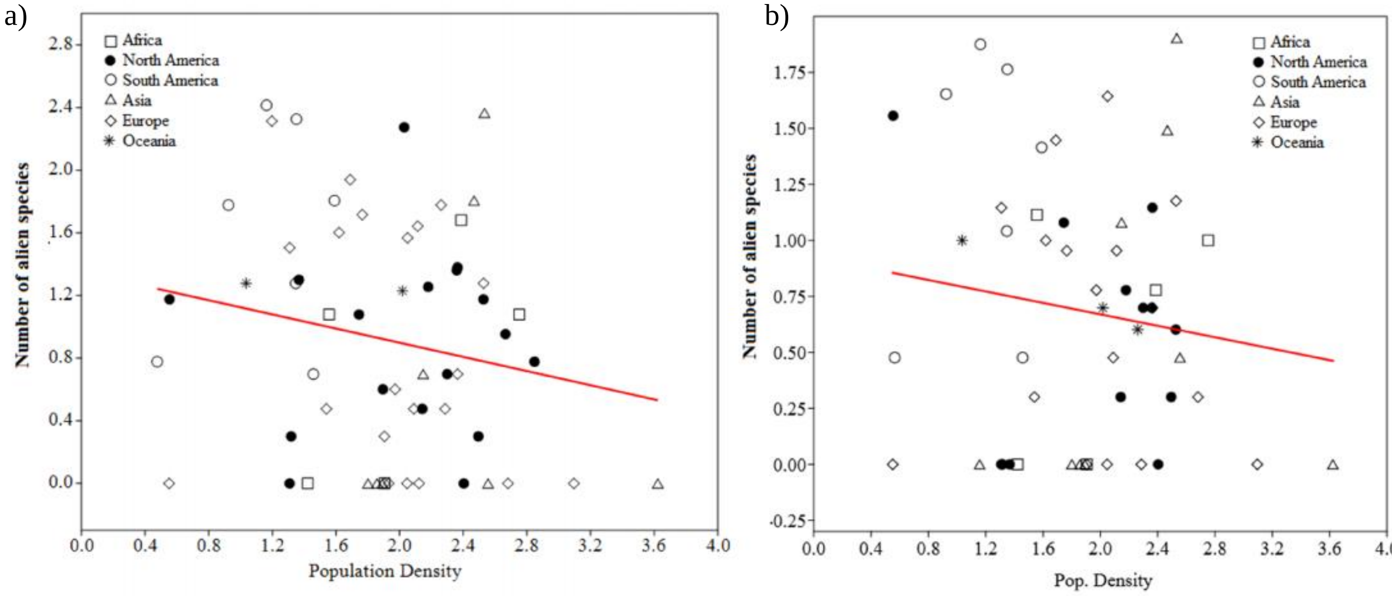

Fig 2. **.** Population density correlations of univariate OLS regressions. a) Environmental impact record. b) Socio-economic impact record.

	n	p-value	r	r2
Pop. Density x Sp. n°/Environmental	61	0.157	-0.183	0.033
Pop. Density x Sp. n°/Socio-economic	54	0.326	-0.136	0.018

Significance levels: *** p ≤ 0.001, ** p ≤ 0.01, * p ≤0.05.

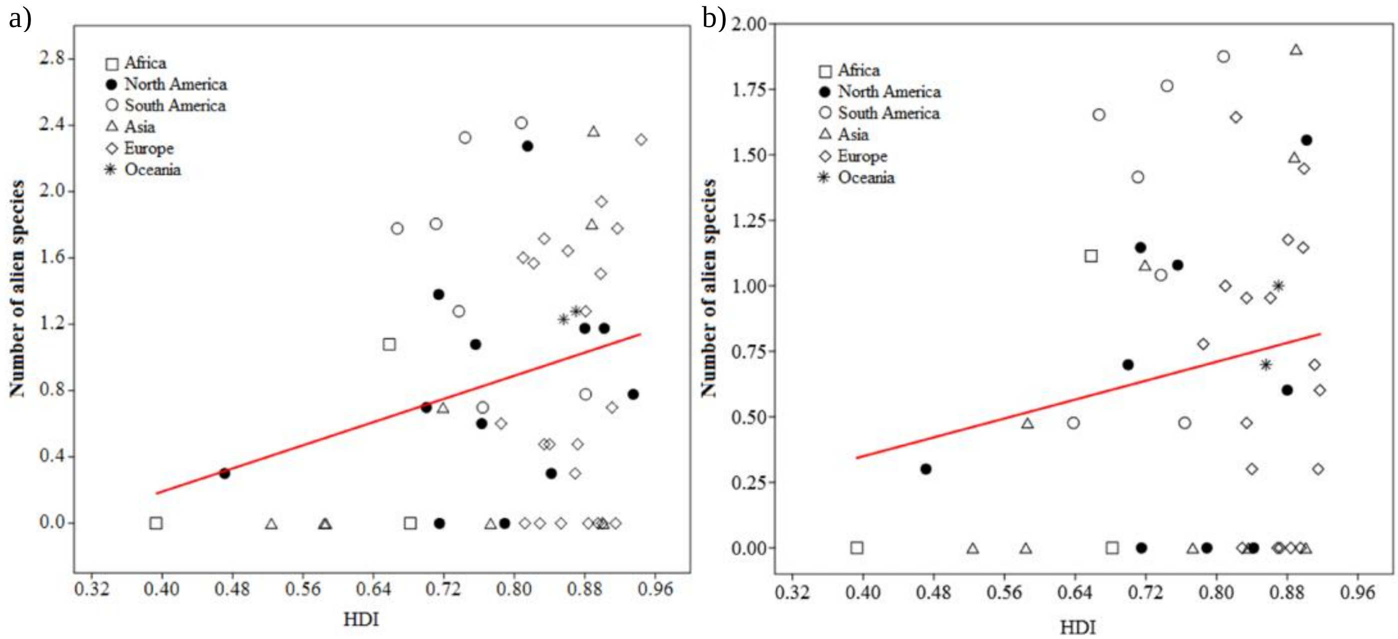

Fig 3. Human Development Index correlations of univariate OLS regressions. a) Environmental impact record. b) Socio-economic impact record.

	n	p-value	r	r2
HDI x Sp. n°/Environmental	54	0.054	0.264	0.069
HDI x Sp. n°/Socio-economic	48	0.22	0.180	0.032

Significance levels: *** $p \leq 0.001$, ** $p \leq 0.01$, * $p \leq 0.05$.

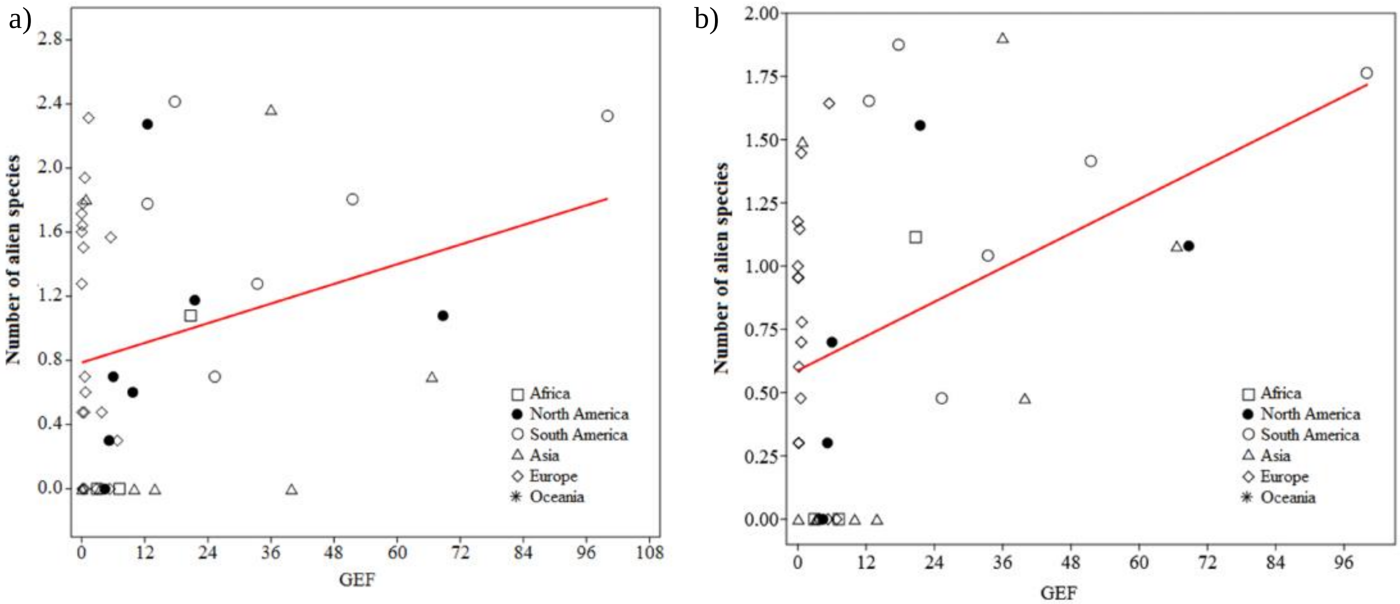

Fig 4. Global Environmental Facility benefits index for biodiversity correlations of univariate OLS regressions. a) Environmental impact record. b) Socio-economic impact record.

	n	p-value	r	r2
GEF x Sp. n°/Environmental	44	0.078	0.268	0.072
GEF x Sp. n°/Socio-economic	39	0.01**	0.406	0.165

Significance levels: *** p ≤ 0.001, ** p ≤ 0.01, * p ≤0.05.