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METHODS

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A framework to support alien species regulation: the Risk Analysis for Alien Taxa (RAAT)

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Abstract

Human livelihoods and well-being in almost all regions of the world depend on taxa which are alien. Such taxa also, however, threaten human health, sustainable development, and biodiversity. Since it is not feasible or desirable to control all alien taxa, decision-makers increasingly rely on risk analyses to formalise the best available evidence of the threats posed and whether and how they can be managed. There are a variety of schemes available that consider the risks of alien taxa, but we argue a new framework is needed: 1) given major recent developments in international frameworks dealing with biological invasions (including the scoring of impacts); 2) so that decisions can be made consistently across taxa, regions and realms; 3) to explicitly set out uncertainties; and 4) to provide decision-makers with information both on the risks posed and on what can be done to mitigate or prevent impacts. Any such scheme must also be flexible enough to deal with constraints in capacity and information. Here we present a framework to address these points – the Risk Analysis for Alien Taxa (RAAT). It outlines a series of questions related to an alien taxon's likelihood of invasion, realised and potential impacts, and options for management. The framework provides a structure for collating relevant data from the published literature to support a robust, transparent process to list alien taxa under legislative and regulatory requirements, with the aim that it can be completed by a trained science graduate within a few days. The framework also provides a defensible process for developing recommendations for the management of assessed taxa. We trialled the framework in South Africa and outline the process followed and some of the taxa assessed to date.

Keywords

Biological invasions, policy, regulations, risk analysis, risk assessment, risk management

Introduction

Species are being moved around the world by humans, both accidentally and deliberately, with the rate of introduction of new species showing few signs of declining (Seebens et al. 2017). Once introduced, some of these species establish and spread without further human assistance. There are also numerous species that have already been introduced and that will likely become invasive in future. While many alien taxa are highly beneficial, some can have significant negative impacts on the recipient environment and human livelihoods (Pimentel 2011; Blackburn et al. 2014). This makes management of the most problematic alien taxa a necessity. However, it is not feasible, desirable or necessary to manage all aliens and prioritisation is needed (McGeoch et al. 2016).

International agreements under the World Trade Organisation (WTO) require the assessment of risks before certain activities involving an alien taxon, especially trade, can be restricted, or before a new taxon should be allowed for import. These agreements recognise the standards set by the International Plant Protection Convention (IPPC; FAO 1996) and the World Organisation for Animal Health (OIE 2011). Such risk assessments are aimed at distinguishing potentially harmful taxa from those that are benign.

We argue that for successful management and the development of efficient regulations, three components are required, namely, risk assessment, risk management, and risk communication. While elements of each have been developed in different cases separately (see for example Branquart et al. 2016; Booy et al. 2017), regulatory decisions regarding biological invasions rest on all three components: (i) risk assessment consists of the likelihood and consequences of an alien taxon causing negative impacts (Daehler and Virtue 2010); (ii) risk management deals with options to reduce the risk, including due consideration of potential benefits; and (iii) risk communication details how the information is made accessible (Branquart et al. 2016). Therefore, besides the mandatory risk assessments prescribed by the international agreements, regulatory decisions need also to take risk management into account, i.e., management feasibility, benefits of the taxon, and potential conflicts between/amongst stakeholders [see van Wilgen and Richardson (2012) for examples of the costs of ignoring such considerations]. Furthermore, decisions are often only successful and implementable if stakeholders understand the risks associated with the taxon. To gain the support from the general public and other stakeholders, engagement and clear communication regarding risks is crucial and this is where risk communication has its place. Therefore, to support decision-makers, the broader process of risk analysis is required (Convention on Biological Diversity 2002). There is a plethora of frameworks that have been developed to address particular parts of the problem, but they are mostly taxon-specific (Leung et al. 2012) and often do not link to probabilities or are not mathematically consistent (Holt 2006). Furthermore, risk analyses need to be transparent and repeatable and align with national and international agreements, policies, and best practice (e.g. Verbrugge et al. 2010; Essl et al. 2011; Heikkilä 2011; Kumschick and Richardson 2013; Roy et al. 2018).

Much progress has been made in recent years in the way we analyse risks and aspects thereof. For example, impact scoring schemes have been developed which enable the comparison of a wide range of impacts between taxa and habitats – most notably the Environmental Impact Classification for Alien Taxa (EICAT; Hawkins et al. 2015, IUCN 2020a, b) and its socioeconomic equivalent, SEICAT (Bacher et al. 2018) (more detail in Consequences section below). More thought has also been given to the management aspect of the decision-making and prioritisation processes (e.g. Booy et al. 2017).

Decisions often have to be made on the basis of limited evidence. Therefore, risk analyses should explicitly highlight uncertainties and flag where recommendations are based on projections. Moreover, consideration should be given as to when the precautionary principle is appropriate. As set out by the Convention on Biological Diversity in their guiding principles related to alien species that threaten ecosystems, habitats or species: "… The precautionary approach should also be applied when considering eradication, containment and control measures in relation to alien species that have become established. Lack of scientific certainty about the various implications of an invasion should not be used as a reason for postponing or failing to take appropriate eradication, containment and control measures" [guiding principle 1 (Convention on Biological Diversity 2002)].

In order to deal with undesirable consequences and to mitigate future impacts, policy frameworks for the regulation of alien taxa have been developed for many countries (McGeoch et al. 2010; Early et al. 2016). For example, the European Union (EU) has developed new legislation to ensure a consistent response to the threat of alien taxa by all member states (EU Regulation 2014). Such regulations often include lists of species for which certain activities like trade, propagation and movement are prohibited or restricted and which require mandatory management interventions (Garcia-de-Lomas and Vilà 2015). Decisions on the categorisation of alien taxa in these lists require a transparent and evidence-based analysis of risk.

Here we present a practical framework for the analysis of risks associated with alien taxa and provide a structure for collating scientific evidence. We provide detailed information on the framework including how and why it was developed and its structure and content. Lastly, we provide some results from applications of RAAT and outline how the framework can aid and support the regulation and listing of alien taxa, using the South African legislative background as an example.

The Risk Analysis for Alien Taxa (RAAT) framework

We first outline how and why the framework was developed and tested, provide general guidance on how risk is scored and confidence estimated, and present the overall structure of the framework followed by a detailed description of each section.

Development and testing of the RAAT

The risk analysis framework presented here was specifically designed for the purpose of listing alien species under the regulatory framework of the South African National

Environmental Management: Biodiversity Act (NEMBA, Act 10 of 2004) Alien and Invasive Species Regulations (hereafter called the NEM:BA A&IS Regulations; Department of Environmental Affairs 2014; for details of how the framework aligns with the regulations, see Suppl. material 1). The development of the RAAT framework was initiated in 2015, in response to the promulgation of the NEM:BA A&IS Regulations. The regulatory lists of 2014 were informed by expert opinion, but the decisions taken and recommendations made were not clearly documented (see Kumschick et al. 2020a for a discussion). As the regulatory lists specify taxa which need to be controlled and for which other restrictions are in place, it has social and economic implications and has been contested in a number of cases [van Wilgen and Wilson (2018); see also Novoa et al. (2015) for a discussion on listing alien Cactaceae]. A framework was therefore required to (retrospectively) provide evidence for listing in a consistent transparent manner (e.g. Woodford et al. 2017).

During the development of this framework, regular meetings with decision-makers [mainly representatives from the Biosecurity Division of what was, at the start of the process, the South African Department of Environmental Affairs (DEA), but became the Department of Forestry, Fisheries and the Environment (DFFtE) in 2020] were held to ensure their needs were taken into account and the framework was relevant for the intended purpose. The first version of the framework was used by graduate students at the Centre for Invasion Biology at Stellenbosch University (CIB) to assess taxa from a wide range of taxonomic groups and feedback from this exercise was used to refine it, providing additional clarification and guidance. The second version was reviewed by the Alien Species Risk Analysis Review Panel (ASRARP), a panel of South African experts set up by the South African National Biodiversity Institute (SANBI) to review risk analyses for alien taxa [both those performed in relation to the import of species not yet present in the country and those performed in relation to the regulation and listing of alien taxa under the NEM:BA A&IS Regulations (Kumschick et al. 2020a)]. The panel includes independent experts on biological invasions and risk analyses, with representatives from private and public entities and experts on a wide range of taxonomic groups. The issues raised by the ASRARP on the framework were mainly related to details in the wording which could lead to misunderstandings. These were subsequently addressed, and a new draft was reviewed by representatives from different organisations, including the DEA, members of the ASRARP, the SANBI, and the CIB. Finally, RAAT was signed off by the ASRARP before submission as a report to the DEA in March 2017. A revised version was subsequently uploaded to a pre-print server to make it widely accessible (Kumschick et al. 2018).

Initially, several risk analyses were piloted by ASRARP members, but after the first three risk analyses were approved, subsequent risk analyses were submitted by SANBI staff, students, and post-docs not affiliated with ASRARP to ensure a separation between the review panel and the assessors. The risk assessors (who had various backgrounds and levels of education, including alien species managers, taxonomists, post-graduate students, and researchers), were trained to use the framework during five courses that were run over 2018–2019 (Table 1, several additional courses were held in 2020 based on an accepted draft of this paper). The courses provided valuable feedback in terms of how the framework should be worded to avoid inconsistencies and to clarify the calculations of likelihood and risk specifically. Moreover, as the risk analyses were submitted for review at the meetings of the ASRARP and reviewed by independent experts, the framework has been further refined by adding sections on management that could help clarify specific issues on sub-specific entities. The framework presented here has thus been tested and refined in practice over two years (Suppl. material 2).

RAAT is yet to be either formally adopted in South African legislation or included as an official guiding document, but it is being used by officials to justify applications to revise the listing of taxa under their mandate. Even though RAAT was initially designed for the purpose of listing alien species under the NEM:BA A&IS Regulations, the intention was always to create a system that can be used more generally to aid decisions regarding management prioritisation and the listing of taxa under policy frameworks. Therefore, throughout the framework, the questions posed and options for answers were designed to be generic and applicable across regions. However, in the Suppl. material 2, these are worded specifically with the South African context in mind for local decision-makers and managers to determine the appropriate categories as referenced in the NEM:BA A&IS Regulations.

Scoring risk and confidence

RAAT consists of a series of questions which need to be answered by the person assessing an alien taxon of interest. The accuracy of an analysis relies, amongst other factors, on ensuring that a thorough literature review on the taxon under assessment is conducted. Some information can be extracted from national and international databases on native and alien species, such as the Global Invasive Species Database (http://www.iucngisd.org/gisd/), CABI's Invasive Species Compendium (https://www.cabi.org/isc/), Global Biodiversity Information Facility (https://www.gbif.org/), and the Red List of Threatened Species (http://www.iucnredlist.org/). However, primary literature should preferably be consulted and included. Information from the native range can be useful, including indigenous knowledge.

If insufficient information is published on the taxon, closely related taxa should be considered, for example, congeners (e.g. Bomford 2008). However, it needs to be clearly stated when such information is used, and which species was selected as a surrogate and why. Species with similar life history traits and behaviour are preferred. All information must be documented and referenced to be able to review how recommendations were developed and when assumptions were made and to facilitate updating the analysis as suitable information becomes available.

Taxonomists and other experts should be consulted for the risk analysis process to fill gaps in literature, especially for sections initially scored data-deficient for a given taxon. Expert opinion is beset with biases that are well understood and described (Burgman 2016). To minimise such biases, all information sources need to be documented, includ-

Table 1. Taxa analysed using the Risk Analysis for Alien Taxa (RAAT) framework under the South African NEM:BA A&IS regulatory lists of 2014 as revised 2016 with recommendations approved by the Alien Species Risk Analysis Review Panel up until end March 2020. Details of permit conditions (including cases where the listing varies depending on specific conditions, for example, for *Oreochromis niloticus*) are not shown. Listing categories are as follows: 1a – Nation-wide eradication target; 1b – Control target; 2 – Control target with permits; 3 – Control targets with certain exemptions. As species listed as 1b can also have exemptions, category 3 is redundant and is not considered as an option in the RAAT framework. All species assessed so far are known to be present in South Africa, except *Myocastor coypus* which was recommended to be listed as "prohibited". LIK is likelihood; CON is consequence; and MAN is management (see Figure 1).

Type of organism	Scientific name	LIK	CON	Risk	MAN	Current listing	Recommended listing
Arthropod	*Acarapis woodi* (Rennie, 1921)	Probable	MO	High	Difficult	1b	1b
Plant	*Acacia stricta* (Andrews) Willd.	Probable	MO	High	Medium	1a	1a
Plant	*Ailanthus altissima* (Mill.) Swingle	Fairly probable	MR	High	Medium	1b	1b
Bird	*Anas platyrhynchos* (Linnaeus, 1758)	Probable	MV	High	Medium	2	1b (with exemptions)
Plant	*Ageratina adenophora* (Spreng.) R.M.King & H.Rob. (= *Eupatorium adenophorum* Spreng.)	Probable	MR	High	Medium	1b	1b
Arthropod	*Carausius morosus* Sinety, 1901 [listed under Phasmatodea species (Jacobson & Blanchi, 1902)]	Fairly probable	MO	High	Difficult	1b (all Phasmatodea)	1b (*Carausius morosus* Sinety, 1901)
Plant	*Chondrilla juncea* L.	Probable	MV	High	Difficult	1a	1a
Plant	*Coreopsis lanceolata* L.	Probable	MO	High	Difficult	1a (Sterile cultivars or hybrids are not listed)	1b (the appropriateness of exemptions for sterile cultivars or hybrids was not assessed)
Mollusc	*Crassostrea gigas* (Thunberg 1793)	Probable	MR	High	Difficult	2	2
Plant	*Eugenia uniflora L.*	Probable	MO	High	Medium	1b	1b (with exemptions)
Plant	*Iris pseudacorus* L.	Probable	MR	High	Difficult	1a	1b
Plant	*Jatropha curcas* L.	Fairly probable	MO	High	Medium	2	1b
Plant	*Lilium formosanum* Wallace (= *L. longiflorum* Thunb. var. *formosanum* Baker)	Probable	MO	High	Difficult	1b	1b
Plant	*Melaleuca hypericifolia* Sm.	Probable	MN	High	Easy	1a	1b
Mammal	*Myocastor coypus* (Molina, 1872)	Unlikely	MR	High	Medium	2	Prohibited
Mollusc	*Mytilus galloprovincialis* Lamarck, 1819	Probable	MV	High	Medium	2	2
Fish	*Oreochromis niloticus* (Linnaeus, 1758)	Fairly probable	MV	High	Difficult	2	2
Plant	*Paspalum quadrifarium* (Lam 1791)	Fairly probable	MO	High	Medium	1a	1b
Arthropod	*Penaeus indicus* H. Milne-Edwards, 1837 [listed as *Fenneropenaeus indicus* (H. Milne-Edwards, 1837)]	Fairly probable	MC	Medium	Difficult	2	Delist
Plant	*Psidium cattleianum* Afzel. ex Sabine	Probable	MO	High	Medium	1b	1b
Bird	*Psittacula krameri* (Scopoli, 1769)	Probable	MV	High	Medium	2	1b
Bird	*Pycnonotus cafer* (Linnaeus, 1766)	Probable	MR	High	Easy	2	1a
Plant	*Ricinus communis* L.	Probable	MO	High	Medium	2	2
Plant	*Robinia pseudoacacia* L.	Fairly probable	MV	High	Difficult	1b	1b
Plant	*Sagittaria platyphylla* (Engelmann) J.G Smith	Probable	MO	High	Difficult	1a	1b
Plant	*Sasa ramosa* (Makino) Makino & Shibata	Very unlikely	MO	Low	Easy	3	Delist
Plant	*Senna bicapsularis* (L.) Roxb	Probable	MO	High	Medium	1b	1b
Plant	*Sphaeropteris cooperi* (F. Muell.) R.M. Tryon	Fairly probable	MR	High	Medium	Not listed	1b
Plant	*Syzygium jambos* L. Alston	Probable	MO	High	Easy	3	1b (with exemptions)
Arthropod	*Vespula germanica* (Fabricius, 1973)	Probable	MV	High	Medium	1b	1b

ing listing which experts were consulted and their expertise in the respective topic. It is also possible, and preferable in many cases, that taxa are assessed in working groups rather than by a single assessor to minimise bias (Burgman et al. 2011). In the South African case, and based on international best practice (e.g. Defra 2015), review of analyses through the ASRARP provides another mechanism to avoid bias (Kumschick et al. 2020a).

Assessors can also, of course, be biased and there is often considerable uncertainty when interpreting data (McGeoch et al. 2012; Vanderhoeven et al. 2017) and which is difficult to avoid. Clear guidance on how to respond to each question in the RAAT and formalised descriptions of each response option is provided in the form of scenarios to minimise assessor bias. It is important to indicate how confident the assessor is in the response provided (Carrington and Bolger 1998). The confidence score should give an indication on how confident the assessor is that the answer provided is correct. This generally depends on the amount and quality of data available on the taxon. We followed the guidelines as described in the European Plant Protection Organisation (EPPO) pest risk assessment decision support scheme and as published in Hawkins et al. (2015) for confidence ratings (see also Suppl. material 5).

Structure of the RAAT

The RAAT is divided into five sections and includes all aspects of risk analysis, namely risk assessment (sections 2 and 3), risk management (section 4), and risk communication (sections 1 and 5) (Fig. 1). The sections are abbreviated with three-letter acronyms: 1) Background (BAC) provides information on the assessor, the taxon under consideration, and information needed to perform the analysis; 2) Likelihood (LIK) assesses biological, ecological, and behavioural traits of the taxon that could lead to its arrival, establishment, and spread; 3) Consequences (CON) include the recorded and potential impacts of the taxon; 4) Risk management (MAN) includes questions related to the ability to control a taxon, whether the taxon is beneficial in some situations, and provides recommendations for management and/or listing of taxa; 5) Reporting provides guidance on how to communicate the outcomes of the analysis. This last section does not consist of questions, but is a compilation of the results of the previous four sections and provides an easily digestible summary for the communication of recommendations to stakeholders. Each section is discussed below.

1) Background

It is important to clearly outline the scope of the analysis to clarify what is assessed, for which region, and by whom. This section therefore includes the region of interest, the taxon for which the analysis is performed, and information on the taxon, as this forms the basis for data collection (Table 2).

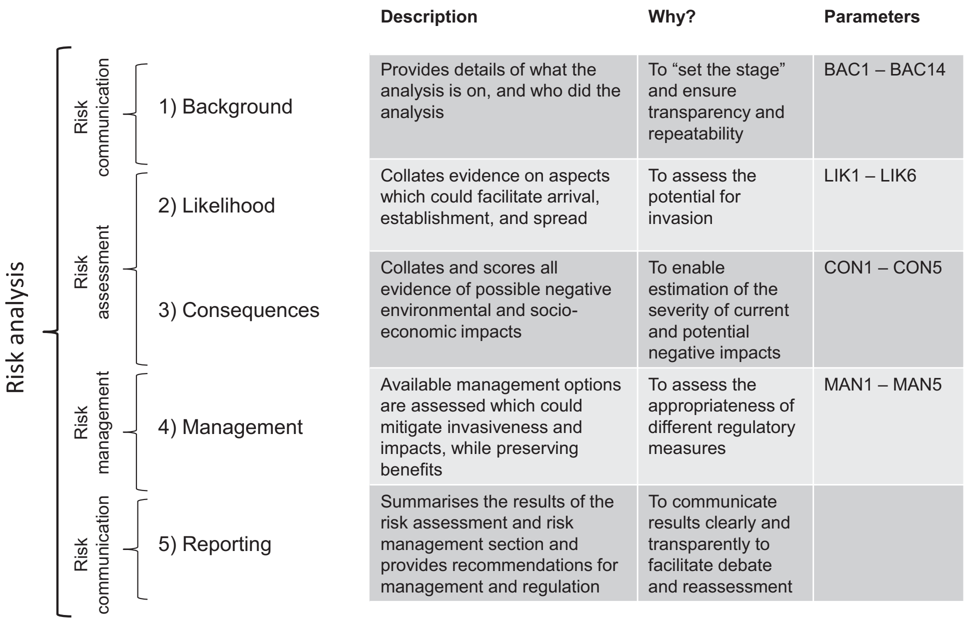

Figure 1. A schematic of the Risk Analysis for Alien Taxa framework described here. For each section a number of parameters need to be assessed (more detail in Table 2).

The region for which the risk analysis is performed is referred to as the *Area* (developed from the concept by D'Hondt et al. 2015). In most cases, analyses will be undertaken at a national level (e.g. South Africa), but the structure of the framework allows the analyses to be undertaken for different spatial units (e.g. for a national park or for the southern African region). However, the *Area* must be clearly specified and all questions referring to the *Area* specifically consider information with respect to the region chosen.

The taxon under assessment is referred to as the *Taxon*. The *Taxon* can be a species, sub-species, infra-specific entity, genus or any other taxonomic level. Risk analyses are mostly carried out on individual species as a standard taxonomic entity as, mostly, this is the level at which information is available, but this is not always appropriate, feasible or desirable. For example, different taxonomic levels are preferable: if the taxonomy of a group is not well resolved (e.g. some genera within the family Cactaceae, Novoa et al. 2015); if species are difficult to distinguish but the whole group (i.e. genus or family) poses a significant threat (e.g. certain taxa of mites or plant pathogenic rust fungi); and if there are important differences between sub-species or infra-specific entities (e.g. varieties and cultivars; see Datta et al. 2020 and Gordon et al. 2016). Ideally the analysis should consider whatever taxonomic grouping for which the risk is the same (e.g. Wilson et al. 2011), though in practice, this is very hard to achieve and species level assessments are therefore most common.

Table 2. A list of the parameters and information needed to complete the Risk Analysis for Alien Taxa.

Section	Parameter	Description	Definition and purpose
Background	BAC1	Name of assessor(s)	To identify the person who performed the assessment.
	BAC2	Contact details of assessor(s)	For means of contacting the assessors in case of questions, further information required or if the assessment needs revision.
	BAC3	Name(s) and contact details of expert(s) consulted	Identifies experts which were consulted.
	BAC4	Scientific name (including the authority) of *Taxon* under assessment	Gives information on the species, sub-species, variety, genus or other taxonomic entity under assessment.
	BAC5	Synonym(s) considered	Information on which synonyms were considered for the assessment.
	BAC6	Common name(s) considered	Information on which common names were considered for the assessment.
	BAC7	What is the native range of the *Taxon*?	Information on the distribution range of the taxon is important for the assessment as the framework is designed for alien species specifically.
	BAC8	What is the global alien range of the *Taxon*?	This is crucial as, for some questions, only information in the alien range is considered.
	BAC9	The *Area* under consideration	Delimits the geographic scope of the assessment area.
	BAC10	Is the *Taxon* present in the *Area*?	Crucial for management recommendations (e.g. prevention vs. control).
	BAC11	Availability of physical specimen	To link the identification of the taxon to a physical sample, as it is important to be able to refine the identity (BAC 4) in the light of new information and following taxonomic revision or the detection of errors in identification.
	BAC12	Is the *Taxon* native to the *Area* or part of the *Area*?	Important for management as this framework only deals with alien species.
	BAC13	What is the *Taxon's* introduction status in the *Area*?	Knowing the introduction status of populations (e.g. as per the Unified Framework of Biological Invasions, Blackburn et al. 2011) can aid with management decisions.
	BAC14	Primary (introduction) pathways	This information will be used to answer questions on likelihood of entry.
Likelihood	LIK1	Likelihood of entry via unaided primary pathways	The probability of the T*axon* to arrive and enter an area without human assistance.
	LIK2	Likelihood of entry via human aided primary pathways	The probability of the *Taxon* to arrive and enter an area human aided.
	LIK3	Habitat suitability	Forms part of the likelihood of a *Taxon* to establish.
	LIK4	Climate suitability	Forms part of the likelihood of establishment.
	LIK5	Unaided secondary (dispersal) pathways	Assesses spread potential.
	LIK6	Human aided secondary (dispersal) pathways	Assesses spread potential aided by humans.
Consequence	CON1	Environmental impact	Includes impacts caused by the *Taxon* on the environment through different mechanisms, based on EICAT (Hawkins et al. 2015).
	CON2	Socio-economic impact	Includes impacts caused by the *Taxon* on human well-being and livelihood, based on SEICAT (Bacher et al. 2018).
	*CON3	Closely related species' environmental impact	If no data on the *Taxon* itself are available, this includes impacts caused by related taxa on the environment through different mechanisms.
	*CON4	Closely related species' socio-economic impact	If no data on the *Taxon* itself are available, this includes impacts caused by related taxa on different socio-economic sectors.
	CON5	Potential impact	Assesses the potential impact of the T*axon* in the A*rea*, if invasive.
Management	#MAN1	What is the feasibility of stopping future immigration?	Important for effectiveness of control, as new influx of propagules needs to be stopped to control the *Taxon* effectively and sustainably.
	#MAN2	Benefits of the *Taxon*	Socio-economic and environmental benefits are included to assess the need of stakeholders for the *Taxon.*
	#MAN3	Ease of management	To provide indication of how easy the *Taxon* is to manage in the *Area* as this will influence risk management decisions.
	#MAN4	Has the feasibility of eradication been evaluated?	Indicates whether the feasibility of eradicating the *Taxon* from the *Area* has been formally evaluated. Note the evaluation of eradication feasibility is a separate process to the risk analysis framework.
	#MAN5	Control options and monitoring approaches available for the Taxon	Provides an overview of control options available.
	#MAN6	Any other considerations to highlight?	Can aid the development of management plans, permit conditions and exemptions.

* not assessed if CON1 and CON2 can be filled in respectively, i.e. information on impact is available for the *Taxon*; # not assessed if risk is low for the *Taxon*

2) Risk assessment: Likelihood

The section on likelihood assesses the probability of the *Taxon* to arrive, establish, and spread in the *Area*, with two questions for each process (arrival, establishment, and spread), resulting in six questions in total (LIK1–LIK6 in Suppl. material 2). These include questions on habitat and climate suitability and likelihood of entry and spread via aided and unaided pathways. Each answer is expressed as a probability value p, with all the levels and scenarios described in the narrative section and each level representing an order of magnitude difference. If the answer is not known after consulting literature and experts, following a precautionary principle, the answer is treated as p = 1 for the rest of the assessment, though noting that no answer was supplied and so highlighting an obvious area where more research is needed (Hulme 2012). For each probability level, we give general examples to provide guidance. These are structured as follows:

- Extremely unlikely (p = 0.000001): as likely as winning the lottery, if you play it once.
- Very unlikely (p = 0.0027): as likely as a new person you meet having their birthday on the same day as yours.
- Unlikely (p = 0.027): as likely as rolling two sixes when playing dice.
- Fairly probable (p = 0.5): as likely as getting heads when flipping a coin, i.e. fifty-fifty.
- Probable (p = 1 for calculation purposes): more likely to happen than not.

The probability levels of all the questions in this section are combined to calculate the likelihood of an invasion occurring. The final likelihood is calculated as the product of the maximum scores for each stage, i.e. p(arrival) [= max(LIK1, LIK2)] × p(establishment) [= max(LIK3, LIK4)] × p(spread) [= max(LIK5, LIK6)] (Suppl. material 2)].

RAAT thus incorporates some basic considerations of probabilities by multiplying the likelihoods of a taxon to cross the barriers in the invasion process, i.e., if the taxon cannot cross a certain barrier, the likelihood of establishment is decreased (Suppl. material 2: Fig. S2).

3) Risk assessment: Consequence

As it is important to get a comprehensive understanding of the potential harm caused by an alien taxon, it has been suggested that both environmental and socio-economic impacts should be included in risk assessments (e.g., Kumschick and Richardson 2013; Roy et al. 2018). The assessment of current and potential impacts, or consequences, is based on recent developments of impact scoring schemes (Blackburn et al. 2014; Nentwig et al. 2016; Bacher et al. 2018). EICAT is used for the assessment of environmental impacts (Blackburn et al. 2014; Hawkins et al. 2015). It was adopted by the International Union for the Conservation of Nature (IUCN) as a standard for the classification of alien taxa (IUCN 2020a, b), to be used alongside the Red List for the conservation of biodiversity. For socio-economic impacts, we initially used parts of the Generic Impact Scoring System (GISS) (Nentwig et al. 2016; see Kumschick et al. 2018). Since then, a new scoring scheme, more similar to EICAT and more consistent in the way impact levels are assigned, was published, namely the SocioEconomic Impact Classification of Alien Taxa (SEICAT) (Bacher et al. 2018). The version of the framework presented here therefore uses SEICAT instead of the GISS (Suppl. material 2), although all approved risk analyses reported in Table 1 are based on the GISS.

These impact scoring schemes have been shown to be intuitive to use, robust (Kumschick et al. 2017a, b), and transparent, and have proven to be applicable for a wide range of taxa (e.g., Kumschick et al. 2015; Evans et al. 2016; Kumschick et al. 2017a; Rumlerova et al. 2017; Hagen and Kumschick 2018; Kesner and Kumschick 2018; Nkuna et al. 2018). This makes them suitable for use as a component in a risk analysis framework. Another common feature of these impact assessment schemes is that all available evidence of impacts in the global alien range (including the *Area*) of the *Taxon* is collated and used for scoring (Hawkins et al. 2015; Nentwig et al. 2016; Bacher et al. 2018; see also Table 3 for an overview of the different impact levels). The guidelines cover each mechanism and sector through which alien taxa can affect the recipient regions, including competition, herbivory, and hybridisation for environmental impacts; and safety, material assets, and health for socio-economic impacts.

Table 3. Impact levels for the assessment of consequences in the risk assessment, based on Hawkins et al. (2015) and IUCN (2020a, b); Environmental impact), Bacher et al. (2018; Socio-economic impact), and this study (Potential impact).

Impact levels	Massive (MV)	Major (MR)	Moderate (MO)	Minor (MN)	Minimal Concern (MC)
Environmental impact (CON1 & CON3)	Causes at least local extinction of native species, and irreversible changes in community composition; even if the alien taxon is removed the system does not recover its original state.	Causes changes in community composition, which are reversible if the alien taxon is removed.	Causes local population declines in native species, but no changes in community composition.	Causes reductions in individual performance, but no declines in native population sizes.	No effect on performance of individuals of native species.
Socio-economic impact (CON2 & CON4)	Local disappearance of an activity from all or part of the area invaded; change is permanent and irreversible for at least a decade after removal of the alien taxon.	Local disappearance of an activity from all or part of the area invaded; change can be reversible within a decade after removal or control of the alien taxon.	Negative effects on well-being leading to changes in activity size; fewer people participating in an activity, but the activity is still carried out.	Alien species make it difficult for people to participate in their normal activities although the number of participants in any activity does not change.	No deleterious impacts reported despite availability of relevant studies with regard to its impacts on human well-being.
Potential impact (CON5)	The *Taxon* is a transformer in its native range, has ecosystem engineering properties or possesses other traits which suggest irreversible impacts on the community composition in the *Area* to occur. The *Taxon* is a pest of agricultural production in the native range and/or has the potential to cause high losses.	The *Taxon* has traits which suggest major impacts on native communities in the *Area*, but these impacts are likely to be reversible. The *Taxon* has traits which can lead to high losses to economy.	The *Taxon* possesses several undesirable traits. Due to the traits of the *Taxon* and/or its behaviour, it is expected to reduce population sizes of at least one native species. Economic loss is expected to be medium.	The *Taxon* does not possess any traits which could lead to effects on native species population sizes, but reduction in native individuals' performance is expected. Minor economic loss is possibly widespread.	Due to the traits of the *Taxon*, no effect on native individuals' performance is expected. No socio-economic loss is expected. The *Taxon* does not possess any undesirable traits.

These impact classification schemes, however, only consider impacts for which evidence is available (see also Kumschick et al. 2020b). Due to the lack of comprehensive impact studies for most species in most regions (e.g. Pyšek et al. 2008; Evans et al. 2016; Bacher et al. 2018; Kumschick et al. 2017a), the impact of alien species is likely under-reported. We therefore included the possibility to use data from congeners or other closely related species with similar life history traits to the RAAT framework (similar to Bomford 2008). Furthermore, to estimate potential and currently unrecorded impacts of the *Taxon* in the *Area*, we include considerations on the *Taxon*'s traits, behaviour, ecology, and impacts recorded in the native range (Table 3). This results in three to five questions related to impact – depending on data availability for the *Taxon* itself (Table 2). As we are interested in what the worst that could happen is, the maximum of the different impact scores is used as the consequence score.

The consequence score, together with the final probability from the Likelihood section, calculated as described above, are used to assess the level of risk (low, medium, high; as shown in Table 4). If the risk is low, no prioritised management or regulations are recommended and there is no requirement to complete the risk management section of the framework. If the risk is medium or high, however, the risk management section must be completed.

4) Risk Management

Generally, the distinction between whether or not (as opposed to how) to regulate a *Taxon* relies on the risks it poses to the recipient environment and economy. For taxa that are not yet present in an area and for which decisions on importation are required, this can be a relatively straightforward process: if the *Taxon* poses a high risk, it should not be allowed for import, but if it is low risk, it can be considered safe for import (e.g. Keller and Kumschick 2017). However, decisions regarding taxa that are already present and potentially well established in an area and are in use for various purposes, also depend on how easily they can be managed. Since management does not happen in isolation from the rest of society, social perceptions and benefits provided by the *Taxon* need to be assessed and accounted for in these cases (e.g., Zengeya et al. 2017). Unlike in the risk assessment section of the framework, where clear answers and probabilities are provided to determine the level of risk, the inclusion of benefits is dependent on the agenda of various stakeholders, priorities of decision-makers and the influence

Table 4. Table on how to determine the risk score from the likelihood and consequence assessments.

		Consequences				
		MC	MN	MO	MR	MV
Likelihood	Extremely unlikely	low	low	low	medium	medium
	Very unlikely	low	low	low	medium	high
	Unlikely	low	low	medium	high	high
	Fairly probable	medium	medium	high	high	high
	Probable	medium	high	high	high	high

of key stakeholders (e.g. Kumschick et al. 2012; Woodford et al. 2017). To keep the process transparent, we make provision for these aspects to outline how the inclusion of benefits influences management decisions and which benefits were included (Suppl. material 2).

Furthermore, once a taxon has been identified as posing a medium or high risk, one needs to consider what can be done to manage the risk. For taxa already present in the *Area* (i.e., for which prevention is no longer an option), this will often require a detailed evaluation of management options, the development of management plans, an assessment of financial resources, and a process of prioritisation of potential interventions (Wilson et al. 2017). Such detailed assessments are beyond the intended scope of the RAAT framework, as they also depend on political decisions and the allocation of resources. However, the RAAT framework provides for some basic management considerations which allow for a broad classification of how to treat certain risks. Therefore, the aim of this section is to provide some guidance as to which broad management goals should be investigated and what information is required in order to prioritise management actions.

The assessment of risk management is more open-ended, but needs to be documented in detail to assure transparency of decisions. In the RAAT framework, this includes socio-economic and environmental benefits, the feasibility to stop future immigration of the *Taxon,* and basic considerations regarding management feasibility (Suppl. material 2). The latter are based on Wilson et al. (2017) and Panetta and Timmins (2004) and include: a) accessibility of populations, b) whether detectability is time-dependent, c) time to reproduction, and d) propagule persistence of the *Taxon*. A scoring approach leads to a basic assessment of the ease of management.

Further to the assessment of these traits, it is important to note that for an assessment of eradication feasibility, a detailed study including, for example, the delimitation of all alien populations of the *Taxon*, population estimates, management trials, and some estimate of the return on investment of different competing strategies, should be conducted (Wilson et al. 2017). Eradication should not be set as a target if not evaluated in detail, as this could lead to a waste of limited resources (e.g., Cacho et al. 2007). To aid this process, there is a question in the framework asking if an eradication feasibility study has been performed for the *Area* (MAN4 in Suppl. material 2) and a further question on control options available (MAN5 in Suppl. material 2).

The answers provided in the risk management section feed into Fig. 2, which leads to broad recommendations on how to manage a *Taxon*. These differ, based on whether the *Taxon* is already present in the *Area*, whether prevention or eradication are feasible goals, and whether the *Taxon* has benefits to the *Area*, such that it might be a conflict species that could be allowed with a permit under certain conditions (Fig. 2).

5) Risk communication

Once the level of risk has been determined and options for management and benefits evaluated, it is crucial to clearly communicate the outcomes of the analysis to stakehold-

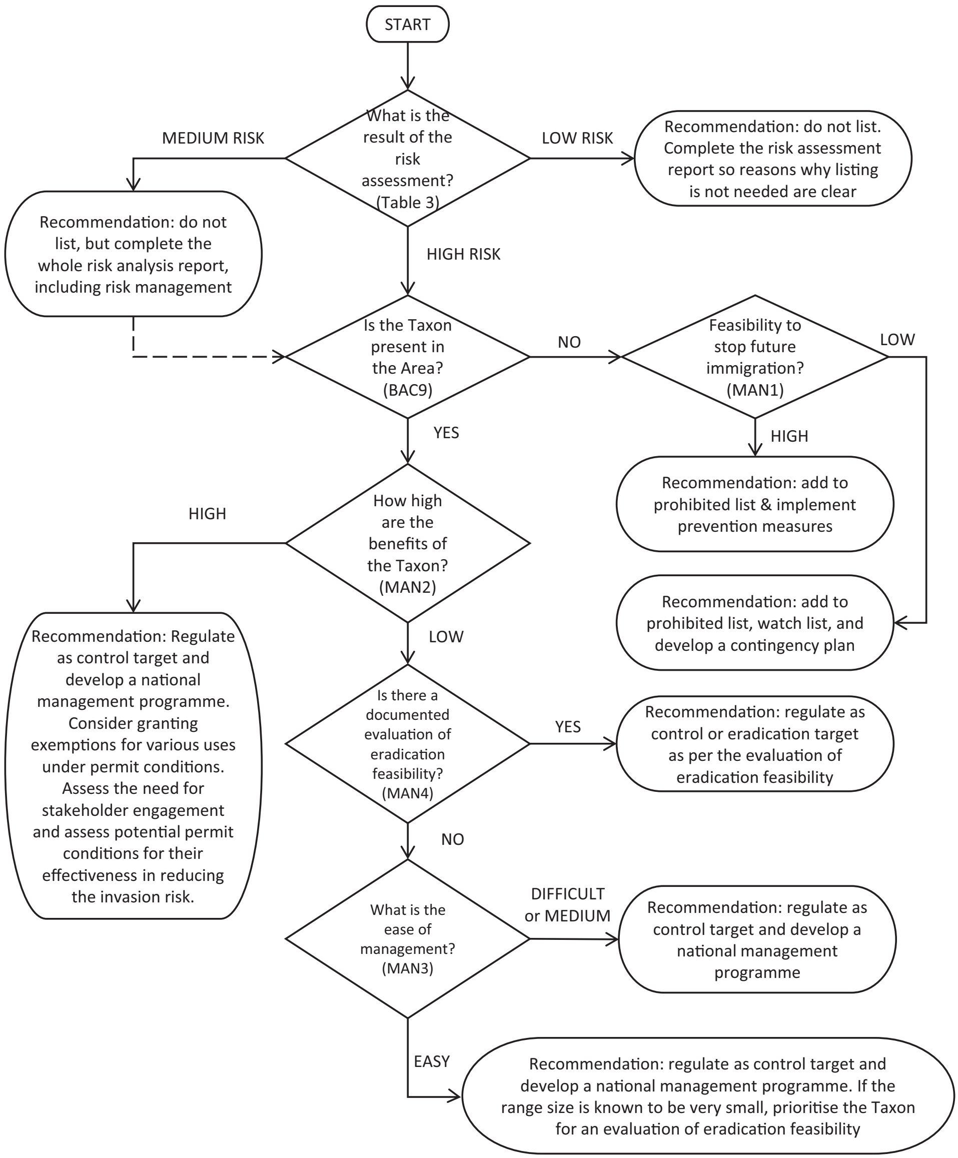

Figure 2. A decision tree for determining the appropriate regulatory response for species which are considered to be of medium or high risk during the risk assessment process. The information in brackets refers to question numbers in the RAAT framework (Table 1 and Suppl. material 2).

ers, including the general public, policy-makers, traders, and users of the *Taxon*. We identify two important components of risk communication. First, stakeholders need to be engaged during the risk analysis process for assessors to obtain information on the *Taxon* and to gain the support of stakeholders in the process (e.g., Novoa et al. 2018). There are often formal regulatory processes of stakeholder engagement and, in contentious cases, an independent scientific assessment might be needed (Scholes et al. 2017), but if conflicts are to be avoided, engagement should happen close to the outset of the process. Second, risk communication is important to provide stakeholders with sufficient information to understand the recommendations and be in a position to know under which circumstances decisions would change, for example, how new information will influence risk. Therefore, communication needs to be simple enough to reach understanding, but needs to provide enough information to underpin the decision.

In the RAAT framework, we incorporated several communication strategies to reach these goals. We provide a decision tree which uses information from the analysis to make recommendations on the management strategy for the *Taxon.* Fig. 2 describes how to arrive at recommendations for the management and regulation from the answers provided in the risk analysis. This depicts a simplified decision-making process which can be easily understood by policy-makers and stakeholders, while the details to feed into the flow diagram are documented and provided in detail in the full analysis. Furthermore, in addition to providing all details of the risk analysis with information on each parameter, we provide a template for an easy-to-digest summary and reporting sheet, including the conclusions from each section, with short descriptions on the *Taxon* itself, impacts, risks, ease of management, and benefits. An example of a summary sheet is given in the Suppl. material 3.

Application in South Africa

As discussed previously, the RAAT framework was tested and applied by different groups. This process has helped us to significantly refine (and we believe improve) the framework over time. It has also highlighted that, while the RAAT framework is fairly straightforward, some scientific experience is needed and assessors must be able to obtain a certain level of knowledge on alien taxa and the processes related to their invasion and impacts. Access to literature and experts is, therefore, also crucial. In South Africa for example, many employees of government agencies who initially tested the framework only had limited access to scientific literature and they therefore initially could not appropriately fill in some of the information required, even though relevant literature was available on the taxon (but not accessible to them).

To date, most taxa analysed with RAAT are of high risk (Table 1), which does not represent an ideal sample of taxa for a test of the applicability of the framework. This bias is due to the mandate of SANBI to analyse species which are currently regulated under the NEMBA A&IS Regulations, but for which no risk analysis had been performed to date. In addition, most taxa analysed so far are already present in South Africa (which was defined as the assessment area for all analyses). Ideally, species with different invasion statuses and risks should be analysed to test the RAAT framework further.

Notably for 13 of the 29 listed species that were assessed, a change in the listing category was recommended (Table 1). This is, again, likely due to the biased selection of taxa – in some cases, taxa were selected for analysis as they were contentious or it was felt the current category was inappropriate. However, it is clear that the listing of taxa, as determined during the original process, will be substantively different from the recommendations obtained by the process outlined here (i.e., completing the RAAT framework with the results reviewed and approved by ASRARP). The RAAT/ASRARP process (see Kumschick et al. 2020a) produces recommendations that are based on the best available scientific evidence, are peer-reviewed, and are transparent. The decision to list taxa, however, is the prerogative of the relevant government departments subject to a mandated requirement for public consultation. As of August 2020, the DFFtE was still in the process of establishing a cross-governmental decision-making panel on the risks of biological invasion. It is anticipated that ASRARP recommendations will be discussed at the meetings of such a panel.

Another lesson learnt was that it was important to train assessors in the application of the RAAT framework if uncertainties and misunderstanding in the questions, answer levels, and verbal descriptions were to be minimised (as also suggested by Sutherland and Burgman 2015). Such training ensures that the assessors applying the framework have a basic level of knowledge on risk analysis, alien taxa, and related processes. The training courses we ran also highlighted some important considerations to be made regarding the application of the RAAT framework. Firstly, there were some insights into the level of prior experience needed to complete a risk analysis. A BSc Hons degree in a relevant field (natural sciences) was mostly sufficient to understand the concepts provided after training, but a postgraduate degree (e.g. Masters) in a relevant field and experience in having authored a scientific publication (and specifically the experience of having responded to critical review comments) is very valuable in order to successfully complete a risk analysis and be able to respond appropriately to ASRARP reviews. Secondly, after training, the time to perform a risk analysis is 4–6 days, excluding the review by ASRARP and external reviewers, with the bulk of the time usually spent reviewing literature on a taxon. This is often increased due to the initial lack of access to primary literature.

While the RAAT framework strives to be objective, there is no guarantee that ASRARP and the assessor conducting the risk analysis agree on the outcome. During ASRARP deliberations it was decided that, if an assessor does not agree with changes requested by the ASRARP, an assessor can withdraw their risk analysis report and their report cannot subsequently be used by ASRARP or a third party. This has only happened once so far, but the issue of recognising potential biases is important – assessors who are knowledgeable on a taxon are likely to have specific views and motivations, while ASRARP members also have their own predilections.

Ideally, several experts should assess the same species and working groups and workshops held to reach final decisions on which species to list under national regulations (Sutherland and Burgman 2015). However, this was not an option in the South African case due to budgetary and time constraints. Increasingly, risk analyses are discussed at appropriate national working groups before submission to ASRARP [e.g., national working groups on alien Cactaceae, alien grasses, and a working group on alien animals in the Cape Floristic Region (Kaplan et al. 2017; Visser et al. 2017; Davies et al. 2020)]. The intention is that the risk analyses, once approved, represent both the best available scientific evidence and are also a consensus of those working on the species.

Dealing with risks that vary significantly with context

Beside the need to set appropriate management goals after risk analysis, there are some other considerations to be made specifically in the South African context. The NEMBA A&IS Regulations set out four potential listing statuses, all linked to specific conditions (Department of Environmental Affairs 2014; Kumschick et al. 2020b): Category 1a: eradication targets; Category 1b: control targets (potentially with exemptions); Category 2: control targets for which certain activities are allowed under permits with conditions; Category 3: control targets with exemptions. During the development and testing of the RAAT framework, it became clear that, with a desktop study (such as the RAAT framework) alone, these categories cannot always be conclusively determined. We therefore recommend that many of the management specific recommendations should be developed on a case by case basis for the species regulated. This includes, for example, suitable permit conditions for category 2 species, management goals for category 1b species (e.g., containment or asset protection, and the need for area-specific management), and the situations under which species can be exempt from conditions (this included category 3 species which are effectively listed the same as category 1b species with some specified exemptions according to the NEM:BA and its A&IS Regulations). Such exemptions could include trees declared as national monuments and protected as "heritage" (e.g., Dickie et al. 2014) should they prove not to contribute to the invasion. A related issue is that of subspecific entities – certain cultivars or varieties could be considered safe for cultivation even if the "parental stock" is invasive (e.g. Datta et al. 2020; Gordon et al. 2016). There is provision within the RAAT framework to assess sub-specific entities separately, but often data on underlying traits are missing (e.g., proof of sterility).

We believe that the RAAT framework is not the place to develop the details of such risk management issues in depth. This should rather be an integral part of the development of national management programmes for particular taxa that can elucidate where and when control should be targeted and when, perhaps, control will be ineffective (for South African examples of such plans, see, for example, van Wilgen et al. 2011; Le Maitre et al. 2015; Terblanche et al. 2016; and the discussion in van Wilgen and Wilson 2018).

Discussion and Way Forward

Biological invasions pose a variety of threats and risk analysis frameworks are needed to explicitly assess and help co-ordinate efforts to manage these. Many decision-support tools for the management of alien taxa have been developed (reviewed by Heikkilä 2011; Leung et al. 2012; Kumschick and Richardson 2013). The RAAT framework takes advantage of the lessons learnt from the application of previous schemes (e.g. Roy et al. 2018) and, therefore, has several key advantages: it provides a comprehensive structure, it addresses all the aspects of risk analysis in one framework, and it is applicable across taxa and regions. RAAT therefore provides a transparent and evidence-based tool to underpin policy decisions and to assist in the prioritisation of alien taxa for management.

Threats posed by biological invasions include not only individual alien taxa, but also invasion pathways and threats posed collectively to specific sites (CBD 2002; McGeoch et al. 2016; Essl et al. 2020). While the RAAT framework focuses on species-based assessments (Kumschick and Richardson 2013), it can feed into pathway and area-based approaches. By formalising risk in a practical and mathematically sound manner, we believe the RAAT framework provides a valuable additional tool for decision-makers, both to assess and manage the threat posed by alien species that are proposed to be deliberately and legally introduced, and to provide a co-ordinated way of providing the evidence base to justify regulating alien species already present in a country.

Ideally, a risk analysis framework for alien species would recommend the most appropriate management goal for an alien species to be regulated (e.g., see Booy et al. 2017). However, the RAAT framework is not exhaustive in terms of making decisions on which management goal is the most suitable for any taxon. Such decisions often need detailed consideration of political and budgetary constraints. In particular, the RAAT framework in isolation does not provide recommendations as to whether a taxon can be eradicated, but rather relies on detailed analysis of eradication feasibility (e.g., Panetta and Timmins 2004; Wilson et al. 2017). Our framework can, however, prioritise taxa for which more information should be gathered for this purpose.

More generally, the RAAT framework does not provide management plans for any taxon recommended for regulation as a control target (Fig. 2). There are several additional considerations that will need to be made when drafting management plans, for instance: Will stakeholders be opposed to management (e.g. access to land)? Are control efforts ethical? Might it be feasible to contain populations? Or should asset protection be the main goal of management? Should resources be spent to develop new control measures, for example, biological control? Such issues are important when attempting management and to reduce and mitigate the risks caused, but need to be considered explicitly outside of the RAAT framework and in many cases need practical considerations outside the realms of a desktop analysis.

In the next phase of development, the RAAT framework will be calibrated to adjust the preliminary cut-off levels set to assign risk categories (e.g. Kumschick and Richardson 2013). The questions, answer levels, and written descriptions as outlined in the Suppl. material 2 will not be affected by this process, but the levels of risk assigned, as shown in Table 3, might change according to the outcome. Generally, the RAAT framework allows for risk analyses to be updated if and when more information becomes available. Cut-off levels for low, medium, and high risk can be adapted if needed or as appropriate, however justification needs to be provided. It will also be important to assess the degree to which a risk analysis performed in South Africa on a given taxon can be used as the basis for a risk analysis of a given taxon in a different country or even a specific part of South Africa. As currently formulated, we suspect information on the likelihoods are context-specific, the potential consequences are more general and management considerations are a mix of the two, but this remains to be tested.

As more taxa in South Africa are analysed, new issues with the RAAT framework will undoubtedly arise. However, we feel that it represents a significant advance in making the process of regulating alien taxa more transparent, defensible, and more clearly linked to international protocols.

Accessibility of data

An updated version of the RAAT framework is appended here (Suppl. material 2, dubbed v1.2), but we plan to maintain the most recent version on the Zenodo server [DOI 10.5281/zenodo.3760907] and would encourage readers to check there for the latest version.

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Supplementary material 1

How the Risk Analysis Framework covers Section 6, Regulation 14-17, in the NEM:BA A&IS Regulations of 2014 (Appendix S1)

Authors: Sabrina Kumschick, John R. U. Wilson, Llewellyn C. Foxcroft

Data type: List of parameters and link to regulations

Explanation note: Questions in the Risk Analysis Framework and the aspects in the NEMBA A&IS Regulations (DEA 2014) they cover (Table s1.1) and aspects not covered in the Risk Analysis Framework which deal with the restricted activity regarding the permit application and are suggested to be requested for permit applications in a separate document (from NEMBA A&IS Regulations; DEA 2014) (Table S1.2).

Link: https://doi.org/10.3897/neobiota.62.51031.suppl1

Supplementary material 2

Risk Analysis for Alien Taxa framework, adapted to South African NEMBA A&IS Regulations (v.1.2) (Appendix S2)

Authors: Sabrina Kumschick, John R. U. Wilson, Llewellyn C. Foxcroft

Data type: Detailed guidelines for RAAT

Explanation note: Detailed guidelines for applying the Risk Analysis for Alien Taxa (RAAT) framework, including the reporting template.

Link: https://doi.org/10.3897/neobiota.62.51031.suppl2

Supplementary material 3

Example of RAAT (Appendix S3)

Authors: Sabrina Kumschick, John R. U. Wilson, Llewellyn C. Foxcroft

Data type: Example risk analysis

Explanation note: Example of a reporting sheet for the risk analysis of Psittacula krameria in South Africa. Note: this has been updated to the most recent format and is slightly different from the approved version.

Link: https://doi.org/10.3897/neobiota.62.51031.suppl3

Supplementary material 4

List of contributors to the risk analysis process in South Africa 2018, 2019 (Appendix S4)

Authors: Sabrina Kumschick, John R. U. Wilson, Llewellyn C. Foxcroft

Data type: List of assessors, reviewers and experts

Explanation note: Only people involved in risk analyses where the recommendation has been approved are noted here; there are many others who are currently involved as assessors, experts or reviewers, but they have not yet been involved in an approved risk analysis. Many other people were involved prior to 2018 (in particular the panel was set up and initially chaired by Philip Ivey), but the risk analysis framework had not been implemented at that stage. A 'Member' is someone who served on the Alien Species Risk Analysis Review Panel (with ex-officio members indicated with an asterisk); an 'Assessor' is someone who conducted a risk analysis; an 'Expert' is a person who is an Assessor and listed as someone who was formally consulted during the development of their risk analysis report; a 'Reviewer' is someone who reviewed a risk analysis report at the bequest of an ASRARP member (i.e. independent from the Assessor). In addition, Khensani Nkuna and Viwe Balfour assisted as part of the ASRARP Secretariat. It is intended that an updated list will be published annually on SANBI's website, but it can also be provided on request.

Link: https://doi.org/10.3897/neobiota.62.51031.suppl4

Supplementary material 5

Guidance regarding the use of the confidence rating (Appendix S5)

Authors: Sabrina Kumschick, John R. U. Wilson, Llewellyn C. Foxcroft

Data type: Guidance on confidence ratings

Explanation note: Guidance regarding the use of the confidence rating (taken from Hawkins et al. 2015, modified from the EPPO pest risk assessment decision support scheme (Alan MacLeod 09/03/2011; revised 28/04/2011; copied from CAPRA, version 2.74; 2)).

Link: https://doi.org/10.3897/neobiota.62.51031.suppl5