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Scoring environmental and socioeconomic impacts of alien plants invasive in Europe

Zuzana Rumlerová · Montserrat Vilà · Jan Pergl · Wolfgang Nentwig · Petr Pyšek

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Abstract The categorization of invasive alien species based on their impact is an important way of improving the management of biological invasions. The impact of 128 alien species of plants in Europe was evaluated using the Generic Impact Scoring System (GISS) originally developed for mammals. Based on information in the literature their environmental and socioeconomic impacts were assessed and assigned to one of six different categories. In each category, the impact was classified on a five-degree scale, which reflects the impact intensity. To identify species with the greatest impacts, we used the maximum score recorded in each category and their sums. Data from the whole invaded range were considered, which resulted in scoring the potential impact of each species, not necessarily currently realized in Europe. Environmental impacts are most often manifested via competition with native species (recorded for 83 % of the species), while socioeconomic impacts are associated mostly with human health (78 %). The sums of environmental and socioeconomic impacts were significantly correlated, which indicates that the same suite of species traits is associated with both types of impacts. In terms of plant life forms, annual plants have on average lower environmental impacts than perennial plants, and aquatic species have a higher socioeconomic impact than other life forms. Applying the GISS to plants, the most species-rich taxonomic group of alien organisms in Europe, is an important step towards providing managers and policymakers with a robust tool for

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Z. Rumlerová · J. Pergl (✉) · P. Pyšek
Department of Invasion Ecology, Institute of Botany, The Czech Academy of Sciences, CZ 252 43 Průhonice, Czech Republic
e-mail: pergl@ibot.cas.cz

Z. Rumlerová · P. Pyšek
Department of Ecology, Faculty of Science, Charles University in Prague, Viničná 7, CZ 128 44 Prague, Czech Republic

M. Vilà
Estación Biológica de Doñana (EBD-CSIC), Avda. Américo Vespucio, s/n, Isla de la Cartuja, 41092 Sevilla, Spain

W. Nentwig
Institute of Ecology and Evolution, University of Bern, Baltzerstrasse 6, 3012 Bern, Switzerland

P. Pyšek
Centre for Invasion Biology, Department of Botany & Zoology, Stellenbosch University, Matieland 7602, South Africa

identifying and prioritizing alien species with the highest impact.

Keywords Environmental impact · Europe · Generic Impact Scoring System · Invasive species · Plant invasions · Socioeconomic impact

Introduction

The total number of alien fungal, plant and animal species introduced into Europe (including introductions within Europe) is ~12,000 (DAISIE 2009; Pergl et al. 2012) and a recent comprehensive analysis reports 4140 naturalized plant species for this continent (van Kleunen et al. 2015) of which about 2440 are known to affect the environment and socioeconomy (Vilà et al. 2010). Because the numbers of established alien species in Europe is still growing with no sign of slowing down (Hulme et al. 2009), and that current invasions and their impacts are consequences of past socioeconomic activities (sensu invasion debt, Essl et al. 2011a), it is reasonable to assume that the impacts of biological invasions will continue to increase in the future. This creates an urgent need for improving the effectiveness of the management of biological invasions in Europe (Kettunen et al. 2009; Scalera et al. 2012; Genovesi et al. 2015). The categorization of invasive species according to their impact is an important tool for prioritizing management actions. Science-based assessment of impacts of individual species is a key requirement for achieving this goal, and it may help to reduce damage to the environment and socioeconomy, which is known to be high, even by conservative estimates (Kettunen et al. 2009).

The interest in research on impacts of biological invasions has grown rapidly in the last decade (Pyšek and Richardson 2010; Jeschke et al. 2014; Kumschick et al. 2015a), yielding theoretical frameworks (e.g., Byers et al. 2002; Levine et al. 2003; Barney et al. 2013; Ricciardi et al. 2013; Blackburn et al. 2014), suggestions for standardization of terminology (Pyšek et al. 2012; Ricciardi et al. 2013; Jeschke et al. 2014) and reviews of methods (Skurski et al. 2014; Barney et al. 2015; Kumschick et al. 2015a, b). This effort has stimulated a large number of case studies that provide a basis for comprehensive assessments and meta-analyses of impact mechanisms as well as illustrations of general patterns (see e.g., Gaertner et al. 2009, 2014; Powell et al. 2011; Vilà et al. 2011, 2015; Hulme et al. 2014 and references therein). For plants, the existing case studies routinely address only a few types of impacts and this may lead to potentially biased predictions (Hulme et al. 2013).

Based on the knowledge of a given species, risk-assessment schemes try to categorize and rank species with respect to the risk they pose if introduced into a new region, mainly with respect to the probability of becoming established and invasive (e.g., Pheloung et al. 1999; Roy 2014; Kumschick and Richardson 2013). Although the potential for an impact is a significant component of risk assessment schemes, 87 % of assessments are primarily based on expert opinions (Leung et al. 2012). Indirectly, expert opinions are also derived from published information, but a direct reference to published literature facilitates further impact analyses and enables its quantification. This can be achieved by a scoring system (Generic Impact Scoring System–GISS); Nentwig et al. 2010; see Nentwig et al. 2016 for a detailed methodological description and review), based, as much as possible, on rigorous evidence published in case studies and categorized in a standard manner, which enables direct comparisons among species. The semi-quantitative scoring based on exactly defined types of impact was originally developed for mammals introduced into Europe (Nentwig et al. 2010), then later applied to birds (Kumschick and Nentwig 2010) and used to compare the magnitude of impacts between both taxonomic groups (Kumschick et al. 2013, 2015a), and recently also elaborated for arthropods (Vaes-Petignat and Nentwig 2014) and fish (van der Veer and Nentwig 2015). This scheme has become the basis for formulating a conceptual framework for all taxa (Nentwig et al. 2016; Kumschick et al. 2012, 2015b; Blackburn et al. 2014).

There are several studies comparing the impacts of species in native versus invaded ranges (e.g., Hejda 2013; Lamarque et al. 2012), which provide vague but significant support for the view that the impact in invaded ranges can be higher, at least for some species (Parker et al. 2013). Therefore, because impact in the native range is rarely measured we used data only from the invaded range in this study. Nevertheless, it is clear that assessment of impact may differ regionally and there is a difference between the actual (observed in the studied region) versus potential (to be expected in the whole invaded range) impacts (Jeschke et al. 2014). Thus "potential impact" (maximal score found in the invaded range) might be a good indicator of future impact, and reasonable basis for management based on the precautionary principle.

Recent reviews reveal that the majority of scoring systems and risk assessment schemes focus mainly on ecological (environmental) impacts of alien species (Essl et al. 2011b; Leung et al. 2012; Roy 2014). However, a complex evaluation addressing ecological as well as socioeconomic impacts is needed for the proper prioritization of invasion management, both for conservation purposes and human well-being (Pejchar and Mooney 2009; Pergl et al. 2016). The advantage of GISS is that it evaluates both environmental and socioeconomic impacts in a comparable way, and thus provides a standardized background for the decision-making procedures used by policymakers and stakeholders (Genovesi et al. 2015; Vaes-Petignat and Nentwig 2014; Kumschick et al. 2015a).

Plants are a taxonomic group in which 5.6 and 5.4 % of the species introduced into Europe are reported to cause environmental and socioeconomic impacts, respectively (Vilà et al. 2010). This is less than for other taxa, in particular, vertebrates and freshwater biota (30 % each), but since about half of all alien species in Europe are plants (Lambdon et al. 2008) then more plants than other taxa are known to have an impact. Early in the 2000s, there were 326 species of plants that were causing ecological impacts and 315 with socioeconomic impacts (Vilà et al. 2010, 2015). This, together with the fact that plants are primary producers and directly affect several trophic levels, which is manifested by a range of types of impacts in a variety of ecosystems (Pyšek et al. 2012), highlights the need for identifying those species with the most severe impacts. Surprisingly, a quantitative assessment of particular plant species, similar to those for the mammals, birds and invertebrates mentioned above, is lacking. Our paper aims to close this gap by applying GISS to alien plants in Europe in order to answer the following questions: (1) Which alien species of plants have the greatest potential environmental and socioeconomic impacts in Europe? (2) Does their ranking in terms of environmental and socioeconomic impacts differ? (3) Are there species traits associated with different magnitudes of impact? (4) What are the mechanisms most frequently associated with these impacts?

Methods

Selection of species

To avoid a subjective selection of the species used in the impact assessment, we performed stepwise selection based on the distribution of candidate species in the region studied and their known impact. The species used in this study were selected from the DAISIE database (www.europe-aliens.org). Species of plants alien to Europe (i.e., with a native range outside Europe; Lambdon et al. 2008), introduced into at least one of the DAISIE regions after 1500 (neophytes), and with an ecological and/or socioeconomic impact recorded in the DAISIE database were selected (152 species). These criteria resulted in the exclusion of archaeophytes (species introduced before 1500; see Pyšek et al. 2004 for definitions), whose main region of origin is the Mediterranean. Indication of impact in the DAISIE database is based on published records (Vilà et al. 2010), but only by a binary description with no indication of the strength (no/known/unknown impact). This information was used to rapidly select those species with a recorded impact in Europe. Of this species pool, only those occurring in more than 10 regions (out of the 86 distinguished in DAISIE) and hence with widespread distribution in Europe, were chosen (104 species). To avoid the exclusion of some widely distributed species because their impact was not reported in DAISIE, we added those with no impact that were recorded in at least 25 regions. Finally, to avoid excluding some important invaders, we checked the list resulting from the above screening against species invasive in Europe listed by Weber (2003). The selection resulted in 128 alien plant species for which evidence of impacts was searched.

Impact scoring

The species were scored using the Generic Impact Scoring System, originally developed for mammals (GISS; Nentwig et al. 2010). The GISS separates the impacts of invasive alien species into environmental and socioeconomic, with each group divided into six different categories (Table 1), that are defined by using a formal description (see El. Appendix 1). In each of these twelve categories, the impact is classified on a five-degree scale reflecting impact intensity, plus a zero impact level for no impact known or detectable. The scoring points represent the intensity levels and range from 1 (minor impact) to 5 (major impact). For the purpose of the present study, the formal Handbook description of the 12 impact categories used for animals was expanded to reflect the ecology of plants and their role in ecosystems, based on case studies of plant impacts, reviews of their mechanisms and our experience of this topic (Vilà et al. 2011, 2015; Pyšek et al. 2012; Hulme et al. 2013).

For each species the information about its impact was searched in (1) ISI Web of Knowledge, by using the species' scientific name combined with keywords indicating its alien/invasive status; (2) databases of invasive species with impacts recorded, namely DAISIE, NOBANIS (The European Network on Invasive Alien Species, www.nobanis.org) and GISD (The Global Invasive Species Database, www.issg.org); (3) other bibliographic sources of information, including regional and national case studies and books mentioned in the primary literature (e.g., Brundu et al. 2001; Sanz-Elorza et al. 2004; Fried 2012). We distinguished those cases in which an impact is searched for in a particular study but not found (0 score assigned) from those when it was not searched for (coded as NA), and hence not used in our analysis. The list of data sources is provided in Appendices S2 and S3.

As the precautionary principle was adopted in this study we obtained information on the *potential* impact of a species in the whole of the area it had invaded, including regions outside Europe (e.g., Bossard et al. 2000; Dufour-Dror 2012). The native range was not considered except to identify if the species is poisonous or spiny, as these traits are unlikely to differ in the native and invaded ranges.

To explore whether the availability of data on impact depends on how frequently the species is studied, the number of studies found in the Web of Knowledge using the name of the species and the keywords "invas* or exot* or weed*" (searched in December 2013) was used as a proxy of research intensity.

Species traits

For each species included in this study we obtained information on the following biological traits: life history (longevity: annual, perennial); life form (grass, herbaceous, shrub, tree, vine, aquatic); plant height; seed size; toxicity (yes/no); type of pollination (insect, wind, water, selfing); dispersal vector (wind, water, zoochory); type of mycorrhiza (ECM—ectomycorrhiza, AM—arbuscular mycorrhiza, none); vegetative reproduction (yes, no). The region of origin of the species was also recorded as follows: Africa, North America, Central America, South America, Asia and Australia. The data on species traits were taken from several databases such as CzechFlor (a working

Table 1 Overview of categories scored in the two impact groups (environmental and socioeconomic), and number of alien species for which the data were found, out of the 128 species screened. Number of scored categories includes also zero scores

1. Environmental impacts	No. of species	2. Socioeconomic impacts	No. of species
1.1 Direct impacts on plants (e.g., allelopathy)	53	2.1 Impacts on agricultural production	42
1.2 Impacts on animals (e.g., through altered food availability or palatability)	46	2.2 Impacts on animal production	15
1.3 Indirect impacts on other species (e.g., through resource competition)	84	2.3 Impacts on forestry production	7
1.4 Impacts through transmission of diseases or parasites	11	2.4 Impacts on human infrastructure	19
1.5 Impacts through hybridization	16	2.5 Impact on human health	74
1.6 Impacts on ecosystems	60	2.6 Impacts on human social life	20
Total with impacts recorded	101	Total with impacts recorded	96

database of the Czech flora held at the Institute of Botany, CAS), BiolFlor (Klotz et al. 2002; www.2.ufz.de/biolflor), United States Department of Agriculture—Natural Resources Conservation Service (www.plants.usda.gov), Pacific Island Ecosystems at Risk (www.hear.org/pier) and Mycorrhizal Associations (www.mycorrhizas.info).

Statistical analyses

The impact of each species in each category was expressed by assigning the maximum score recorded in the above sources. If different sources report different levels of impact for a given category, only the highest score was considered. This decision was based on the worst case scenario principle (in accordance with Blackburn et al. 2014); that is, the potential impact of a species can be independent of conditions that mediate its realized impact in areas it invades. Based on these maximum scores, for each species and impact group (environmental, socioeconomic) two measures were calculated: (1) "logarithmic sum" of all values scored across the six categories ($\log_{10}(\Sigma(10$^impact values$))$ and (2) variance among categories. Logarithmic sum was used to reflect the exponential nature of the gradual increase in the levels of the GISS system, when individual levels of impact are of different orders of magnitude (El. appendix S3).

The significance of the relationship between species' impact scores and research intensity (the number of studies on the species on the Web of Science); between species' impact scores and the number of regions it occupies; and between species environmental and socioeconomic impact scores was tested using Pearson's product-moment correlation test. All analyses were done in R (Crawley 2007; R Development Core Team 2010).

Regression trees were used for the exploratory analysis with the maximum scores of impact in both groups (environmental, socioeconomic) as a dependent variables, and species' biological traits and the region of origin as explanatory variables. Square roots of inverse values of the numbers of species within genera were used as weights to minimize the effects of phylogenetic autocorrelations between closely related species. Plants for which no information was found were not included in the analyses. Regression trees were chosen because of their flexibility and robustness, ability to deal with combinations of categorical and numeric explanatory variables and capacity to take into account missing data (De'ath and Fabricius 2000). Trees were constructed in CART Pro v. 7.0 (Breiman et al. 1984; Steinberg and Colla 1997; Steinberg and Golovnya 2006). Series of 50 cross-validations were run and the modal (most likely) single optimal tree was chosen for description. Ten-fold cross-validation was used to choose the optimal tree based on the one-SE rule (Breiman et al. 1984). The optimal tree was presented graphically, with the root standing for undivided data at the top, and the terminal nodes, describing the most homogeneous groups of data, at the bottom of the hierarchy.

One-way ANOVA was used to test for the significance of the effect of life forms on impact scores and Tukey's HSD test for post hoc testing of the differences among particular life forms.

Results

Availability of information on impacts

The 128 species studied belong to 94 genera and 51 families. In total, 358 publications and 20 fact sheets from web sites (NOBANIS, ISSG, USDA and AGRIC) were used (in appendix S2 are shown only unique references for impact values) to assign 450 scores to the species. From these species, 55 and 29 are native to North and South America, respectively, 27 to Asia, 20 to Africa, 13 to Central America and seven originate from Australia. In terms of life history and life form, the data set included 37 perennial herbaceous plants, 34 annual herbaceous plants, 20 shrubs, 18 trees, seven aquatic plants, eight vines, seven perennial grasses and four annual grasses. Note that the totals exceed the number of species as some are assigned to several geographical regions based on their native ranges and life histories.

We did not find any information on environmental and socioeconomic impacts for 27 and 32 species, respectively. Therefore, these species were not included in the analyses. Only one species in each group, *Elaeagnus commutata* for environmental (category 1.3), and *Echinocystis lobata* for socioeconomic impacts (category 2.1) was assessed but zero impact found. This resulted in 101 species that were reported to have at least some environmental and 96 with reported socioeconomic impacts, i.e. 79 and 75 % of the total number of species assessed, respectively (Table 1).

The sum of species maximal impacts across all categories in both groups were not correlated with the number of studies on the species recorded on the Web of Science ($r = 0.086$, $df = 126$, $p = 0.336$). This indicates that the probability of recording a high impact does not increase with research intensity.

Species with the greatest potential impacts

Environmental and socioeconomic impacts can be combined as the scores in the two impact groups are correlated across species (see below). *Lantana camara*, *Eichhornia crassipes*, *Elodea canadensis*, *Crassula helmsii*, *Fallopia japonica* and *Heracleum mantegazzianum* are the top six European invaders, with overall potential impacts exceeding one third of the possible sum of scores (Fig. 1).

In terms of categories, representing different mechanisms of environmental impact and socioeconomic sectors affected, competition with other species (category 1.3) was the most frequent among the environmental impacts, recorded in 84 species (83 %) of the total species with impact). Impact on human health (category 2.5) was the most often recorded among socioeconomic impacts, with evidence found for 74 species (78 %). Some of the impacts are rarely recorded, namely transmission of diseases (category 1.4, 11 %) and hybridization with native species (category 1.5, 16 %) among environmental, and impact on forestry production (category 2.3, 7 %) among socioeconomic impacts (Table 1).

Regarding the magnitude of impacts, environmental impacts were strongest on competition and ecosystem functioning. The scores in categories of socioeconomic impacts were generally of similar magnitude, with competition and ecosystem impact being the highest (Fig. 2).

Correlation between the total impact of a species and the number of regions it occupies was not significant ($r = -0.152$, $t = -1.667$, $df = 118$, $p = 0.098$) revealing that widespread species do not have a stronger impact than those with (currently) a restricted distribution. This correlation was significant neither for environmental nor socioeconomic impacts ($r = -0.183$, $t = -1.8474$, $df = 99$, $p = 0.068$; and $r = 0.068$, $t = 0.653$, $df = 94$, $p = 0.516$, respectively). However, there was a significant correlation between environmental and socioeconomic impacts of a given species ($r = 0.279$, $t = 2.499$, $df = 74$, $p < 0.05$).

The effect of species traits

Only life history was correlated with impact when the optimum regression tree for maximal environmental impact was used to identify the relevant traits among the whole suite of traits considered. The tree had two terminal nodes, with plant longevity as the split (Fig. 3a). Annual plants had lower impact than perennials. The regression tree for socioeconomic impact had two terminal nodes and indicates that aquatic plants have on average a considerably higher impact than other life forms (Fig. 3b).

As regression trees indicated that the only biological traits affecting the impact scores were those related to life form, we tested the differences in impacts with respect to this trait using the sum of impacts. There was a significant difference (one-way ANOVA; $F = 3.443$; $df = 5, 95$; $p < 0.01$) in environmental impacts (Tukey HSD) for only vines and aquatic plants (difference: 1.6; $p = 0.054$; Fig. 4a). For socioeconomic impacts, the differences were among the following life histories, at a lower significance level than for their environmental impact ($F = 3.073$; $df = 5, 90$; $p < 0.05$): aquatic plants had higher sums of economic impacts across categories than terrestrial herbaceous plants (difference: 1.4; $p = 0.004$) and trees (difference: 1.5; $p = 0.009$) (Fig. 4b).

Discussion

Plant invaders with the greatest impacts in Europe: What do the measures tell us?

For more than 75 % of alien plant species that are currently widespread in Europe there is some information on impact reported in the literature. This is linked with another finding of this study, that once the impact of an alien species of plant is studied, some level of impact is likely to be detected. For only two species in each group, environmental and economic, were impacts studied but not found. Although it might also reflect, at least to some extent, that species are selected for study in which a significant impact is a

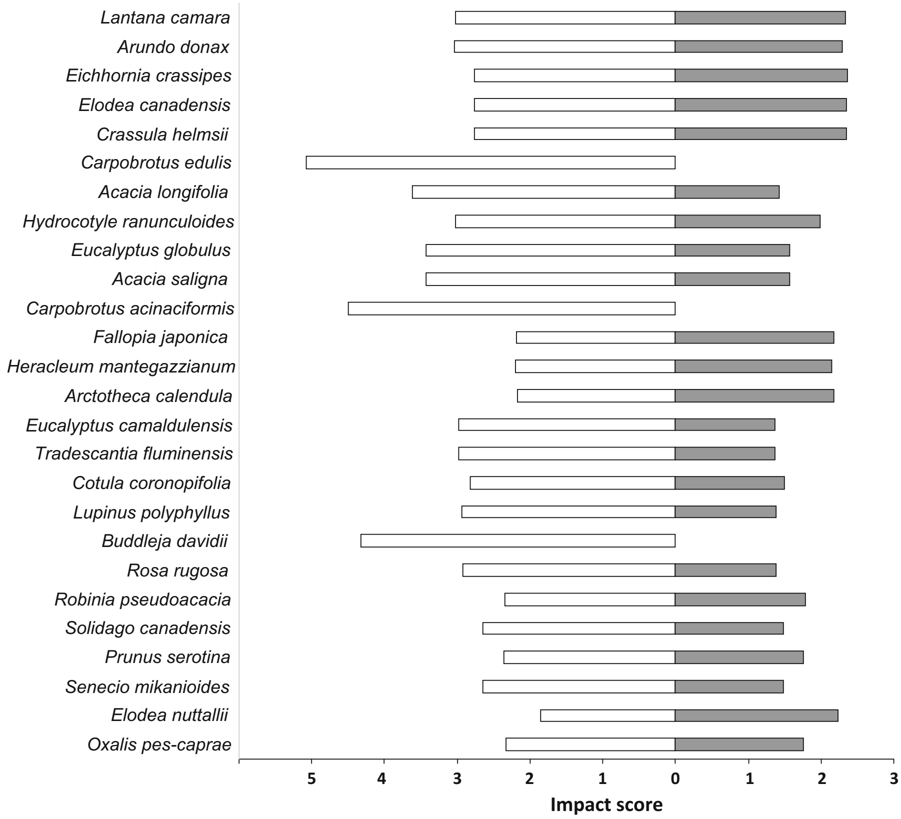

Fig. 1 Top 26 alien species ranked according to decreasing logarithmic sum of all impact scores across categories of environmental (*white bars*) and socioeconomic (*grey bars*) impacts

priori expected (Hulme et al. 2013), overall it supports recent suggestions that alien species, once established, are very likely to have some impact (Ricciardi et al. 2013; Blackburn et al. 2014).

We did not find a correlation between the number of regions occupied by an alien plant and the total sum of its impact scores. The top three species with the highest impact (*Lantana camara*, *Arundo donax* and *Eichhornia crassipes*) are present only in 13, 17 and 11 regions, respectively (out of a total of 86). Of the top three species in terms of distribution (*Elodea canadensis*, *Galinsoga parviflora* and *Conyza canadensis*, present in 58, 45 and 44, respectively) the latter two have moderate average impacts of 3 and 3.5, and only *Elodea canadensis* has a massive impact.

The significant correlation between environmental and socioeconomic impacts indicates that the species with a high environmental impact have specific traits (life form being the most important in our analysis) that are also associated with a high economic impact, such as the aquatic life form in e.g. *Elodea canadensis* or *Eichhornia crassipes*. There are also species with a high environmental but low or no socioeconomic impact (e.g. *Carpobrotus edulis* or *Acacia saligna*).

The total logarithmic sum for both groups provides a robust measure for identifying species with the highest overall potential impacts in Europe, with *Lantana camara*, *Eichhornia crassipes*, *Elodea canadensis*, *Crassula helmsii*, *Fallopia japonica* and *Heracleum mantegazzianum* at the top of the list. Still, the lists of 24 species with highest environmental and socioeconomic impacts differ, and only nine species are on both lists (Table 2), underlining the importance of measuring both impact groups. The sum of scores captures the species' summary impact and its overall magnitude, and may thus provide robust information for prioritization at country scale (in terms of legislative support and financial resources) as well as a basis for management or inclusion in international prevention systems. Possibility of using the maximal score instead of the sum of scores would be in accordance with the recently proposed scheme for the classification of alien species based on the magnitude of their environmental impacts where the assignment of a

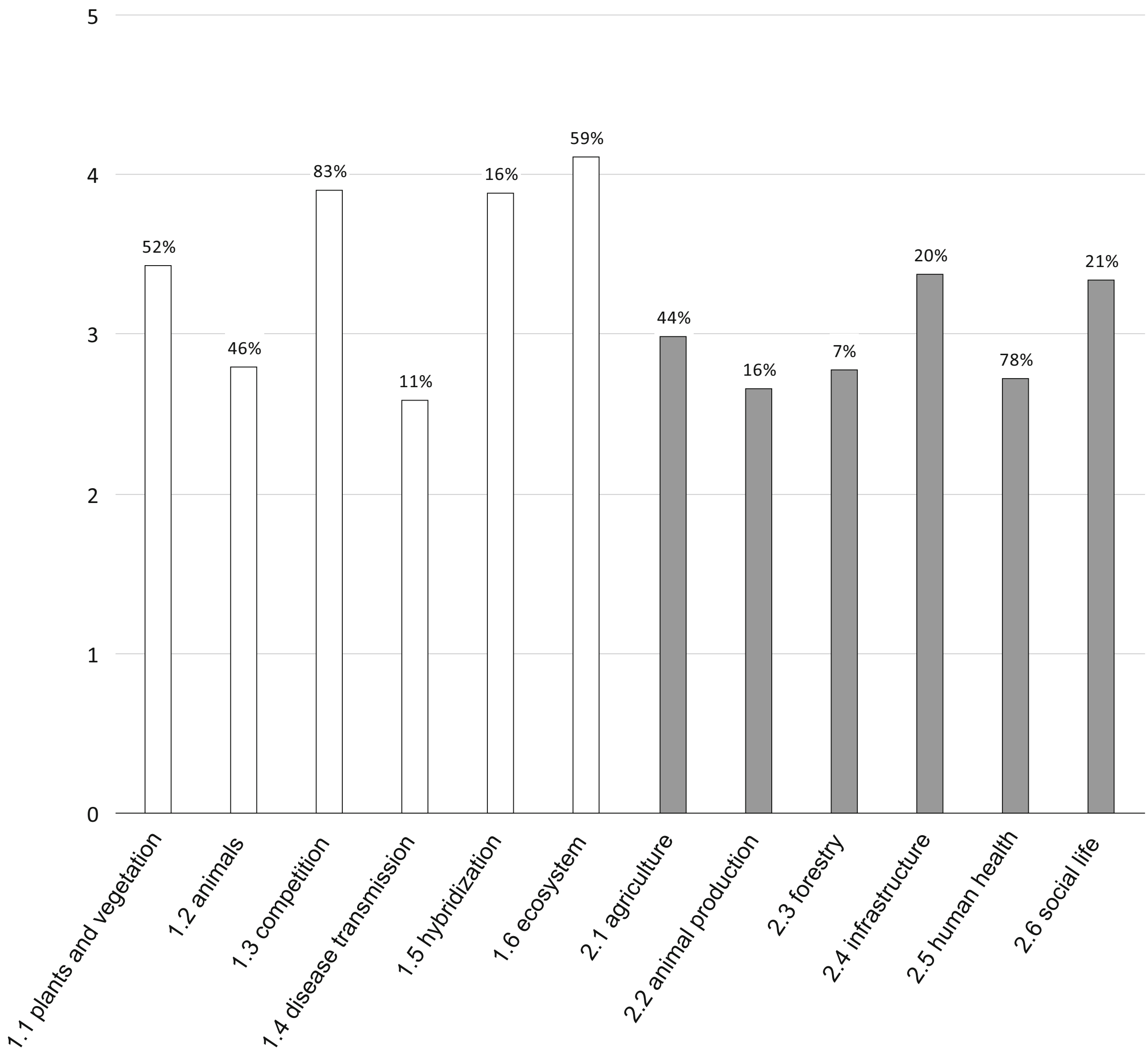

Fig. 2 Mean impact (based on the logarithmic maximal scores per species) for categories of environmental (*white bars*) and socioeconomic (*grey bars*) impacts. The percentages of cases (species) with recorded impacts (from species screened) is indicated above the *bars*

species corresponds to the highest level of deleterious impact associated with any of the impact categories (Blackburn et al. 2014).

Using a GISS classification system to compare the results based on scoring with other existing information systems in Europe provides standardized and science based method for prioritizing management. For example, only six out of the 24 top species in terms of environmental impact are listed among the most harmful plant species in European protected areas (Pyšek et al. 2013). The comparison with harmful species in protected areas also shows that the GISS system is better at identifying a wider range of species than those based on personal or expert opinions.

Potential and actual impacts

Our using GISS was motivated by the need for an information base for predicting the impacts of plant invasions in Europe. This information system can be used for risk assessment, where the potential impact of a species should be the most important basis for the

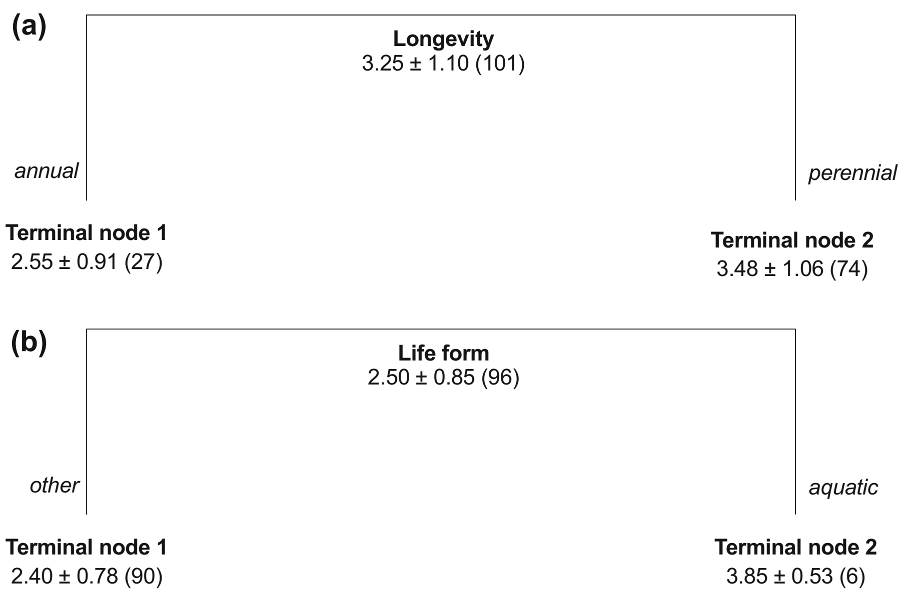

Fig. 3 Regression tree analysis of environmental (**a**) and socioeconomic (**b**) impact screened for 128 species of alien plants in Europe. For each split and node the average value of the maximum (logarithmic) scores of impacts, standard deviation and number of samples (species) is shown

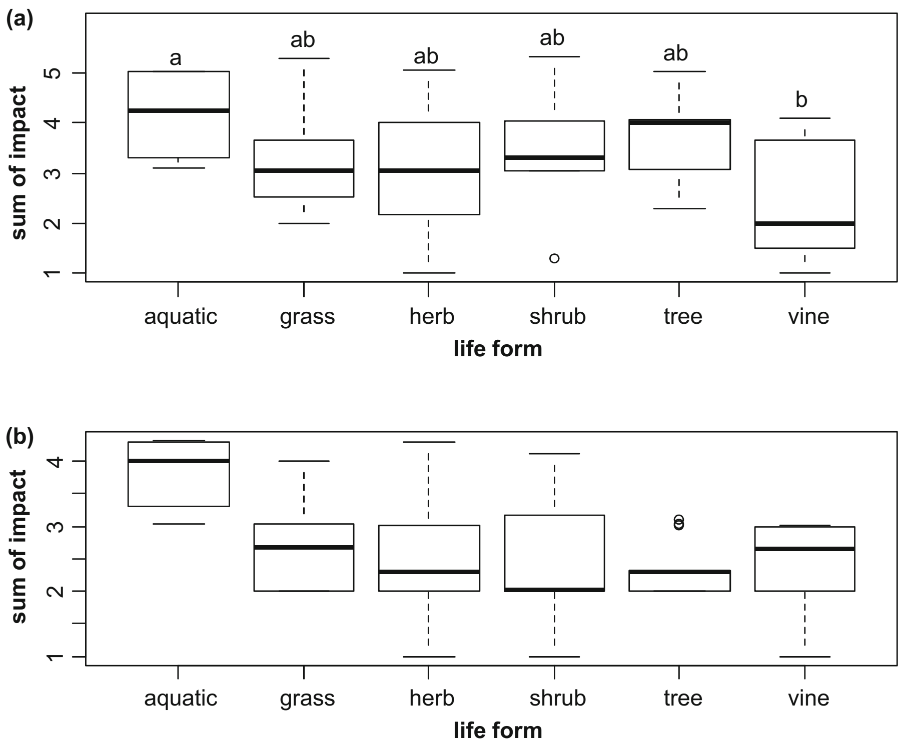

Fig. 4 Comparison of environmental (**a**) and socioeconomic (**b**) impacts for 128 alien species of plants in terms of their life forms and based on sums of impacts. Significant (**a**) $p < 0.01$, differences are marked with *different letters. Median, quantiles, minumum and maximum are shown*

decision, for example for black listing or whether or not to allocate resources for its management (Pergl et al. 2016). That impacts of plant invasions have been rigorously studied only in the last decade or so has two important consequences: the research still suffers from serious biases and information on the impacts of many species is not yet available (Pyšek et al. 2012; Hulme et al. 2013). This lack of information means that there is not enough data to assess the impacts of the species studied specifically for Europe. It is thus currently necessary to use all the information available on the impacts of a species from throughout its invaded

Table 2 Alien species ranked according to decreasing sum (logarithmic) of values across environmental and socioeconomic impacts. *Per.* – *perennial*

Environmental impact						Socioeconomic impact					
Species	Environ. impact	Total impact	Life form	No. of Publ.	No. of regions	Species	Socioecon. impact	Total impact	Life form	No. of Publ.	No. of regions
Lantana camara	5.32	5.35	Shrub	282	13	*Eichhornia crassipes*	4.32	5.05	Aquatic	263	11
Arundo donax	5.30	5.32	Per. grass	84	17	*Crassula helmsii*	4.30	5.05	Aquatic	9	17
Carpobrotus edulis	5.08	5.08	Per. herb	48	22	*Elodea canadensis*	4.30	5.05	Aquatic	69	58
Eichhornia crassipes	5.05	5.12	Aquatic	263	11	*Lantana camara*	4.11	5.32	Sh rub	282	13
Elodea canadensis	5.05	5.12	Aquatic	69	58	*Fallopia japonica*	4.05	4.08	Per. herb	94	36
Crassula helmsii	5.05	5.12	Aquatic	9	17	*Arctotheca calendula*	4.05	4.04	Ann. herb	23	14
Acacia longifolia	5.04	5.04	Tree	71	10	*Heracleum mantegazzianum*	4.01	4.08	Per. herb	87	25
Eucalyptus globulus	5.01	5.01	Tree	104	13	*Arundo donax*	4.00	5.30	Per. grass	84	17
Hydrocotyle ranunculoides	5.01	5.02	Aquatic	17	12	*Elodea nuttallii*	4.00	3.32	Aquatic	40	26
Acacia saligna	5.01	5.01	Tree	71	15	*Abutilon theophrasti*	4.00	None	Ann. herb	594	34
Carpobrotus acinaciformis	4.49	4.49	Per. herb	4	14	*Ambrosia artemisiifolia*	3.32	3.48	Ann. herb	301	33
Eucalyptus camaldulensis	4.34	4.34	Tree	77	11	*Conyza canadensis*	3.32	3.08	Ann. herb	205	44
Tradescantia fluminensis	4.34	4.34	Per. herb	18	15	*Cyperus eragrostis*	3.32	3.00	Per. grass	2	20
Cotula coronopifolia	4.32	4.33	Per. herb	1	24	*Ricinu s communis*	3.32	2.30	Ann. herb	76	33
Lupinus polyphyllus	4.32	4.32	Per. herb	16	30	*Hydrocotyle ranunculoides*	3.30	5.01	Aquatic	17	12
Buddleja davidii	4.32	4.32	Shrub	27	23	*Ambrosia trifida*	3.30	3.33	Ann. herb	71	25
Rosa rugosa	4.31	4.31	Shrub	22	28	*Opuntia maxima*	3.30	3.32	Shrub	4	10
Solidago canadensis	4.11	4.12	Per. herb	81	36	*Robinia pseudoacacia*	3.11	4.08	Tree	103	42
Senecio mikanioides	4.11	4.12	Vine	2	12	*Datura stramonium*	3.08	3.04	Ann. herb	201	40

Table 2 continued

Environmental impact						Socioeconomic impact					
Species	Environ. impact	Total impact	Life form	No. of Publ.	No. of regions	Species	Socioecon. impact	Total impact	Life form	No. of Publ.	No. of regions
Heracleum mantegazzianum	4.08	4.35	Per. herb	87	25	*Paspalum distichum*	3.05	3.05	Per. grass	18	26
Fallopia japonica	4.08	4.37	Per. herb	94	36	*Prunus serotina*	3.04	4.08	Tree	86	24
Prunus serotina	4.08	4.12	Tree	86	24	*Oxalis pes-caprae*	3.04	4.05	Per. herb	39	22
Robinia pseudoacacia	4.08	4.12	Tree	103	42	*Lagarosiphon major*	3.04	3.48	Aquatic	30	14
Myriophyllum aquaticum	4.05	4.05	Per. herb	44	17	*Amorpha fruticosa*	3.04	3.04	Shrub	16	17

Within the same impact value, species are ranked based on the total sums of impacts (total impact). To make the data in the table comparable with ranking in Fig. 1, the same number of top 24 species are shown. Also shown are the life form, research intensity expressed as the number of publications dealing with the species identified by WoS search (No. of publ.), and number of regions in Europe in which the species is reported to occur in the DAISIE database (No. of regions)

range. However, using information from throughout the invaded ranges to score the impact must be done with caution because species invade different communities with different environmental conditions, which will affect the magnitude and type of impact of these species; such differences can be inferred from comparing studies on the impact of the same species from different environments (Greenwood and Kuhn 2013; Rückli et al. 2013). In general terms, this phenomenon has been demonstrated by Brewer and Bailey (2014) who investigated differential impacts within and among multiple alien species in relation to invaded communities and associated environmental conditions. These authors found that the impacts were more likely to be associated with undisturbed rather than disturbed habitats, and were greater in habitats with low soil fertility.

Bearing these issues in mind and the fact that we considered the highest impact recorded (as suggested by Blackburn et al. 2014) when there were multiple reports in the literature from different regions, the impacts summarized in this study need to be considered as 'potential'. Such an approach, based on information on impact from the whole of the invaded range of a species rather than only Europe, has another large-scale implication; the results are valid not only for Europe but also globally. Using data from the whole alien distribution range also helps to overcome the problem of the lack of information for specific regions; Europe in our case. The rather scarce data for the scored species from Europe alone also prevented us from rigorously comparing the impact scores for Europe with those in other parts of invaded ranges of the species studied.

When inferring the 'actual' impact from the 'potential' impact quantified by this scoring system, one needs to take into account the distribution and abundance of the species (Nentwig et al. 2010) and consider the fact that alien plant impacts are shaped by environmental conditions and cannot be assumed to be similar across an entire species range (Hulme et al. 2014). This is illustrated by *Lantana camara*, the species with the highest sum of scores in our database. The high impact score for this species is mainly due to studies conducted in Australia, where it is widely distributed and among the most serious invaders of this continent (Bhagwat et al. 2012) but in Europe it has a high impact only in the Mediterranean region (http://www.europe-aliens.org), to which it is confined. Possibly the species has not spread into other parts of Europe due to climatic constraints. Thus, despite its high score, it is not potentially the most dangerous species in Europe other than in a few Mediterranean countries, but may become more dangerous in the future within a climate change scenario.

Species traits and mechanisms of impact

Globally, some species traits, namely life form, height and type of pollination, are related to the probability that a species will have a significant impact in areas it invades (Pyšek et al. 2012). Our results also indicate that in terms of biological traits the severity of the impacts of alien plants in Europe can be linked to their life form and life history: perennial plants are more likely to have stronger environmental impacts than annual species. The positive effect of the invader's longevity could be associated with the greater likelihood of perennial species, including trees and shrubs, to exert a long-term impact in areas they invade. Different life histories of aliens (perennial vs. annual) and the magnitude of their impacts need to be considered when drawing conclusions. For example, invasive perennial plants replacing native annuals might have an impact of different magnitude as succession proceeds, compared to annual invasive plants replacing native annuals. Strong impacts, both environmental and socioeconomic, are associated with an aquatic life form. Aquatic ecosystems are specific in that every change in environmental conditions, e.g. shading of water surface, can severely impact other water organisms (Dodds 2002). The socioeconomic impact of aquatic plants is mainly on human infrastructures, where they compromise dams, reservoirs and river channels, which result in great economic losses (e.g. Oreska and Aldridge 2010). The awareness of the high impacts of aquatic alien species (see also Brundu 2015) is reflected in the efforts of e.g. EPPO, who provide lists of species prioritized for eradication, which include several aquatic invaders (https://www.eppo.int/INVASIVE_PLANTS/ias_lists.htm#A1A2Lists).

This study provides some insights into the mechanisms by which plant species impact an invaded ecosystem. The most common mechanism is competition, which was recorded in 75 % of the cases studied and commonly occurs between alien and native species (e.g., Daehler 2003). Competition between alien and native species underlie changes in plant communities and/or ecosystem functioning, such as decreases in species diversity or changes in ecosystem production (Levine et al. 2003; Liao et al. 2008). Among other mechanisms known to have an impact, hybridization is quite common between some alien and native plants (Daehler and Carino 2001), and can increase a species' invasiveness (Vilà et al. 2000), but this is only reported for 13 alien species. Our data, however, do not allow us to distinguish whether hybridization between alien and native plants is understudied, or its existence does not automatically mean that native species are seriously impacted.

Conclusion

The use in this study of GISS, which was previously applied to various groups of alien organisms in Europe (Kumschick and Nentwig 2010; Nentwig et al. 2010; Kumschick et al. 2012, 2015a, b; Vaes-Petignat and Nentwig 2014), indicates that it can also be used to rigorously assess the impacts of plants. Extending the assessment to plants, the most numerous taxonomic group with alien organisms in Europe (Lambdon et al. 2008; DAISIE 2009; van Kleunen et al. 2015), is an important step towards providing managers and policymakers with a robust tool for identifying and prioritizing species for allocating resources for prevention and control. In this study we scored the impacts of widespread alien species of plants in Europe, which provides information that can be used in risk assessments of problematic species. Rigorous risk assessments are a necessary prerequisite for correctly implementing the recently approved regulation on invasive alien species in the European Union (Official Journal of the European Union on November 4th, issue L 317/35, Regulation 1143/2014; Genovesi et al. 2015). The scoring system used in this study (Nentwig et al. 2016), and other schemes currently being developed such as EICAT (Blackburn et al. 2014; Hawkins et al. 2015) can, however, be used as an early warning tool, by focusing on species that have a high potential impact but are not yet widespread in Europe because they arrived only recently or are restricted in their distribution by factors, such as climate, which may change in the future.

A further step in applying the GISS scheme could be to use less widespread species, or those that are important only regionally, to assess their impact scores at a spatial scale that is most relevant for management. Assessing species by their impact categories, which are specific mechanisms for generating impacts, facilitates more flexible management. By obtaining more definite information on the type of impact an invasive species is likely to have, management authorities can scale their response to the variation in impact severity and specificity, depending on local environmental conditions. GISS can be applied regionally simply by considering only those species that occur (or could arrive) in a given country or region. For management it is important to remember that impact is context-dependent and when decisions are made at a regional scale, they need to be based on information that relates to that scale. For particular species, the general patterns can be then verified, and regionally specific patterns identified, on a national scale.

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