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REVIEW

A review of impact assessment protocols of non-native plants

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Abstract Impact assessment protocols (i.e. scoring systems) for non-native species have been developed and implemented relatively recently, driven by an increasing demand for desk study approaches to screen and classify non-native species, considering their environmental and socio-economic impacts. While a number of impact assessment protocols have been developed, there are no clear guidelines to help researchers, environmental practitioners and policy-makers understand their differences, uses and limitations, and to ultimately assist in the choice of protocol and practical implementation. In this review, we compare the main structure of 26 impact assessment protocols used for non-native plants. We describe these protocols in terms of the impact types that they include, the way in which impacts are categorized and ranked, how uncertainty is considered, and how the overall score is calculated. In general, environmental impacts are included more often than socio-economic impacts. Impacts are rated by estimates of the intensity, extent, persistence and reversibility of the impact. Uncertainty is mainly estimated by the availability and quality of the scientific information, but also by the agreement and

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relevance of the available evidence on impacts beyond the region in which the impact is assessed (including the assessment of climatic similarity with other invaded areas). The final impact score is usually calculated as the sum of scores, the maximum score achieved across all impact types, or a rule-based aggregation of impacts in order to provide a final rank of the non-native species. We finally indicate issues related with transparency, redundancy, clarity, friendliness, scope, scaling, reproducibility and flexibility as key challenges for impact assessment improvement.

Keywords Decision-making · Environmental impacts · Risk analysis · Scoring system · Socio-economic impacts · Uncertainty

Introduction

Risk assessment protocols (i.e. scoring methods) for non-native species are scientific evidence based studies that support policy-makers in their decisions regarding the management of such species (Andersen et al. 2004). They evaluate the likelihood of non-native species to invade and cause harm in a defined area (Lodge et al. 2016; Vanderhoeven et al. 2017). Risk assessments are usually divided into four "components" that consider the potential for a non-native species to enter a region, establish, spread and cause impacts (Leung et al. 2012; Roy et al. 2017). This review focuses on the impact component (i.e. impact assessment), which is often the key to inform decisions on management and policy.

Here, we define impact as any significant change in the magnitude and direction of an environmental or a socio-economic pattern or process brought about by biological invasions (Jeschke et al. 2014; Ricciardi et al. 2013). For plants, the most studied environmental impacts include decreases in native species diversity and alterations in nutrient cycling (Vilà et al. 2011). However, there is a growing concern about impacts on economies and society such as losses in crop yields, damage to infrastructure, diminished water resources, and many other alterations of ecosystem services and human well-being (Vilà and Hulme 2017a).

The full magnitude of the impact of a particular species in an area depends on its distribution, local abundance and *per-capita* effect (Parker et al. 1999). However, despite quantitative attempts to integrate several impact metrics into a single function (Barney et al. 2013), accurate quantitative assessments of impact are difficult to estimate and scale-up for three major reasons: (1) detailed information of all impacts is often lacking, (2) impacts are strongly context-dependent, and (3) impacts are usually measured at the local scale (Ricciardi et al. 2013). For instance, most of the evidence on the impacts of non-native plants comes from case studies conducted at small spatial scales such as control *vs.* invaded field plots, or greenhouse experiments with and without the non-native species of interest (Kumschick et al. 2015), considering only a few impact types at a few sites (Hulme et al. 2013). Therefore, there is a need for systematic impact assessment protocols that synthesize data on impact from disparate scientific studies, help identifying and prioritizing which non-native species might cause the most harm, and consider the relevance of extrapolations made from local-scale studies to other areas of interest.

There are many circumstances in which impact assessments are more appropriate to use than risk assessments. First, the list of non-native species that should be ideally assessed is often very long, whereas resources devoted to environmental management are limited. Because risk assessments are time-consuming, a preliminary prioritization of species that represent a future threat is often necessary and can be achieved by assessing their impacts through, for example, horizon scanning (Roy et al. 2014).To assist the implementation of the EU legislation, Carboneras et al. (2018) used quick impact assessments to rank 900 non-native species as potential candidates for listing, prioritizing 207 of them for a more comprehensive risk assessment. Second, impact assessments are also carried out in situations where the species to score and rank are already widespread within the region under assessment, to optimize the use of resources for management. For example, the Generic Impact Scoring System (GISS) has been recently used to identify 149 of the "worst" invasive species in Europe from a pool of 486 species (Nentwig et al. 2018). Finally, impact assessments can also be used to allow or ban the introduction, commercial use and import of species classified into "white" and "black lists", respectively (Burgiel and Perrault 2011). Such listing of species approach has also been implemented for already present non-native species within a country (e.g. Branquart et al. 2009 for Belgium; Essl et al. 2011 for Austria; Faulkner et al. 2014 in South Africa).

Many impact assessments are conducted by environmental administrations as desk studies; and they are fundamental for conservationists, environmental managers and policy-makers to prioritize efforts for preventing, monitoring, controlling and eradicating non-native species (Gallardo and Aldridge 2013). A review of impact assessment protocols is therefore needed to better understand the characteristics, uses and limitations of current protocols, which have been developed under different contexts and with different objectives. Such understanding is essential for new assessors to select the most appropriate protocol to their needs.

Here, we provide an overview of 26 impact assessment protocols used for non-native plants. We describe their structure and application, and we also provide guidance to developers of impact assessment methods. We focus on plants as they are known to be the most species-rich group of established non-native species worldwide (Olenin and Didžiulis 2009; Seebens et al. 2017), whose impacts have been relatively well-studied (Vilà et al. 2010, 2011). Furthermore, the largest number of impact assessment protocols has been developed for this taxon (Leung et al. 2012). Thus, generic insights gained from using this model taxon will be informative for other taxa as well. Specifically, we describe impact assessment protocols in terms of (1) considered impact types, (2) scoring used to rate impacts, (3) evaluation of uncertainty, and (4) calculation of a final impact score *per* species. We also highlight the main challenges inherent within impact assessment protocols, and suggest ways for improvement to make them more accessible to practitioners.

Selection of impact assessment protocols

To achieve representation across a range of impact assessments, we compiled a list of protocols that have been used for plants collated by Randall et al. (2008), Leung et al. (2012) and Roy et al. (2017), and supplemented it with the Web of Science, searching the terms "(risk assessment OR impact assessment) AND (plant invasions OR non-native plant OR alien plant) AND (environmental impact OR socioeconomic impact OR ecological impact)". However, we must note that many impact assessment protocols used at the national level or by different agencies are not accessible through open sources or they are published in other languages than English.

We identified all risk assessment protocols that had a component of impact from the retrieved 169 documents. We discarded papers on quantitative predictive models of impacts because our focus was on scoring methods that can be used by non-academic practitioners, without the need of further field or experimental data (see the distinction between both approaches in Leung et al. 2012). When a protocol was applied in multiple regions with minor modifications, we only considered the original publication describing the methodology. We also realized that numerous versions of the same protocol have been circulated as papers indexed in the Web of Science, the grey literature, booklets, internet pages, etc. In these cases, we selected the most widely used reference. From each protocol, we extracted information on: the geographic and taxonomic scope; whether it focuses on impact exclusively or includes risks on other invasion stages (entry, establishment, spread); impact types examined, how impacts are rated and final scores calculated, and if uncertainty is considered. We did not include protocols that lack a description on how impacts are rated, and final scores calculated. For each reference, the total number of citations in Google Scholar was calculated as an estimation of its popularity (Appendix I of Electronic supplementary material). While our review may have overlooked protocols that have not been published in journals indexed in the Web of Science or are not readily available online, we believe that it is a valid representation of the range of protocols used by researchers and managers to assess the impacts of non-native plants.

In total, we identified 26 protocols: eleven are applied to specific countries, while the others have a regional or global scope. Sixteen are specific for plants, two for aquatic organisms, and eight were designed for a wide range of taxa. Most protocols are part of more comprehensive risk assessments including risk of establishment, spread, and some even assessing management success (e.g. Hiebert and Stubbendieck 1993). Protocols assessing impacts exclusively have appeared over the last decade, mainly as quick-screening tools to prioritize non-native plants (e.g. Brunel et al. 2010), or for ranking the species by their impact and establishing black lists of non-native species (e.g. Blackburn et al. 2014).

Structure and content of impact assessment protocols

Which environmental impacts are assessed?

The number of questions of the impact assessment protocols ranged from only one to 24 (Appendix I of Electronic supplementary material). These questions addressed environmental impacts more frequently than socio-economic impacts (mean ± S.D. = 5.65 ± 4.06 environmental questions, mean ± S.D. = 3 ± 2.91 socio-economic questions; paired t-test = 3.46, $P = 0.002$). Environmental impacts can be classified by impacts to different levels of ecological organization, that is, impacts to populations and species, communities and trophic interactions, and ecosystems (Pyšek et al. 2012) (Table 1).

The most common assessed environmental impact of non-native plants on other species is the displacement and decline of native species (Table 1). Moreover, half protocols specifically include a question on the displacement of vulnerable or rare species (Kenis et al. 2012; Koop et al. 2012; Morse et al. 2004; Parker et al. 2007; Sandvik et al. 2013). This information is useful for concurrent prioritization of native species of conservation concern and the control of non-native species. For example, Miller et al. (2010) provide an assessment tool to quantify the impact on rare plant species in Nebraska (USA). This assessment accounts for the extent of habitat types of concern, the consequences of the non-native present, and the degree of rare and endangered species occurring in these habitats.

With regard to impacts on communities, a decline in native species diversity is usually included in protocols as one of the most frequently investigated impacts in the literature (Vilà et al. 2011). Sometimes the questions focus on undesirable non-native plant traits that can interfere with the resident vegetation, for example by climbing or overtopping, because these features imply non-native species dominance that modifies the vertical and horizontal vegetation structure.

Changes in the trophic interactions by non-native plants require scientific information on modifications of mutualistic interactions such as pollinators, seed dispersers or soil microorganisms (Table 1). This impact type might overlap with the question on native animal displacement (e.g. by reduction of nesting sites), and can thus be double-counted (Table 1).

In general, despite the high variety and large extent of ecosystem impacts that non-native plants can cause (Vilà et al. 2011), they often have less weight in protocols than impacts on the biota (e.g. Blackburn et al. 2014). Impacts on ecosystem processes and patterns are considered but with only a few questions (Appendix I of Electronic supplementary material, Table 1), normally focusing on physical or chemical alterations that can be supported by a large variety of variables related to many ecosystem processes, from primary production to nutrient and water cycling. Changes in disturbance regimes are often included but mostly limited to a specific question, usually about changes in fire hazard and erosion. Modification of succession is sometimes considered, but difficult to assess because the effect of the non-native species on succession can be confounded by the effects of disturbance driving invasion. Nevertheless, changes in succession can be inferred by temporal vegetation changes.

Finally, there is increasing interest in the impacts of non-native plants on ecosystem services (Vilà and Hulme 2017a). Some recently developed impact assessments explicitly assess the impact on ecosystem services (EFSA 2011, D'Hondt et al. 2015). In some cases, there are clear proxies to evaluate impacts on ecosystem services, e.g. impacts on carbon sequestration and biomass production can be used as proxies for impacts on climate change; litter production and litter depth can be proxies for erosion control. Although many regulating and cultural services are difficult to quantify, there are novel unconventional approaches that allow for such assessments. For instance, the influence of non-native species on cultural services has been recently assessed by considering the presence of non-native plants in postcards and touristic guides as proxies for their impacts on recreation and ecotourism, respectively (Vaz et al. 2018).

Which socioeconomic impacts are assessed?

Seventy-two percent of impact assessment protocols contained questions on socio-economic impacts, although the number of questions (from one to ten) was considerably smaller compared to environmental

Table 1 Synthesis of main types of environmental impacts of non-native plants considered in impact assessment protocols, classified into ecological levels of organization (i.e. populations and species, communities and trophic interactions, and ecosystems), variables usually employed in the scientific literature and difficulties of interpretation

Ecological level	Impact types	Variables	Difficulties
Populations and species (77%)	Genetic integrity, interbreeding, hybridization, introgression	Genetic diversity and structure, interbreeding	Confirmation of this impact requires genetic analysis
	Displacement, decline of native species	Native plant cover, survival, seed-set, seedling establishment, animal density, egg production	Differences in fitness do not always translate to species declines
	Harm to vulnerable, rare species	Rare and endemic plant cover, seed set, seedling establishment, animal density, egg production	Most studies do not mention the conservation status of affected species
	Outcompete native plants	Plant size, growth, cover, density-dependent abundance	Can overlap with displacement of native species
	Allelopathy	Seed germination, seedling mortality, secondary compounds of non-natives	Can overlap with displacement of native species
Community and trophic interactions (85%)	Decline of native diversity	Native species diversity, richness, composition	Increases in species diversity is perceived as no impact
	Climbing, overtopping, forming dense thickets, monospecific stands	Horizontal and vertical vegetation cover, relative abundance of non-natives	Can overlap with displacement of native species
	Change structure and composition of vegetation, reduce yield	Plant species diversity and composition, vertical vegetation cover, biomass	Can overlap with declines on native species
	Transference of pathogens, parasites, vector of damaging species	Prevalence and abundance of pathogens, parasites	Can overlap with impact on trophic interactions
	Change trophic interactions	Pollinator and biocontrol organism diversity, activity, composition	Can overlap with displacement of native species
Ecosystems (96%)	Physical modification of habitats or ecosystems	Soil litter content, standing dead biomass, vertical vegetation cover	Can overlap with change in vegetation structure and composition
	Chemical modification of habitats or ecosystems, alteration of soil chemistry	Soil C, N, P pools, ratios and availability, microbial activity, organic matter and litter decomposition	Can overlap with changes in ecosystem functions
	Changes in ecosystem function, processes	Net primary production, soil C, N, P pools, stoichiometry and nutrient availability, microbial activity, OM and litter decomposition, water availability	Can overlap with chemical modifications
	Decline in conservation status of habitats and natural resources	Native species composition, habitat disturbance	Difficult to assess. Can be confounded with decline of vulnerable spcies or native species diversity
	Modification of succession	Temporal vegetation changes and shifts, species turn-over	Difficult to assess. Can be confounded with changes in disturbance regime
	Increase in fire hazard, promotes fire, change in fire regimes, flammability	Fire frequency, area and speed, dead biomass accumulation, plant area/volume, plant tissue quality	Detection of changes in fire regime requires long term monitoring
	Effect on erosion	Sediment or soil loss or accumulation	Empirical evidence requires long term studies

Values in parenthesis are the percentages of protocols with inclusion of impacts on the indicated ecological levels

Table 2 Synthesis of the main socio-economic impacts of non-native plants considered in impact assessment protocols, classified by activity sectors and with examples of corresponding variables examined in the scientific literature

Sector	Impact types	Variables
Agriculture, horticulture and forestry (46%)	Weed in agriculture, reduces irrigation and competes for water, reduces fiber production	Crop production, costs of herbicides, costs of management
Farming (46%)	Reduces animal health and production, toxic or unpalatable to livestock, influences grazing, alters water quality, restricts animal movement	Livestock production, costs of feeding, costs of management
Human health and safety (54%)	Hazard upon contact, allergenic, toxic, reduces food	People injured or intoxicated, allergenicity, spines present
Tourism and leisure (39%)	Limits recreation area and activities, human access and social life, visual impact, affects landscape aesthetics, restricts movement of people	Forms thickets and monospecific stands, decrease number of visitors, costs of removal and restoration
Infrastructure and buildings (31%)	Erosion, interferes with human access and property, damage to cultural sites, restricts movement of vehicles, obstructs water flow and use	Over-cover or form cracks on buildings, clogs pipes, costs of removal and restoration
Commerce and trading (15%)	Lower commodity value, market losses, reduces produce values	Commodity stock and quality

Values in parenthesis are the percentages of impact assessment protocols with inclusion of impacts on the indicated sectors

impacts (Appendix I of Electronic supplementary material, Table 2). Some protocols consider impacts on the economy or society in general in a single question (Ou et al. 2008), but most protocols specify impacts on the agriculture, horticulture, livestock and forestry sectors; human health; tourism and leisure; infrastructure and buildings (e.g. Brunel et al. 2010; Koop et al. 2012; Nentwig et al. 2016). A few protocols also considered impacts on commerce and trading, quantified as decreases in commodity values or market losses (Table 2).

Impacts of non-native plants on agriculture and livestock are widely considered in the protocols. These impacts are described on the basis of whether the non-native species is a weed or unpalatable (Pheloung et al. 1999). Indirectly, non-native plants such as macrophytes interfering with irrigation and water quality can also exert socio-economic influence (Orr 2003). Many protocols refer to animals or grazing in general, and thus the assessor has to identify in the scientific literature whether the non-native plant is affecting wildlife (e.g. deer), livestock (e.g. cows), or both. Surprisingly, impacts on hunting or angling are not explicitly mentioned, although they are considered recreational activities.

The impact of non-native species on human health is of paramount importance (Rabitsch et al. 2017) but considered in less than half of the protocols. These impacts refer to species posing a hazard upon contact, being toxic or allergenic. It is important to bear in mind that some non-native plant species might cause such impacts even if they are not invasive, nor even established in the wild, such is the case of allergenic ornamental plants in urban parks (Nentwig et al. 2017).

Impacts to tourism are considered in many different ways including questions on limits to recreational area and activities, restrictions to the movement of people, and visual impacts affecting the perception of landscape aesthetics (Johnson 2009; Koop et al. 2012; Nentwig et al. 2016; Table 2). For example, the Weed Risk Analysis for Victoria, Australia, has several questions relating to the impact on social values including human access to land, reduction of aesthetics and recreational land-use, being injurious or toxic to people and damaging indigenous or European cultural sites (Benke et al. 2011).

In many protocols, management costs are not included within a specific socio-economic impact question, but are mentioned across all impact types, as a way to score the impact (see next section). For example, in the GISS, impact scores are highest if the impacts are not reversible despite high management costs (Nentwig et al. 2016).

The Socio-Economic Impact Classification of Alien Taxa (SEICAT) is the only protocol focusing exclusively on socio-economic impacts. SEICAT is based on the capability approach from welfare economics (Bacher et al. 2018). The impacts considered in SEICAT are on safety, material and immaterial assets, public health, and social, spiritual and cultural relationships. Currently, SEICAT is at a proof-of-concept stage and has only been applied to non-native amphibians and mammals (Hagen and Kumschick 2018).

How are impacts rated?

The scientific approaches to investigate the impacts of non-native plants include observations or experiments comparing invaded and non-invaded reference sites, before-after invasion, and gradients of the level of invasion by non-native species (Kumschick et al. 2015). The intensity of non-native species impacts can be quantified by the relative increase or decrease of the variable of study in sites colonized by the species compared to the reference state (Ricciardi et al. 2013).

In impact assessment protocols, assessors are usually requested to interpret the published evidence and score each impact type using a binary (e.g. yes/no; Garry Oak Ecosystems Recovery Team 2007) or multiple-level scale (e.g. high, intermediate or low; Brunel et al. 2010), or a mixture of both (Koop et al. 2012). For instance, in the Generic Ecological Impact Assessment for Alien Species in Norway, each impact is classified as severe, high, potentially high, low and unknown (Sandvik et al. 2013). Usually, the "unknown" category is an independent level (Branquart et al. 2009; Morse et al. 2004), but in some protocols it is merged into the "no impact" level, often without guidance on how to tease them apart.

To facilitate scoring, protocols usually provide guidance on how to rate impact, sometimes with explicit values or ranges, and with examples of application for each impact level. For instance, Morse et al. (2004) defines quantitatively the levels of impact on native plants and animals as significantly high (> 50% decrease of individuals), moderate (20–50%), or low (5–20%). Even in such cases, differences between the levels of impact are not precise (Johnson 2009). Moreover, quantitative impact levels are not always desirable because of the lack of studies providing the necessary data, whereas binary or multi-level questions are usually easier to complete with the available evidence.

In some protocols there can be different scales and increments depending on the importance of the impact type considered (Hiebert and Stubbendieck 1993; Miller et al. 2010) and weighting is then inbuilt in the final scoring. A few protocols provide continuous impact levels (e.g. EFSA 2011).

In some protocols the magnitude of a particular impact depends on the significance and intensity of the change in a series of variables (Tables 1 and 2). For example, in the protocol used to rank non-native plants in island ecosystems in Xiamen, China (Ou et al. 2008), the impact on native plant and animal species is split into seven impact subtypes and the rating depends on how many subtypes are affected.

Moreover, impact scoring not only depends on the intensity of an impact, but it also takes into account other criteria of judgement, namely the extent, persistence, reversibility and transferability to similar climates (Table 3). The extent of an impact can be inferred from the spatial coverage of the invader (*sensu* Parker et al. 1999), the number of habitats that the non-native species invade (Warner et al. 2003), and the conservation status of these habitats (Miller et al. 2010). The impact will be highest if the non-native species is widespread across many habitats and/or occurs in high value habitats such as protected areas. The magnitude of the impact can also be dependent on how many native species are affected, the impact being highest if it extirpates several common native species, and lowest if it only reduces the recruitment of some (Morse et al. 2004).

Persistence refers to the frequency, constancy and length of the occurrence of the impact along time. Persistence is important for rating non-native plants that can affect people health (e.g. allergenicity). For instance, the Victorian Weed Risk Assessment in Australia (Benke et al. 2011) classifies non-native species as "high impact" if they cause an impact throughout the year and "medium impact" if they only cause problems at certain times of the year. Persistence can also be indicated by how long the impact lasts. Hiebert and Stubbendieck's (1993) protocol prioritizes species for management and control based on whether they have a long-term or a short-term impact, arbitrarily assigning 10 years as the distinction between both levels. Evidence for the temporal occurrence of impact is highly difficult to collect,

Table 3 Main criteria used in impact assessment protocols to rate the magnitude of the impact of non-native plants with indication of best-case examples

Criteria	Rationale	Best case examples
Intensity	The magnitude of the impact increments with the amount of the change of an environmental or socio-economic property or process	Most protocols (Appendix I of Electronic supplementary material)
Number of impacts	Impact of the species increases if changes occur at several levels of ecological organization, through several mechanism, and/or in different socio-economic sectors	Ou et al. (2008)
Spatial extent	The magnitude of the impact scales up with the area of distribution of the species	GABLIS (Essl et al. 2011), EPPO-PRI (Brunel et al. 2010)
Number and status of affected habitats	The relevance of the impact increases with the species invading different habitat types, and if they are of conservation concern	Morse et al. (2004), Miller et al. (2010), EPPO-EIA (Kenis et al. 2012)
Number and status of affected species	The impact is of higher concern if the non-native affects native species of conservation concern	Warner et al. (2003), Morse et al. (2004), Miller et al. (2010), EPPO-EIA (Kenis et al. 2012)
Persistance	A non-intermittent, long-lasting or permanent impact is highly detrimental	Victorian Weed Risk Assessment Method (Benke et al. 2011), Hiebert and Stubbendiek (1993)
Reversibility	Non-native species can have legacy effects even after removal	Warner et al. (2003), EICAT (Hawkins et al. 2015)
Transferability to similar climate	Species pre-adapted to the climatic conditions in the introduced range will perform very well and cause impacts	GB-NNRA (Mumford et al. (2010), GABLIS (Essl et al. 2011)
Interaction with climate change	Climate change can increase the potential impact of the non-native species	GB-NNRA (Mumford et al. 2010), GABLIS (Essl et al. 2011)

except if long-term studies have been conducted (Yelenik and D'Antonio 2013).

Reversibility refers to the potential of the change to reverse back to the pre-invasion conditions or to some desirable state. For instance, the Environmental Impact Classification for Alien Taxa (EICAT, Hawkins et al. 2015) only scores impact as "massive" when the impact is irreversible. It is well known that some non-native species have legacy effects, especially on soil properties. However, reversibility is highly difficult to evaluate because it requires information on the effectiveness of control and restoration management practices, which are highly context dependent (Andreu et al. 2010).

Finally, the potential impact for non-native plant species that have not fully spread in the area of concern can be forecasted using data from climatically similar regions (Gallardo et al. 2016). Some protocols also include the potential of the impact to increase under climate change if the species fulfils its climatic niche (Essl et al. 2011). However, we still need more research on the potential synergistic effects between invasions and climate change (Walther et al. 2009).

How is uncertainty considered?

There is always uncertainty associated with a risk assessment. Sources of uncertainty can be classified as linguistic, associated with the communication of the procedure to use the risk protocol; stochastic due to unknown variations of the invasion process; and epistemic, that is, on the level of knowledge about the non-native species and/or invaded ecosystem (see Box 1 in Leung et al. 2012).

Stochastic uncertainty is critical when assessing potential impacts in regions not yet invaded or being invaded. It is irreducible and it refers to the spatio-temporal variability in the magnitude of the impact. Scientists are the most familiar with this context-dependency. It is well-known that properties of the recipient environment and the non-native species, as well as introduction history, interact in many different ways influencing impact (Parker et al. 1999; Ricciardi et al. 2013; Vilà et al. 2006). While context-dependency is perceived by the general public and also by policy-makers as a shortcoming (Lodge et al. 2016), it is critical that informed decisions on impacts are made even when there is evidence of high spatio-temporal variability. In general, protocols follow the precautionary approach, favoring the highest impact level in case of uncertainty (e.g. Blackburn et al. 2014; D'hondt et al. 2015; Kenis et al. 2012).

Epistemic or knowledge uncertainty is related to the level of knowledge of impacts caused. For example, the criteria for categorizing invasive non-native plants that threaten wildlands in Arizona, California and Nevada in US (Warner et al. 2003) rate uncertainty for each impact type in the following decreasing semi-quantitative five levels of confidence based on the type and amount of evidence: (1) the available information comes from refereed journals; (2) non-refereed journals and books, proceedings, staff reports and Internet sources citing refereed journals; (3) observations and Internet sources from qualified professionals; (4) anecdotal, third-person experiences, uncorroborated reports and non-expert web-pages; and finally, (5) no information available. Indeed, many protocols request to document the available information supporting the score (Hawkins et al. 2015). It requires years to investigate and publish in peer-reviewed journals the impacts of a particular non-native species. Therefore, in general, knowledge uncertainty is low for non-native species that have been in a specific area for a long time or for well-known non-native species somewhere in the globe, but is high for emerging non-native species for which there is scarce information.

Some protocols integrate elements of both the quality of the evidence (epistemic uncertainty) and agreement among sources of evidence (stochastic uncertainty) following the IPCC framework (Mastrandrea et al. 2011). Several protocols also include extrapolation of the spatial scale of evidence as a source of uncertainty. Assessments based on evidence generated at spatial scales that are much smaller than the spatial scales covered by the assessment are likely to be subject to great uncertainty (Hawkins et al. 2015).

Based on the precautionary principle, many protocols recommend application of a high level of uncertainty when the species is absent in the assessed area. However, uncertainty may be reduced when there is ample evidence on impact in a region that is similar to the region of interest (Nentwig et al. 2017). This "impact elsewhere" criterion is crucial to identify the potential impact of non-native species that have not been introduced yet into the assessed region (Kenis et al. 2012). In various protocols, the species can be classified as "data deficient" if uncertainties are high, following the same principles than for the IUCN species Red List (Blackburn et al. 2014, Hawkins et al. 2015). Similarly, the Environmental Impact Assessment and List Classification on Non-native Organisms in Belgium (Branquart et al. 2009) classifies the species as data deficient when there is insufficient information to score at least one impact type.

It is crucial to account for the assessor uncertainty, i.e. personal biases that affect the evaluation of a species. Results from a study comparing the influence of assessors using 10 different risk protocols revealed substantial differences in species ratings (Gonzalez-Moreno et al. subm.). Some protocols aim to reduce this source of uncertainty by requesting more than one assessor, or making use of an expert panel to reach consensus on a score and moderate across diverging ratings (Mumford et al. 2010; EFSA 2011). Many protocols provide a detailed guidance on how to reduce personal uncertainty (Brunel et al. 2010).

Finally, it is worth stressing that more than 13,000 non-native plant species have naturalized worldwide (van Kleunen et al. 2015), but peer-reviewed information is available for less than 200 of them (Pyšek et al. 2012), with less than ten species comprising one third of the total number of scientific studies published so far (Hulme et al. 2013). Thus, epistemic uncertainty will be likely high for most non-native species irrespective of the protocol. This type of uncertainty can be reduced by advancing the research on the impacts of understudied non-native species. There is also a need to identify the impact types with the highest uncertainty, because this will highlight the impacts that require in-depth quantification across space and time. In particular, we envision high levels of uncertainty on the impacts of non-native plants on cultural services because their evaluation is based on human perception, and therefore highly subjective.

How is the final impact score calculated?

The final impact score of non-native species is usually calculated as the sum of scores, the maximum score achieved across all impact types, or a rule-based aggregation of impacts in order to provide a final rank of the species (Appendix I of Electronic supplementary material). For instance, the EPPO Prioritization protocol (Brunel et al. 2010) uses a categorization matrix to define the final scoring based on the maximum adverse impact and its extent (spread potential *sensu* the protocol). Similarly, GABLIS (Essl et al. 2011) combines the evidence of at least one potential impact with the extent of the species distribution in order to rank the species across three different levels.

It is an advantage if the protocol offers the flexibility to give weighted values to impacts depending on the purpose and context of the assessment. For instance, socio-economic impacts could be weighted based on the relative importance of each sector to the economy in the region of interest. In some protocols weighting of different impacts can be done to calculate the final score (e.g. GISS Nentwig et al. 2016; and HARMONIA + D'hondt et al. 2015).

A few reviewed protocols do not automatically calculate a final score but assessors have to decide it based on scores assigned to previous questions on different impacts and give arguments for their decision. This is the case for the Great Britain Non-native Risk Assessment (Baker et al. 2008) and the Cal-IPC (Warner et al. 2003).

In some risk protocols, an aggregated uncertainty value is also assigned as the final uncertainty score for the non-native species. For example, the Weed Risk Management for North South Wales uses the percentage of "do not know" answers as an indicator of overall uncertainty for each species impact (Johnson 2009). The uncertainty value could be also incorporated into the final impact scoring (Kenis et al. 2012), using a rule-based matrix model such as the one described in Holt et al. (2012). More details on techniques for calculation of final scoring can be found in Heikkilä (2011), Holt et al. (2012) and Leung et al. (2012).

Recommendations to improve impact assessment protocols

Since the pioneering Australian Weed Risk Assessment (WRA) (Pheloung et al. 1999) was developed almost 20 years ago, many new protocols have been published and continue to appear. The diversity of approaches to risk assess the impacts of non-native species is apparent from our review of protocols. Many of them are presented in different formats, for different forums, and as different documents (e.g. book chapters, papers to journals, administration documents, Internet Webpages) with varying degrees of detail. This is perhaps in response to the needs from different end-users and specifically academic, management and policy requirements. Therefore, we highlight the following key issues as challenges for improvement of existing and prospective impact assessment protocols: transparency, redundancy, clarity, user-friendliness, scope, scaling, reproducibility and flexibility (Table 4).

- *Transparency* Protocols have to be transparent, concise and unambiguous about the impact types considered and how to score them. To increase clarity, it is better to disentangle the types of impact into single ecological metrics, rather than integrative variables. For example, several protocols deal with impacts on native ecosystems using a large variety of variables on ecosystems processes. To avoid ambiguity, impacts on native ecosystems should be separated into specific questions addressing at least three processes: soil nutrient cycling, water cycling, and disturbance regimes. The same applies to questions about socioeconomic impacts that do not explicitly state which sectors are affected (Orr 2003) but could be classified as impacts to the socio-economic sectors indicated in Table 2.
- *Redundancy* Protocols should avoid double counting, especially when using the sum as the final score because there is a direct relationship between the number of questions about impact and the risk of double counting. This is the case of questions formulated both as the mechanism and as the outcome (Table 1). For example, in GISS (Nentwig et al. 2016) the impact of invaders on native plants is assessed in several questions based on whether the mechanism is through allelopathy, competition or changes in soil conditions, but many scientific studies do not disentangle those.
- *Clarity* Protocols need to provide clear guidelines and examples on how to answer the questions, how to score the impacts, and how to account for uncertainty. Assessors need to indicate how sure

Table 4 Challenges of impact assessment protocols, their relevance, recommendations for addressing these, and best-case examples

Challenge	Relevance	Recommendations	Best case examples
Transparency	The assessment should be unambiguous and unequivocal on impacts and methods considered	The formulation of phrases and questions has to be consistent. Organize it in sections and subsections by impact types	EICAT (Hawkins et al. 2015), GISS (Nentwig et al. 2016)
Redundancy avoidance	The protocol should avoid double counting	Avoid questions that overlap impact types. Do not mix questions about mechanisms and patterns outcome	GABLIS (Essl et al. 2011), HARMONIA + (D'hondt et al. 2015)
Clarity	The protocol needs to provide concise guidelines to make the assessment straight-forward	Provide a good description of each aspect included in the assessment, examples on how to answer each question and assign scores	EPPO-EIA (Kenis et al. 2012), EICAT (Hawkins et al. 2015)
User-friendly	The protocol needs to be useful for practitioners with different levels of expertise	Training resources, online version or supporting software might facilitate usage	ISEIA (Branquart et al. 2009), EPPO-PRI (Brunel et al. 2010)
Broad scope	The protocol should include a wide range of impacts to screen a wide range of taxa in a wide range of habitats	Has to be comprehensive to allow comparing several taxa. Not restricted to few impacts, taxa or habitats of concern	GISS (Nentwig et al. 2016), HARMONIA+ (D'hondt et al. 2015)
Scaling	Many assessments are based on studies conducted at the local scale and for other regions	Specify the spatial and temporal scale of the impact, and whether the species causes impact in locations with similar climate	GB-NNRA (Mumford et al. 2010)
Reproducibility	It has to contain systematic elements for the protocol to be repeated in another spatio-temporal context	Document the sources of information used. Repeat the assessment at regular intervals	EICAT (Hawkins et al. 2015), GISS (Nentwig et al. 2016)
Flexibility	The protocol has to be subject to further adaptations and improvements	Build it in a modular way to allow for aggregation and updates	GB-NNRA (Mumford et al. 2010), EPPO-EIA (Kenis et al. 2012)

they are on rating the specific impact types, not only when evidence is contradictory or incomplete, but also when the quality of the available evidence is poor (e.g. inadequate sampling design or consideration of interacting factors). Also, protocols should clearly distinguish the categories "no impact" from "unknown impact". The latter refers to a lack of evidence of impact and thus it is a measure of uncertainty, not a measure of the magnitude of impact as in the former case. Protocols that rate impact using a binary (yes/no) response (e.g. Pheloung et al. 1999; Garry Oak Ecosystem Recovery Team 2007) and early developed protocols that did not include uncertainty (Appendix I of Electronic supplementary material) cannot distinguish between these two different answers.

- *User-friendliness* Protocols need to be user-friendly, providing templates and algorithms to reduce the subjectivity of the assessment, especially to assist non-experts. However, in some protocols, rating impacts require statistical expertise. For example, NGEIAAS (Sandvik et al. 2013) developed by the Norwegian Biodiversity Information Center cannot be fully used by practitioners not familiar with the mathematical requirements to rate impact. The same holds for the EFSA (2011) protocol which scores the impacts of non-native species on provisioning and regulating ecosystem services by calculating the probability distributions of impact rates (Gilioli et al. 2017). Training resources, tutorials, and on-line availability in different languages such as those provided by HARMONIA + are particularly useful (D'hondt et al. 2015). The similarity of the protocols rationale to familiar risk assessments in other environmental fields helps for their implementation. For example, EICAT (Blackburn et al. 2014) and SEICAT (Bacher et al. 2018) have taken advantage of protocols for assessing extinction risks from the IUCN Red List, and have used approaches from climate science for assessing uncertainty.

- *Scope* Assessments should include a wide range of impacts and all invaded environments of concern. It is important to consider impacts not only in natural and semi-natural habitats but also in anthropogenic habitats, such as agricultural and urban, because these are the main places of entry and spread for many non-native plant species. For example, aquatic and terrestrial plants differ in their impacts, with aquatic plants generally scoring highest because their impacts on the socio-economy sectors can be important (Gallardo et al. 2016; Rumlerová et al. 2016). Apart from habitats, there is a need for impact assessment protocols to contemplate all socio-economic sectors to identify potential conflicts (i.e. positive *vs.* negative impacts of a given non-native species for different societal sectors). For example, in spite of significant environmental and agricultural impacts, many introduced non-native crabs are perceived as offering new economic opportunities for the fishing and gastronomic sectors (Vilà and Hulme 2017b). Conflicts will be identified, if all socio-economic sectors are evaluated in the same impact assessment, preferably using the same currency.
- *Scaling* Likewise, protocols require scaling procedures. Most of the times assessments are based on studies conducted at the local scale and not in the region of concern. When protocols refer to large areas (e.g. continents) that include several biogeographical regions, it is important to identify which regions have the most suitable climate for the species to cause impact, and which habitats will be the most susceptible to be impacted. Some protocols indicate a time-frame for the impacts to occur in the context of future climate change (e.g. GB-NNRA, GABLIS), but this information is difficult to anticipate for many non-native species for which even the equilibrium distribution under current climate is unknown.
- *Reproducibility* Protocols need to be systematic and reproducible. Impact assessments should allow for reassessments in a different spatial or temporal context. Impact assessments rely on the evidence that is available at the time of assessment, and new scientific evidence may warrant a re-evaluation of risks (Gallardo et al. 2016). As such, prioritized lists should be dynamic and reflect changes in knowledge and management options. Documenting the sources of information, particularly using published scientific literature, is needed to repeat and adapt the impact assessment for a particular plant species to a different site and time (Hawkins et al. 2015).
- *Flexibility* Protocols have to be flexible in order to be amenable for improvement. Protocols often follow a modular structure with different impact types aggregated into wider classes (Nentwig et al.2016). This type of structure can easily be updated with further impact types or modules if the method to aggregate scores follows a clear rationale. Indeed, many European countries have updated previous national protocols to comply with the EU Regulation on Alien Invasive Species (Regulation 1143/2014).
- *Accuracy* Finally, accuracy is another quality that any assessment should have (Gordon et al. 2008). However, the precision to which the final score conforms to a "correct" degree of impact posed by the non-native species is difficult and somehow tautological to test. Theoretically, for non-native species not present in a region, accuracy of a protocol could be tested by comparing the final score for the pre-invasion impact assessment with the post-invasion impact assessment. Validation of impact assessments could also include post-hoc testing of a list of non-native species that are already known to have a real impact versus a list of non-native species that do not have an impact. Another venue that might inform on the accuracy of impact assessments would be to compare the consistency of species rankings among different impact assessment protocols (e.g. Turbé et al. 2017).

Conclusions

Preventing the impacts of non-native species has been one of the main aims in invasion science (Simberloff and Alexander 1998). Impact assessment protocols offer a cost-effective and rapid screening tool to prioritize non-native species for prevention, early warning or management. Based on a review of a large number of protocols, we have provided recommendations for improvement to increase the reliability of assessment outcomes. We have done so, not with the aim of advocating the development of new protocols, rather to improve those existing.

Impact assessment protocols ultimately try to make highly diverse data comparable. They are dependent not only on scientific information of the intensity of environmental and socio-economic impacts, but also on their variability, persistence and reversibility in space and time. The assessment of impacts on ecosystem services is in high demand, but there is not yet enough scientific literature to quantify impacts on complex ecosystem services that have a global dimension (e.g. climate change regulation), or that are dependent on subjective values and norms (e.g. cultural services). Moreover, considering that the studies available on impacts refer to only a few non-natives and some impacts are more studied than others (Hulme et al. 2013; Essl et al. 2017), it is necessary to identify the species and impact types for which uncertainty is high, and therefore require more research.

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