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BIODIVERSITY REVIEW

Species-based risk assessments for biological invasions: advances and challenges

Sabrina Kumschick* and David M. Richardson

Centre for Invasion Biology, Department of Botany and Zoology, Stellenbosch University, Matieland 7602, South Africa

*Correspondence: Sabrina Kumschick, Department of Botany and Zoology, Centre for Invasion Biology, Stellenbosch University, Matieland 7602, South Africa.
E-mail: sabrina.kumschick@alumni.unibe.ch

ABSTRACT

Aim An increasingly important component of invasive species management involves the formal assessment of risks associated with particular species becoming invasive and causing impact. We evaluated recent developments in risk assessment (RA) for alien species, with special emphasis on species-based pre-border assessments for intentional introductions. Our aim was to identify important advances and key challenges.

Location Global.

Methods A literature review was done to determine which approaches have been developed and fine-tuned over the last two decades, which of these have worked best and which are most widely used. We identified priorities for improving our ability to assess risks.

Results The review is divided into sections on various types and foci of RAs: invasion stage, taxon, ecosystem, assessment method and impact type. RAs for plants are the most advanced, with the Australian Weed Risk Assessment (A-WRA) being the most widely applied and tested protocol. Based on the history of the A-WRA, we highlight advances that have been made in assessing risk of alien species for pre-border control and identify remaining challenges.

Main conclusions Currently available RAs have proven to be cost-effective, but there is room for substantial improvement. Further work is needed to separate likelihood and consequence more explicitly, and provide better and more objective means for assessing risks of impact. Types and levels of uncertainty need to be more effectively incorporated. Advanced RA protocols are needed for taxa other than plants and vertebrates. The latest insights from research in invasion ecology need to be incorporated, and advances in other fields must also be taken into account.

Keywords

Australian Weed Risk Assessment, biological invasions, consequence, impact, invasiveness, invertebrates, likelihood, plants, risk assessment, vertebrates, WRA.

INTRODUCTION

Species introduced to areas outside their native ranges are a growing threat to biodiversity worldwide. Although many alien species are essential for survival and others bring diverse benefits to human societies, a small proportion of alien species become invasive and may damage ecosystems and economies (Pyšek & Richardson, 2010). Management of invasive species requires multifaceted interventions, one of them being to prevent the introduction of new species with a high risk of becoming invasive. Objective and accurate screening is crucial as prevention is the most cost-effective intervention (Keller *et al.*, 2007a) and because there is no sign that rate of introductions is slowing (Hulme *et al.*, 2009).

Levels of uncertainty concerning establishment and especially invasion success of alien species are generally high, and factors determining success differ between taxa and are context-specific (e.g. Mack, 1996; Richardson & Pyšek, 2012). Multiple layers of uncertainty make the evaluation of alien

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species well suited to consideration within the paradigm of RA as such inherent complexity demands formal, objective and transparent procedures for conceptualizing, elucidating and evaluating components of risk. Formal RA protocols also provide the means for compartmentalizing and attaching levels of uncertainty to different elements of risk (e.g. Koop *et al.* 2012). For invasion science (Kueffer & Hirsch Hadorn, 2008; Richardson, 2011), formal RA also provides a framework for 'book-keeping' and identifying priorities for further research. In the context of open trade, restrictions of the movement of species between countries require officially recognized RA standards. Under the World Trade Organisation (WTO) Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement), three such standards are recognized: the Office International des Épizooties (OIE), the Codex Alimentarius Commission (human health) and the International Plant Protection Convention (IPPC). Importantly, hardly any RA systems for alien species follow any of these rules completely (but see EPPO, 2011). However, governments are increasingly seeing the need for preventing potentially harmful alien species from being introduced, and the requirement for formal RA protocols is becoming embedded in legislation in many parts of the world (McGeoch *et al.*, 2010). This is also leading to the fine-tuning of previously developed protocols to better serve the needs set out in different legal instruments.

This paper aims to: (1) provide an overview of different RA approaches for alien species developed around the world and for different taxa, (2) assemble key aspects of success and failure relating to different facets of RA and to (3) suggest priorities for research to improve the effectiveness of RA protocols. Furthermore, based on the history of the Australian Weed Risk Assessment (A-WRA), we discuss advances that have been made in assessing risk of alien species for pre-border control and highlight remaining challenges for alien plant and animal RAs.

METHODS

An extensive literature search was conducted using publications listed in the ISI Web of Knowledge, references cited in these papers and key contributions in the grey literature. We only considered publications which describe, suggest, use or adapt RAs (risk assessment defined here as a part of the risk management process, assessing the potential of an alien species to establish, spread and cause impact in the target area) for species-based pre-border control. Such RAs cover intentional introductions triggered by permit application for the importation of species. We only considered RAs dealing with plant and animal introductions. RAs for microorganisms and fungi are not included. Very little work has been done on developing species-based RAs for these groups. Also, many of these species are pathogens, which are covered by plant-, animal- and human health sectors (e.g. Cook & Proctor, 2007; McKenzie *et al.*, 2007; EPPO, 2011) and therefore outside the scope of this paper.

We screened each RA for information on (1) invasion stage, (2) taxon, (3) the type(s) and number of ecosystems considered, (4) assessment method, and (5) impact type. We discuss each of these aspects in the following sections and identify priorities for future research.

INVASION STAGE

Species pass through different stages in the invasion continuum (Blackburn *et al.*, 2011). Some RAs look at the risk of introduction (e.g. Campbell, 2009), others look at establishment (e.g. Kolar & Lodge, 2002). Many RAs, however, do not distinguish clearly between stages or they look at 'weediness' or 'invasiveness' (e.g. Pheloung *et al.*, 1999). However, different factors influence the success of a given species or population at each stage (Dawson *et al.*, 2009; Leung *et al.*, 2012; Kumschick *et al.*, 2013). Any attempt to predict the success of an introduced species or population therefore needs to define the stages under consideration.

TAXON

Most RAs for alien species are taxon-specific (Kolar & Lodge, 2002), meaning that plants, vertebrates and invertebrates are usually assessed in separate RAs. Work on RAs for alien species largely reflects the attention given to different taxa in the invasion literature in general (Pyšek *et al.*, 2008). Generally, more research has been done on species with higher impacts (Heikkilä, 2011). A few RAs are, however, multitaxon oriented (Brunel *et al.*, 2010; Essl *et al.*, 2011), allowing for the same RA to be used for several taxa. Such RAs assume that all invaders share certain general traits, trait-combinations or trait-environment interactions ('syndromes') that distinguish them from non-invaders.

In the following section, we present key aspects of some of the most widely used/cited RAs for different taxa.

Plants

Introduction of plants can happen in many different ways. They can be introduced as fully grown plants (e.g. ornamentals), in which case RA is relatively straightforward. However, introduction in the form of seeds, deliberately or as contaminants, is common and raises problems like proper species identification and detection in the first place. Another potential issue is the differentiation of cultivars, hybrids, genetically engineered organisms, etc. that may have different probabilities of invasion, but which may be difficult to regulate differentially. Even though RA for plants are more advanced than those for other taxa performing the assessment is not always simple for these reasons.

The literature on invasion ecology is dominated by botanical studies, with close to 50% of case studies on invasive species dealing with higher plants (Pyšek *et al.*, 2008). As expected, therefore, more RA frameworks have been developed for plants than for any other major group. All vascular plants are often assessed together in the same RA, although some RAs for plants cover specific biomes or certain groups of plants (e.g. Tucker & Richardson, 1995; Reichard & Hamilton, 1997; Champion & Clayton, 2001).

By far the most widely used RA framework for plants is the A-WRA system (Pheloung *et al.*, 1999). This semiquantitative system comprises 49 questions which produce a score according to which species are classified as 'accepted for import', 'evaluate further' or 'rejected'. The accuracy of the A-WRA (i.e. its capacity to correctly identify invasive species) is usually high, ranging from an average of 80% weeds rejected (Weber *et al.*, 2009) to 90% major invaders correctly identified (Gordon *et al.*, 2008). The A-WRA has been adapted for use in regions of the world outside Australia and New Zealand for which it was developed (e.g. Kato *et al.* 2006; Gordon *et al.*, 2008; Nishida *et al.* 2009) and extended to reduce the number of species in the 'evaluate further' category (Daehler *et al.*, 2004). Key developments in the use of the A-WRA (Appendix S1 in Supporting Information) are outlined in more detail in the Discussion.

The A-WRA has proven inadequate for aquatic plants (e.g. Gordon & Gantz, 2011). Therefore, Champion & Clayton (2000, 2001) developed a system specifically for aquatic plant introduced to New Zealand, which has been adapted and proven useful for the United States (Gordon *et al.*, 2012).

The system developed by Reichard & Hamilton (1997) is a decision tree for woody plants developed for the United States. Despite some clear errors in selecting 'non-invasive' species in the training set (Rejmánek *et al.*, 2005), this semi-quantitative system works fairly well in identifying invasive woody plants in North America, but does not perform well for Central Europe (Křivánek & Pyšek, 2006) and Hawaii (Daehler & Carino, 2000). Furthermore, it does not take into account the suitability of tested species to climatic conditions in the new range, and the misclassification rate for establishment success is therefore increased.

The EPPO decision-support scheme was initially developed for the plant health sector but also includes potential pest plants. It is widely applied in Europe for assessing the risk of introducing pests (Brunel *et al.*, 2010; EPPO, 2011). According to IPPC standards (FAO, 2013), it assesses probability of entry, establishment, spread and impact. Kenis *et al.* (2012) provide guidance for assessing environmental impacts of quarantine species.

Vertebrates

Vertebrates have been mainly introduced as pets, livestock and game, as well as to 'improve' local faunas, with release and escape being the main mechanisms (Hulme *et al.*, 2008). In contrast to other taxa like plants, they are mainly introduced as adults due to their life cycles, and detection is generally easier because of their larger size. Only rarely are vertebrates contaminants of other introduced goods; this makes RA for this group theoretically more straightforward than for other groups.

Box 1: How important and reliable is climate matching for assessing the risk of establishment and invasion?

Close climate matching is generally a fundamental requirement for invasive success. A close match between the climate in native and introduced ranges is usually associated with high levels of establishment success and invasive behaviour across taxa (Hayes & Barry, 2008). However, introduced species may sometimes occupy distinct climatic niches in the introduced range compared to areas where they are native, particularly when they have invaded highly modified environments (Broennimann *et al.*, 2007; Gallagher *et al.*, 2010; Roura-Pascual *et al.*, 2011). Substantial climatic niche shifts are, however, rare in terrestrial plant invaders (Petitpierre *et al.*, 2012). Climate matching is a powerful tool in RA for invasive species management, but should not be the only predictor used to determine whether a species is likely to establish in a new region. Matching should consider climatic conditions in the native range as well as conditions in introduced ranges in other parts of the world, if the species has been introduced elsewhere (Broennimann & Guisan, 2008).

Richardson & Pyšek (2012) reviewed key questions relating to the role of climate (and broader 'environmental matching' that is considered in some RA schemes) at different stages and phases of the invasion continuum. Most screening models, while explicitly acknowledging the pivotal role of climate matching, use very crude metrics for scoring the level of matching between native and novel ranges (discussion in van Wilgen *et al.*, 2009). Many protocols lump broad-scale (macro) climatic parameters and diverse other abiotic factors to score the degree of 'environmental matching', again mostly without elaboration of the driving mechanisms and processes (Drake & Lodge, 2006). Furthermore, most RAs are not specific on the methods to be used to assess climatic suitability for the species in the new range (e.g. Pheloung *et al.*, 1999; but see Bomford, 2008).

The EPPO scheme assesses host distribution, area of potential impact as well as climatically suitable areas (EPPO, 2011). Several problems with mapping have been identified within the framework of PRATIQUE (www.pratiqueproject.eu) and solutions have been suggested (e.g., Kriticos *et al.*, 2012). Furthermore, it has been suggested to combine such maps to get a better estimate of the area at risk (Baker *et al.*, 2012).

Fewer RA schemes have been developed for assessing invasiveness of vertebrates than for plants, and those that have been proposed have not been as widely applied (Appendix S2 in Supporting Information). As for plants, one of the most extensive systems for assessing the risk of alien vertebrates was developed for Australia and (partly) New Zealand. Bomford (2008) developed slightly differing models to evaluate establishment success of mammals and birds, reptiles and amphibians, and freshwater fish to be introduced to Australia (and New Zealand, for mammals and birds). These models all include climate matching as a fundamental predictor of establishment success (Bomford *et al.*, 2009) (Box 1). They first quantitatively assess the risk of establishment success and reject all species with high risk; remaining species are assessed semiquantitatively in more detail for their risk of becoming pests. As far as we know, these RA schemes have only been applied in Australia (Massam *et al.*, 2010; Henderson & Bomford, 2011).

The Aquatic Nuisance Species Task Force (1996) developed a system that is divided into likelihood of establishment and spread and likelihood of impact. This system therefore fits into a general RA framework, but needs additional guidance for consistent usage. It has been developed for the United States and applied to snakes (Reed & Rodda, 2009).

Other RAs for vertebrates are listed in Appendix S2.

Unlike the most important RAs for plants, RAs for vertebrates have not been applied and tested widely (but see Henderson & Bomford, 2011; van Wilgen & Richardson, 2012). Their accuracy level might also be lower because of a smaller 'sample size'; there are fewer vertebrate species than plants, and therefore also fewer species are transported and introduced outside of their native range. Working with such lower number of introduced vertebrates than plants makes prediction of further invaders more difficult and therefore less accurate.

Invertebrates

Most RAs for invertebrates do not cover all invertebrate groups. Various RAs have been developed either for a smaller group within invertebrates (e.g. ants, Ward *et al.*, 2008; molluscs, Keller *et al.*, 2007b) or for plant pests, including certain invertebrates (e.g. EPPO, 2011).

Importantly, for invertebrates, the main intentional introductions are for the purpose of biocontrol. In these cases, the RAs focus on experimental tests of agent specificity to the target pest (Box 2). Introduction as contaminants in containers and other unintentional introductions are also critical for these groups. However, we focus on RA for species (as opposed to pathways) which are most useful when the introduction is intentional (e.g. for import permit applications).

Box 2: Special cases of risk assessment for alien species: Biological control agents and biofuel plants as examples

All organisms to be introduced should be subjected to normal pre-border RA, and should not be allowed to enter a region if substantial risk of invasiveness and/or impact is indicated. Special cases like biological control agents and plant species introduced for the production of biofuel need to undergo some form of additional screening to further elucidate dimensions of risk to inform management or mitigation procedures.

Biological control agents are assessed in much more detail than other intentionally introduced species (e.g. Zimmermann *et al.* 2004). Legislation in most countries requires the risk of impacts on non-target organisms and the potential effects on the pest species to be assessed experimentally. This is in contrast to other introductions of alien species, where only empirical data from the literature is collated without the requirement for additional data gathering.

Almost every plant species mentioned in the burgeoning literature on **biofuels** is either known to be invasive or, in cases where the species has not been widely planted, has the potential to become invasive. High-risk plant species are likely to be approved for biofuel production in some regions. Consequently, RA procedures need to inform strategies for cultivation practices and policies for surveillance and monitoring to mitigate potential impacts due to invasiveness.

ECOSYSTEM SPECIFICITY

Some RAs for alien species focus on certain ecosystems, mostly aquatic (freshwater and marine) systems. For example, Ricciardi & Rasmussen (1998) deal with aquatic organisms in general, including fishes, aquatic plants and mussels in the same RA system. Similarly, see Campbell (2009) and Dahlstrom *et al.* (2011) for reviews of marine RAs. Other systems narrow the scope of assessment by focusing on selected taxa within a specific ecosystem (e.g. Kolar & Lodge, 2002). A broader applicability of these RAs might be very limited as the assessment was done under such a narrow range of environmental conditions. These RAs are species-based, but are specifically designed for a particular ecosystem and the species within this system. However, they might be more accurate than RAs that are designed to be applicable across multiple ecosystems, as they only deal with factors that are important for one particular ecosystem/region. For a pre-border RA, however, it seems more practical to aim for protocols can be applied to any kind of ecosystem.

The most widely used RA for alien species thus set out to evaluate risk across a wide range of ecosystems (e.g. Pheloung *et al.*, 1999; Bomford, 2008; EPPO, 2011). Considering the broad and varying conditions in different ecosystems, it seems surprising that these RAs nevertheless have a high accuracy when it comes to flagging potentially harmful species (e.g. the A-WRA on average rejecting 80% to 90% of weeds). However, it suggests that incorporating the myriad of specific interactions between particular species and features of given ecosystems might not be essential for identifying species with a high risk of becoming invasive. This in turn suggests that a very general form of 'invasiveness' or 'weediness' (i.e. syndromes or traits that contribute to persistence, proliferation and spread in disturbed environments) is being identified in such models, and that RAs which are useful for more than one of the above described taxa might be useful (see Discussion).

ASSESSMENT METHOD

Three main methodological approaches for RA can be found in the literature: qualitative, semiquantitative and quantitative. Because the majority of RAs include some kind of impact assessment that is usually qualitative, most RAs are at least semiquantitative. Furthermore, most RAs evaluate establishment success of a species using mainly quantitative methods, but use qualitative measures for the evaluation of potential for impact.

Few RAs are either fully qualitative or fully quantitative. Qualitative RAs are generally based on expert knowledge and are undertaken by expert-decision panels based on their experience (Fowler, 2004). Quantitative RAs usually aim to evaluate establishment success of species to be introduced (e.g. Kolar & Lodge, 2002; van Wilgen *et al.*, 2009).

Scoring systems, usually semiquantitative, are often applied for evaluating risk. The two most widely used RAs worldwide (Pheloung *et al.*, 1999; Bomford, 2008) use simple scoring systems. Several approaches for evaluating scores have been adopted. The summed score can be categorized (as in Pheloung *et al.*, 1999), or can be presented on a continuous scale that allows ranking according to invasion potential (e.g. Parker *et al.*, 2007; Koop *et al.* 2012). The rationale, and strengths and weaknesses of different scoring systems are discussed in Box 3.

Box 3: Scoring systems in species-based risk assessments for alien species

Many RAs for alien species include some kind of scoring, either of impact or other factors (e.g. traits more likely to lead to establishment result in a higher score than those less obviously correlated with establishment success). The rationale for the weights assigned to different factors and cut-off levels are not always explained and have been the subject of debate and deliberation.

The A-WRA (Pheloung *et al.*, 1999), the RA tested most widely for plants around the world (Gordon *et al.*, 2008; see also Appendix S1), uses a scoring system to assess the risk of a species of becoming weedy. However, it is debatable how meaningful the cut-off levels are for purposes and conditions other than the ones for which the system was developed. In the case of the A-WRA, it was found that cut-off levels originally defined were not very accurate for aquatic plants (Champion & Clayton, 2000, 2001; Gordon & Gantz, 2011), and generally that too many species were placed in the category of 'evaluate further' (see Daehler *et al.*, 2004 for second screening of unclassified species). In some cases, different cut-off levels may be appropriate for different assessment regions (e.g. Nishida *et al.* 2009; test of A-WRA for Japan). Consequently, before applying an RA system in a region outside that for which it was originally designed, sensitivity analyses need to be done to explore the influence of different cut-offs and to validate outputs. More attention should be given to assessing the influence of weights assigned to primary and secondary indices in scoring systems, for example using the Analytic Hierarchy Process (e.g. Ou *et al.*, 2008).

Another approach used in RAs for invasiveness is to evaluate establishment/invasion potential with decision trees (e.g. Reichard & Hamilton, 1997). The advantage of such trees is that they are usually relatively easy to use as they only require yes/no answers. However, in case of knowledge gaps, the decision tree RA can in many cases not be completed. This is usually not the case in a scoring system, although some systems define a minimum number of questions to be answered to arrive at a conclusion (e.g. Pheloung *et al.*, 1999).

One caveat of scoring is that weightings and cut-off levels are crucial and must be carefully chosen and re-evaluated for each new country/region/situation where a given RA system is applied. More information in this regard appears in Box 3. Not only selection of appropriate cut-off levels, but also testing of RA accuracy can be improved. A crucial point is that when testing an RA for accuracy, the test group should not be part of the group initially used to populate the RA, and the generally low base-rate of alien species' success needs to be taken into account (Lonsdale & Smith, 2001).

IMPACT TYPE

Many RAs include some kind of impact assessment in the evaluation process. However, different sets of impact are included, and what exactly is meant by 'impact' differs between systems. The lack the consistency in approaches for defining and quantifying impacts in invasion ecology in general (Hulme *et al.*, 2013) is acutely reflected in RAs for invasive species. Some RAs focus on environmental impact (e.g. Essl *et al.*, 2011), whereas others also take into account some aspects of socio-economic impacts (e.g. EPPO, 2011).

Many RAs evaluate whether a species has had impacts elsewhere, in the native range or in other regions where it has been introduced. This measure is then used as an indication of whether a species is likely to replicate such impacts in the new region. However, such assessments must be handled with care (Box 4). Furthermore, if we want to assess the full risk of a species, we need to incorporate all possible risks of impact into the RA (e.g. Kumschick *et al.*, 2012). Generally, how to effectively incorporate impact into RA and how to predict impact need to be studied more thoroughly (Pyšek *et al.*, 2012; Simberloff *et al.*, 2013), and better metrics for capturing, categorization and quantification of impact are urgently needed.

Box 4: How useful is it to consider 'invasive success elsewhere' and/or 'impact elsewhere' in risk assessments for alien species?

The performance of a species elsewhere, either in its native range or in other regions where it is introduced, is widely used to assess the likelihood of the species establishing, becoming invasive, and having impact. Where a species has a history of introduction, use, and dissemination in areas outside its native range, its performance in these areas (i.e. whether it has become invasive where it has had sufficient opportunities) is a good predictor of its potential invasiveness in other areas (e.g. Panetta, 1993; Gordon *et al.*, 2008). With the increasing availability of global syntheses and databases, it is becoming easier to answer the question 'invasive elsewhere?' that is included in most RAs for alien species. Such a question is only useful if the species in question has been introduced to environmentally similar regions in other regions and has had enough time to become established or invasive. Such a caveat is not always given sufficient weight in RAs (but see e.g. Bomford, 2008 for evaluation of climate match to areas with susceptible native species or communities). 'Impact elsewhere' is generally a good predictor of impact in the new introduced range (Hayes & Barry, 2008) and is widely used in RAs (e.g. Bomford, 2008). Whether an introduced species will have negative impacts and how severe these could be are however dependent on many factors, including habitat characteristics and species composition in the introduced range. For example, one could ask whether the endangered species with which an introduced species is known to hybridise is present in the target region, or in neighbouring countries; see Smith *et al.* (2005) for the example of the ruddy duck, *Oxyura jamaicensis* in Spain/UK. Impact elsewhere should not be ignored in the assessment of risk of a species to be introduced into a new area. However, it should be possible to make a decision without having to evaluate impact elsewhere, and this factor should not be the main factor leading to a decision of acceptance or rejection of a species.

Furthermore, assessment of likelihood to establish/spread and impact (the consequence of establishment) is in most cases assessed with the same scoring system, and the scores are summed. This effectively implies that these two parts of RA are substitutable which is clearly not the case as impact relies on establishment and potentially spread (without establishment and spread there is no impact). The two factors should therefore be assessed in separate steps of the RA process (e.g. Koop *et al.* 2012). Daehler & Virtue (2010) describe a possible way to implement this separation with the A-WRA.

DISCUSSION

Invasion biologists seek to explain why some introduced species are more successful than others at a given locality. Almost all RAs for screening species for invasiveness are based on such research, thereby applying a retrospective, deductive approach as the foundation for assessing risk of invasiveness (Hayes & Sliwa, 2003; Kolar, 2004). In other words, RAs for alien species are generally built around knowledge about determinants of establishment and invasion success of past introduction events. They do not systematically explore standard elements of risk (see Daehler & Virtue, 2010 for definitions of terms), namely likelihood of the consequence (in our case, likelihood of the hazard to establish and spread) and consequences (impact) (but see Aquatic Nuisance Species Task Force 1996; Koop *et al.* 2012).

The main focus in the development of species-based RA for pre-border assessments has been on the usability and adaptability of certain schemes to other areas and taxa, rather than improving accuracy in the original area and on general improvements to the structure of the RA protocol to provide a more systematic evaluation of aspects of risk.

As there is no such comprehensive documentation on animal RA as there is for plants, we focus on plants in the following sections of the discussion. However, the conclusions drawn from plant RAs are also applicable to animal RAs.

Based on the history of the A-WRA (Appendix S1 in Supporting Information), we have highlighted advances which have been made in RA for alien species since the first legal implementation of such a system (details on the studies mentioned in this paragraph appear in Appendix S1 in Supporting Information). The A-WRA is highly accurate as originally developed, and its accuracy and predictive power have been further increased by adding a second screening for species in the 'evaluate further' category (one study), extending the system for aquatics (three studies), specifying the usage of climate matching (one study) and the system in general (one study). Furthermore, the choice of cut-off levels has been evaluated (four studies). The A-WRA is transferable to many very diverse regions (13 studies) and taxa (three studies), and is applicable for special cases among introduced species (Box 2), like biofuels (three studies). It can be used for purposes other than pre-border control, for example, as prioritization tool for management (two studies) or for pathway analysis (one study). Furthermore, it can be accommodated within a standard RA set-up to separate likelihood and consequence components of risk (three studies).

The weaknesses detected in the original system are that (i) aquatic species need a separate RA system, (ii) many species are classified as 'evaluate further', (iii) cut-off levels for the different categories of risk are not constant for different purposes and (iv) levels of risk for some closely related taxa cannot be determined (e.g. *Acacia*; Wilson *et al.*, 2011). However, all these points except the last one have been dealt with, and refinements have improved the usefulness of the system. Furthermore, point (iv) might not be considered a weaknesses of the system, but rather reflects that in some cases, separating species into low and high risk species on the basis of the questions asked in systems such as the A-WRA is not particularly meaningful. In the case of the *Acacia* example mentioned above, current evidence suggests that all taxa are potentially invasive (Gibson *et al.*, 2011) and that historical outcomes of introduction (and therefore the notions of invasive versus non-invasive) are determined by factors other than those captured in systems such as the A-WRA (Castro-Díez *et al.*, 2011).

For taxa other than plants, similar issues as detected in the A-WRA could play a role: for example, similar to (i) (see above) aquatic animals are usually evaluated in separate systems from their terrestrial relatives (e.g. aquatic invertebrates, Tricarico *et al.*, 2010), (iii) cut-off levels for accepting/rejecting a species always need to be evaluated for new conditions (see also Box 3) and (iv) because closely related species share many of the traits evaluated in RAs, distinguishing their invasion potential is a problem for all taxa.

Many RAs have been developed since the first implementation of the A-WRA in 1997, many of them building on the A-WRA model. However, in direct comparison, other systems are usually less accurate in rejecting invaders and accepting non-invaders (e.g. Křivánek & Pyšek, 2006). It is therefore strongly recommended that before a new system is implemented in practice, its performance should be tested against already existing ones, especially the A-WRA in the case of plants, and also potentially for other taxa. Due to the long implementation period of this system compared to others, and the high interest it has generated in the invasive species research community, many (potential) problems of the system have been identified and (at least partly) solved.

Scope for improvement

Species-based RA protocols are lacking for some taxa like certain invertebrates. More research is needed to determine invasion success of these understudied taxa, so that such insights can be fed into existing RAs for other taxa (e.g. the A-WRA), or lead to the development of new RA systems. All possible taxa need to be covered by RA for pre-border control to be more effective and applicable.

Approaches for tallying scores/results for different modules of RA procedures to arrive at meaningful estimates of risk of invasion are often arbitrary. Cut-off levels (low risk/high risk) might not be constant for different purposes (such as different regions or taxa), and rigid, widely applied cut-offs are unlikely to stand up to questioning in courts of law. These need to be subjected to sensitivity analyses to determine how different combinations of factors affect the outcome of assessments under different circumstances. They need to be rigorously tested and regularly updated, and adapted for new taxa and/or regions (Box 3).

Impact is too arbitrarily incorporated in RAs in many cases. For example, impact is evaluated with reference to ‘undesirable traits’ in the A-WRA. Strong evidence is emerging that impacts are generated by the interaction of species traits, features of the environment and other factors (e.g. Dick *et al.*, 2013). It is clearly unrealistic to expect the risk of impacts to be adequately captured by scores based on lists of ‘undesirable traits’. One approach is to identify traits correlated with impact, as has been done for birds and mammals (Nentwig *et al.*, 2010; Kumschick *et al.*, 2013). There is much scope for transferring such insights into RA protocols. Furthermore, the often qualitative nature of impact descriptions can lead to inconsistencies between different assessors. To prevent such problems, impact-scoring systems have been developed in an attempt to standardize impact assessment (e.g. Kumschick & Nentwig, 2010; Kumschick *et al.*, 2012). Generally, accuracy, consistency and transparency of impact assessments in RAs need to be improved (see e.g. Kenis *et al.*, 2012; Box 4).

Taxon specificity

The lack of RA systems for certain taxa is a concern. In some cases, systems developed for well-studied taxa have been adapted for application for understudied taxa (e.g. using the A-WRA for aquatic invertebrates), and some RAs are explicitly developed for use across multiple taxa. This raises the question of how important it is to develop taxon-specific RA schemes. Justification for the taxon-scope of given RA protocols is largely lacking. Possible reasons for this include the general separation of biological research into botany, zoology and microbiology, leading to specialization of invasion biologists in these fields. Several examples show that RAs can indeed be broad enough to be applied successfully across a wide range of taxa, sometimes with modifications. The EPPO (2011) decision-support scheme, developed for plant health protection, can be used for several disparate groups, like plants, certain invertebrates and fishes. Surprisingly, also the A-WRA (originally developed exclusively for plants) has, with minor modifications, been useful for assessing the invasion potential of fishes (Copp *et al.*, 2005) and invertebrates in aquatic systems (Tricarico *et al.*, 2010). Even though plants and animals have radically different life cycles and life-history traits, those with the potential to spread (and also those that cause impacts) seem to share features that distinguish them from those that do not establish, spread or cause impacts. Correlates of such ‘universal invasiveness’ require further study.

Philosophical underpinnings

The purpose of pre-border RA for alien species is to reduce the likelihood of the intentional introduction of potentially harmful species into a given region. Although RAs like the A-WRA have proved cost-effective in their current form (Keller *et al.*, 2007a; Springborn *et al.*, 2011), there is much room for improvement in the accuracy of such RA protocols. It is important to recognize that such systems will never be perfect. There are several fundamental reasons for this. Firstly, the RA systems reviewed in this paper are built on the foundation of empirical evidence of past invasions. It is unrealistic to expect perfect (or perhaps even very good) predictions based on the reconstruction of historical introductions and invasions. This is because every element of invasions – for example, the scale and make-up of species movements, the individual and collective roles of different drivers of invasion – is changing rapidly, and the value of expecting invasions of the future to follow similar trajectories of those in the past is tenuous ('the ghost of invasion past problem'; Kueffer *et al.*, 2013). Major advances in RA for alien species will rely on improved insights on mechanistic roles of major drivers and determinants of success at each stage of the invasion continuum and of impacts, rather than correlative insights based on historic combinations that are unlikely to be relevant into the future. In the interim, it seems sensible to expect RA protocols like those reviewed in this paper to offer only pointers to likely scenarios. Such uncertainty, and ways of accommodating it in formulating management strategies, is a key challenge for research on biological invasions. Precautionary approaches are essential.

Other sectors have a longer history of RAs and therefore more experience; such insights need to be drawn into research on invasive alien species to inform key areas of RA. For example, the plant health sector assesses similar issues to those that are relevant for invasive alien species – many plant pests are alien species (EPPO, 2011). Many of the abovementioned problems are being addressed or have been dealt with in the plant health sector. For example, the incorporation of uncertainties (Holt *et al.*, 2012) and impact (Kenis *et al.*, 2012; Bremmer *et al.*, 2012) in the EPPO scheme, and the achievement of higher consistency (Schrader *et al.*, 2012) are considered. All these improvements have been studied within the framework of PRATIQUE (Baker, 2012; www.pratiqueproject.eu) and most could be easily adapted to apply to RAs for invasive alien species – some already include certain aspects of invasion (e.g. Kenis *et al.*, 2012 include impact assessment for pest plants). So, as important as it is for specialists of different taxonomic groups to work together, it is also crucial to seek solutions for some issues from fields of research other than invasion ecology.

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REFERENCES

Baker, R.H.A. (2012) An introduction to the PRATIQUE research project. *EPPO Bulletin*, **42**, 1–2.

Baker, R.H.A., Benninga, J., Bremmer, J., Brunel, S., Dupin, M., Eyre, D., Ilieva, Z., Jarošik, V., Kehlenbeck, H., Kriticos, D.J., Makowski, D., Pergl, J., Reynaud, P., Robinet, C., Soliman, T., Van der Werf, W. & Worner, S. (2012) A decision-support tool for mapping endangered areas in pest risk analysis. *EPPO Bulletin*, **42**, 65–73.

Blackburn, T.M., Pyšek, P., Bacher, S., Carlton, J.T., Duncan, R.P., Jarošík, V., Wilson, J.R.U. & Richardson, D.M. (2011) A proposed unified framework for biological invasions. *Trends in Ecology and Evolution*, **26**, 333–339.

Bomford, M. (2008) *Risk assessment models for establishment of exotic vertebrates in Australia and New Zealand*. Invasive Animals Cooperative Research Centre, Canberra.

Bomford, M., Kraus, F., Barry, S.C. & Lawrence, E. (2009) Predicting establishment success for alien reptiles and amphibians: a role for climate matching. *Biological Invasions*, **11**, 713–724.

Bremmer, J., Petter, F. & Baker, R. (2012) Improvements to the economic impact assessment section of the EPPO PRA scheme. *EPPO Bulletin*, **42**, 13–20.

Broennimann, O. & Guisan, A. (2008) Predicting current & future biological invasions: both native and invaded ranges matter. *Biology Letters*, **4**, 585–589.

Broennimann, O., Treier, U.A., Müller-Schärer, H., Thuiller, W., Peterson, A.T. & Guisan, A. (2007) Evidence of climatic niche shift during biological invasions. *Ecology Letters*, **10**, 701–709.

Brunel, S., Branquart, E., Fried, G., van Valkenburg, J., Brundu, G., Starfinger, U., Buholzer, S., Uludag, A., Joseffson, M. & Baker, R. (2010) The EPPO prioritization process for invasive alien plants. *OEPP/EPPO Bulletin*, **40**, 407–422.

Campbell, M.L.. (2009) An overview of risk assessment in a marine biosecurity context. *Biological invasions in marine ecosystems, ecological studies 204* (ed. by G. Rilov and J.A. Crooks), pp. 353–373. Springer, Berlin.

Castro-Díez, P., Godoy, O., Saldaña, A. & Richardson, D.M. (2011) Predicting invasiveness of Australian acacia on the basis of their native climatic affinities, life history traits and human use. *Diversity and Distributions*, **17**, 934–945.

Champion, P.D. & Clayton, J.S.. (2000) Border control for potential aquatic weeds. Stage 1. Weed risk model. *Science for Conservation 141*. Department of Conservation, Wellington, New Zealand.

Champion, P.D. & Clayton, J.S.. (2001) A weed risk assessment model for aquatic weeds in New Zealand. *Weed risk assessment* (ed. by R. H. Groves, F. D. Panetta and J. G. Virtue), pp. 194–202. CSIRO Publishing, Collingwood.

Cook, D. & Proctor, W. (2007) Assessing the threat of exotic plant pests. *Ecological Economics*, **63**, 594–604.

Copp, G.H., Garthwaite, R. & Gozlan, R.E.. (2005) *Risk identification and assessment of non-native freshwater fishes: concepts and perspectives on protocols for the UK*. Cefas Science Technical Report No. 129. Cefas, Lowestoft.

Daehler, C.C. & Carino, D.A. (2000) Predicting invasive plants: prospects for a general screening system based on current regional models. *Biological Invasions*, **2**, 93–102.

Daehler, C.C. & Virtue, J.G. (2010) Likelihood and consequences: reframing the Australian weed risk assessment to reflect a standard model of risk. *Plant Protection Quarterly*, **25**, 52–55.

Daehler, C.C., Denslow, J.S., Ansari, S. & Kuo, H.C. (2004) A risk-assessment system for screening out invasive pest plants from Hawaii and other Pacific islands. *Conservation Biology*, **18**, 360–368.

Dahlstrom, A., Hewitt, C.L. & Campbell, M.L. (2011) A review of international, regional and national biosecurity risk assessment frameworks. *Marine Policy*, **35**, 208–217.

Dawson, W., Burslem, D.F.R.P. & Hulme, P.E. (2009) Factors explaining alien plant invasion success in a tropical ecosystem differ at each stage of invasion. *Journal of Ecology*, **97**, 657–665.

Dick, J.T.A., Gallagher, K., Avlijas, S., Clarke, H.C., Lewis, S.E., Leung, S., Minchin, D., Caffrey, J., Alexander, M.E., Maguire, C., Harrod, C., Reid, N., Haddaway, N.R., Farnsworth, K.D., Penk, M. & Ricciardi, A. (2013) Ecological impacts of an invasive predator explained and predicted by comparative functional responses. *Biological Invasions*, **15**, 837–846.

Drake, J.M. & Lodge, D.M. (2006) Allee effects, propagule pressure and the probability of establishment: risk analysis for biological invasions. *Biological Invasions*, **8**, 365–375.

EPPO (2011) *Guidelines on Pest Risk Analysis: decision-support scheme for quarantine pests*. Available at: http://archives. eppo.org/EPPOStandards/pra.htm (accessed 1 December 2012).

Essl, F., Nehring, S., Klingenstein, F., Milasowszky, N., Nowack, C. & Rabitsch, W. (2011) Review of risk assessment systems of IAS in Europe and introducing the German-Austrian Black List Information system (GABLIS). *Journal for Nature Conservation*, **19**, 339–350.

FAO (2013) *Pest risk analysis for quarantine pests. International Standards for Phytosanitary Measures Publication No. 11*. FAO, Rome.

Fowler, L.. (2004) *Weed-initiated pest risk assessment guidelines for qualitative assessments: version 5.3. U.S.* Department of Agriculture (USDA), Riverdale, MD.

Gallagher, R.V., Beaumont, L.J., Hughes, L. & Leishman, M.R. (2010) Evidence for climatic niche and biome shifts between native and novel ranges in plant species introduced to Australia. *Journal of Ecology*, **98**, 790–799.

Gibson, M.R., Richardson, D.M., Marchante, E., Marchante, H., Rodger, J.G., Stone, G.N., Byrne, M., Fuentes-Ramírez, A., George, N., Harris, C., Johnson, S.D., Le Roux, J.J., Miller, J.T., Murphy, D.J., Pauw, A., Prescott, M.N., Wandrag, E.M. & Wilson, J.R.U. (2011) Reproductive biology of Australian acacias: important mediator of invasiveness? *Diversity and Distributions*, **17**, 911–933.

Gordon, D.R. & Gantz, C.A. (2011) Risk assessment for invasiveness differs for aquatic and terrestrial plant species. *Biological Invasions*, **13**, 1829–1842.

Gordon, D.R., Onderdonk, D.A., Fox, A.M. & Stocker, R.K. (2008) Consistent accuracy of the Australian weed risk assessment system across varied geographies. *Diversity and Distributions*, **14**, 234–242.

Gordon, D.R., Gantz, C.A., Jerde, C.L., Chadderton, W.L., Keller, R.P. & Champion, P.D. (2012) Weed risk assessment for aquatic plants: modification of a New Zealand system for the United States. *PLoS ONE*, **7**, e40031.

Hayes, K.R. & Barry, S.C. (2008) Are there any consistent predictors of invasion success? *Biological Invasions*, **10**, 483–506.

Hayes, K.R. & Sliwa, C. (2003) Identifying potential marine pests – a deductive approach applied to Australia. *Marine Pollution Bulletin*, **46**, 91–98.

Heikkilä, J. (2011) A review of risk prioritization schemes of pathogens, pests and weeds: principles and practices. *Agricultural and Food Science*, **20**, 15–28.

Henderson, W. & Bomford, M. (2011) *Detecting and preventing new incursions of exotic animals in Australia*. Invasive Animal Cooperative Research Centre, Canberra.

Holt, J., Leach, A.W., Knight, J.D., Griessinger, D., MacLeod, A., van der Gaag, D.J., Schrader, G. & Mumford, J.D. (2012) Tools for visualizing and integrating pest risk assessment ratings and uncertainties. *EPPO Bulletin*, **42**, 35–41.

Hulme, P.E., Bacher, S., Kenis, M., Klotz, S., Kühn, I., Minchin, D., Nentwig, W., Olenin, S., Panov, V., Pergl, J., Pyšek, P., Roques, A., Sol, D., Solarz, W. & Vilà, M. (2008) Grasping the routes of biological invasions: a framework for integrating pathways into policy. *Journal of Applied Ecology*, **45**, 403–414.

Hulme, P.E., Pyšek, P., Nentwig, W. & Vilà, M. (2009) Will threat of biological invasions unite the European Union? *Science*, **324**, 40–41.

Hulme, P.E., Pyšek, P., Jarošík, V., Pergl, J., Schaffner, U. & Vila, M. (2013) Bias and error in understanding plant invasion impacts. *Trends in Ecology and Evolution*, **28**, 212–218.

Keller, R.P., Lodge, D.M. & Finnoff, D.C. (2007a) Risk assessment for invasive species produces net bioeconomic benefits. *Proceedings of the National Academy of Sciences USA*, **104**, 203–207.

Keller, R.P., Drake, J.M. & Lodge, D.M. (2007b) Fecundity as a basis for risk assessment of nonindigenous freshwater molluscs. *Conservation Biology*, **21**, 191–200.

Kenis, M., Bacher, S., Baker, R.H.A., Branquart, E., Brunel, S., Holt, J., Hulme, P.E., MacLeod, A., Pergl, J., Petter, F., Pyšek, P., Schrader, G., Sissons, A., Starfinger, U. & Schaffner, U. (2012) New protocols to assess the environmental impact of pests in the EPPO decision-support scheme for pest risk analysis. *Bulletin OEPP/EPPO Bulletin*, **42**, 21–27.

Kolar, C.S. (2004) Risk assessment and screening for potentially invasive fish. *New Zealand Journal of Marine and Freshwater Research*, **38**, 391–397.

Kolar, C.S. & Lodge, D.M. (2002) Ecological predictions and risk assessment for alien fishes in North America. *Science*, **298**, 1233–1236.

Koop, A.L., Fowler, L., Newton, L.P. & Caton, B.P. (2012) Development and validation of a weed screening tool for the United States. *Biological Invasions*, **14**, 273–294.

Kriticos, D.J., Reynaud, P., Baker, R.H.A. & Eyre, D. (2012) Estimating the global area of potential establishment for the western corn rootworm (*Diabrotica virgifera virgifera*) under rain-fed and irrigated agriculture. *Bulletin OEPP/EPPO Bulletin*, **42**, 56–64.

Křivánek, M. & Pyšek, P. (2006) Predicting invasions by woody species in a temperate zone: a test of three risk assessment schemes in the Czech Republic (Central Europe). *Diversity and Distributions*, **12**, 319–327.

Kueffer, C. & Hirsch Hadorn, G. (2008) How to achieve effectiveness in problem-oriented landscape research: The example of research on biotic invasions. *Living Reviews in Landscape Research*, 2, http://www.livingreviews.org/lrlr-2008-2 (accessed 1 March 2013).

Kueffer, C., Pyšek, P. & Richardson, D.M. (2013). Integrative invasion science: model systems, multi-site studies, focused meta-analysis, and invasion syndromes. *New Phytologist* (in press).

Kumschick, S. & Nentwig, W. (2010) Some alien birds have as severe an impact as the most effectual alien mammals in Europe. *Biological Conservation*, **143**, 2757–2762.

Kumschick, S., Bacher, S., Dawson, W., Heikkilä, J., Sendek, A., Pluess, T., Robinson, T.B. & Kühn, I. (2012) A conceptual framework for prioritization of invasive alien species for management according to their impact. *NeoBiota*, **15**, 69–100.

Kumschick, S., Bacher, S. & Blackburn, T.M. (2013) What determines the impact of alien birds and mammals in Europe? *Biological Invasions*, **15**, 785–797.

Leung, B., Roura-Pascual, N., Bacher, S., Heikkilä, J., Brotons, L., Burgman, M.A., Dehnen-Schmutz, K., Essl, E., Hulme, P.E., Richardson, D.M., Sol, D. & Vilà, M. (2012) TEASIng apart alien-species risk assessments: a framework for best practices. *Ecology Letters*, **15**, 1475–1493.

Lonsdale, W.M. & Smith, C.S. (2001) Evaluating pest-screening systems – insights from epidemiology and ecology. *Weed risk assessment* (ed. by R.H. Groves, F.D. Panetta and J.G. Virtue), pp. 52–60. CSIRO Publishing, Collingwood, Australia.

Mack, R.N. (1996) Plant invasions: early and continuing expressions of global change. *Past and future rapid environmental changes: the spatial and evolutionary responses of terrestrial biota* (ed. by B. Huntley, W. Cramer, A.V. Morgan, H.C. Prentice and J.R.M. Allen), pp. 205–216. Springer-Verlag, Berlin.

Massam, M., Kirkpatrick, W. & Page, A. (2010) *Assessment and prioritisation of risk for forty exotic animal species*. Invasive Animals Cooperative Research Centre, Canberra.

McGeoch, M.A., Butchart, S.H.M., Spear, D., Marais, E., Kleynhans, E.J., Symes, A., Chanson, J. & Hoffmann, M. (2010) Global indicators of biological invasions: species numbers, biodiversity impact and policy response. *Diversity and Distributions*, **16**, 95–108.

McKenzie, J., Simpson, H. & Langstaff, I. (2007) Development of methodology to prioritise wildlife pathogens for surveillance. *Preventive Veterinary Medicine*, **81**, 194–210.

Nentwig, W., Kühnel, E. & Bacher, S. (2010) A generic impact-scoring system applied to alien mammals in Europe. *Conservation Biology*, **24**, 302–311.

Nishida, T., Yamashita, N., Asai, M., Kurokawa, S., Enomoto, T., Pheloung, P.C. & Groves, R.H. (2009) Developing a pre-entry weed risk assessment system for use in Japan. *Biological Invasions*, **11**, 1319–1333.

Ou, J., Lu, C. & O'Toole, D.K. (2008) A risk assessment system for alien plant bio-invasion in Xiamen, China. *Journal of Environmental Sciences*, **20**, 989–997.

Panetta, F.D. (1993) A system of assessing proposed plant introductions for weed potential. *Plant Protection Quarterly*, **8**, 10–14.

Parker, C., Caton, B.P. & Fowler, L. (2007) Ranking nonindigenous weed species by their potential to invade the United States. *Weed Science*, **55**, 386–397.

Petitpierre, B., Kueffer, C., Broennimann, O., Randin, C., Daehler, C. & Guisan, A. (2012) Climatic niche shifts are rare among terrestrial plant invaders. *Science*, **335**, 1344–1348.

Pheloung, P.C., Williams, P.A. & Halloy, S.R. (1999) A weed risk assessment model for use as a biosecurity tool evaluating plant introductions. *Journal of Environmental Management*, **57**, 239–251.

Pyšek, P. & Richardson, D.M. (2010) Invasive species, environmental change and management, and health. *Annual Review of Environment and Resources*, **35**, 25–55.

Pyšek, P., Richardson, D.M., Pergl, J., Jarošík, V., Sixtova, Z. & Weber, E. (2008) Geographical and taxonomic biases in invasion ecology. *Trends in Ecology and Evolution*, **23**, 237–244.

Pyšek, P., Jarošík, V., Hulme, P.E., Pergl, J., Hejda, M., Schaffner, U. & Vilà, M. (2012) A global assessment of invasive plant impacts on resident species, communities and ecosystems: the interaction of impact measures, invading species' traits and environment. *Global Change Biology*, **18**, 1725–1737.

Reed, R.N. & Rodda, G.H. (2009) *Giant constrictors: biological and management profiles and an establishment risk assessment for nice large species of pythons, anacondas, and the boa constrictor*. U.S. Geological Survey Open-File Report 2009-1202, 302 pp.

Reichard, S.H. & Hamilton, C.W. (1997) Predicting invasions of woody plants introduced into North America. *Conservation Biology*, **11**, 193–203.

Rejmánek, M., Richardson, D.M., Higgins, S.I., Pitcairn, M.J. & Grotkopp, E. (2005) Ecology of invasive plants: State of the art. *Invasive alien species: a new synthesis* (ed. by H.A. Mooney, J.A. McNeely, L. Neville, P.J. Schei and J. Waage), pp. 104–162. Island Press, Washington, DC.

Ricciardi, A. & Rasmussen, J.B. (1998) Predicting the identity and impact of future biological invaders: a priority for aquatic resource management. *Canadian Journal of Fisheries and Aquatic Sciences*, **55**, 1759–1765.

Richardson, D.M. (2011) Invasion science: the roads travelled and the roads ahead. *Fifty years of invasion ecology. The legacy of Charles Elton* (ed. by D.M. Richardson), pp. 397–407. Wiley-Blackwell, Oxford.

Richardson, D.M. & Pyšek, P. (2012) Naturalization of introduced plants: Ecological drivers of biogeographic patterns. *New Phytologist*, **196**, 383–396.

Roura-Pascual, N., Hui, C., Ikeda, T. *et al.* (2011) Relative roles of climatic suitability and anthropogenic influence in determining the pattern of spread in a global invader. *Proceedings of the National Academy of Sciences USA*, **108**, 220–225.

Schrader, G., MacLeod, A., Petter, F., Baker, R.H.A., Brunel, S., Holt, J., Lech, A.W. & Mumford, J.D. (2012) Consistency in pest risk analysis – how can it be achieved and what are the benefits? *EPPO Bulletin*, **42**, 3–12.

Simberloff, D., Martin, J.L., Genovesi, P., Maris, V., Wardle, D.A., Aronson, J., Courchamp, F., Galil, B., García-Berthou, E., Pascal, M., Pyšek, P., Sousa, R., Tabacchi, E. & Vilà, M. (2013) Impact of biological invasions: what's what and the way forward. *Trends in Ecology and Evolution*, **28**, 58–66.

Smith, G.C., Henderson, I.S. & Robertson, P.A. (2005) A model of ruddy duck *Oxyura jamaicensis* eradication for the UK. *Journal of Applied Ecology*, **42**, 546–555.

Springborn, M., Romagosa, C.M. & Keller, R.P. (2011) The value of nonindigenous species risk assessment in international trade. *Ecological Economics*, **70**, 2145–2153.

Tricarico, E., Vilizzi, L., Gherardi, F. & Copp, G.H. (2010) Calibration of FI-ISK, an invasiveness screening tool for nonnative freshwater invertebrates. *Risk Analysis*, **30**, 285–292.

Tucker, K.C. & Richardson, D.M. (1995) An expert system for screening potentially invasive alien plants in South African fynbos. *Journal of Environmental Management*, **44**, 309–338.

Ward, D.F., Stanley, M.C., Toft, R.J., Forgie, S.A. & Harris, R.J. (2008) Assessing the risk of invasive ants a simple and flexible scorecard approach. *Insectes Sociaux*, **55**, 360–363.

Weber, J., Panetta, F.D., Virtue, J. & Pheloung, P. (2009) An analysis of assessment outcomes from eight years' operation of the Australian border weed risk assessment system. *Journal of Environmental Management*, **90**, 798–807.

van Wilgen, N.J. & Richardson, D.M. (2012) The roles of climate, phylogenetic relatedness, introduction effort, and reproductive traits in the establishment of non-native reptiles and amphibians. *Conservation Biology*, **26**, 267–277.

van Wilgen, N.J., Roura-Pascual, N. & Richardson, D.M. (2009) A quantitative climate-match score for risk-assessment screening of reptile and amphibian introductions. *Environmental Management*, **44**, 590–607.

Wilson, J.R.U., Gairifo, C., Gibson, M.R. *et al.* (2011) Risk assessment, eradication, and biological control: global efforts to limit Australian acacia invasions. *Diversity and Distributions*, **17**, 1030–1046.

Zimmermann, H.G., Moran, V.C. & Hoffmann, J.H. (2004) Biological control in the management of invasive alien plants in South Africa, and the role of the Working for Water programme. *South African Journal of Science*, **100**, 34–40.

SUPPORTING INFORMATION

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

Appendix S1 The development, uses and adaptations of the Australian Weed Risk Assessment system (A-WRA).

Appendix S2 Risk assessment systems for vertebrates.

BIOSKETCHES

Sabrina Kumschick is an ecologist whose work focuses mainly on biological invasions. Her main interests are risk assessment and the quantification of impacts of invasive species.

Dave Richardson works mainly on the ecology of woody plant invasions. He is Director at the Centre for Invasion Biology at Stellenbosch University, South Africa (http://academic.sun.ac.za/cib/), where **Sabrina Kumschick** is currently a post-doctoral fellow.

Author contributions: S.K. and D.M.R. conceived the ideas; S.K. collected the data, analysed the data and led the writing with substantial input from D.M.R.

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