International survey explores how risk assessment tools for invasive species can be utilized successfully

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Abstract

Over the last few decades, the value of risk assessment tools in predicting biological invasions has become widely recognized. Risk assessment tools for invasive species are applied in a wide variety of contexts, with assessors operating in all parts of the world, in conjunction with many types of organizations, and with various objectives. We know that assessors' access to resources (including funding, training, data, and tools) often depends on where they work, what taxa they study, and what organizations they are associated with. However, we still lack a complete picture of precisely where, why, and how risk assessment tools are most frequently implemented. A clearer understanding of what tools work well in certain situations and what resources are necessary to use them will help assessors to select the correct tool for their situation. We also know little about whether the application of these tools (including the time, labor, and data that are used, as well as whether the output meets widely held standards for risk assessment) is influenced by situational factors (including where and why risk assessment is conducted, and what tools are used). I surveyed risk assessors, asking them questions about where and why they conduct risk assessment, what resources they use throughout the process, and how their results are used by the scientific community. Responses to my questionnaire suggest that risk assessment for invasive species is most commonly conducted for terrestrial plant species in western industrialized nations by workers for government agencies and research institutions, although many different risk assessment tools are used. I also found that uncertainty and peer review were often incorporated into the results, but that the results were often not made publicly accessible. Furthermore, I found that the situational contexts in which risk assessment is applied often influence the tools and data that are utilized, the extent to which uncertainty and peer review are included in the results, and the way the results are shared. My survey provides a clearer picture of how risk assessment is being applied, which aspects of risk assessment work well, and which aspects could use improvement.

Introduction

The threat posed by invasive species has become increasingly apparent, and global forecasts show that introductions of non-native species, as well as their impacts, will continue to accumulate (Early et al., 2016; Essl et al., 2011; Seebens et al., 2015, 2017). The outcomes of introductions are influenced by dispersal pathways, recipient ecosystems, and traits of the species that are being introduced (McGeoch et al., 2016; Moles et al., 2008; van Kleunen et al., 2010). Information about the characteristics of each of these components can be used to predict which species are likely to become invasive, as well as where (Fournier et al., 2019; Kolar & Lodge, 2001; Novoa et al., 2020). The usefulness of these characteristics as predictive variables has enabled the development of accurate and efficient risk assessment tools (D'hondt et al., 2015; Koop et al., 2012; Pheloung et al., 1999). Risk assessment forms the basis of risk analysis, and is supported by risk management and risk communication (J. Hill et al., 2020; Kumschick et al.,

2020; Vanderhoeven et al., 2017). Risk assessment tools are most frequently used to quantify and compare the relative risk of invasive species, but they are also sometimes used to analyze the risk posed by introduction pathways, the risk to recipient ecosystems, or a combination of the three (McGeoch et al., 2016; Novoa et al., 2020). Because risk is a function of both likelihood and consequences (Daehler & Virtue, 2010), a risk assessment tool considers both the potential for establishment and spread as well as the magnitude of potential impacts (Kumschick et al., 2020).

The management of invaders is most cost-effective when introductions of invaders are prevented or invaders are detected and identified early after their introduction (Epanchin-Niell, 2017; Keller et al., 2007). Thus, risk assessment protocols have gained popularity because they enable decision-makers to reject the intentional introduction of risky taxa and prioritize the management of incipient invaders (Martinez et al., 2020; Reaser et al., 2020). Additionally, risk assessment tools have become widely recognized as organized, objective, and transparent frameworks for communicating different elements of risk (Kumschick & Richardson, 2013). Though several risk assessment tools have repeatedly demonstrated high rates of accuracy (Copp et al., 2009; Gordon et al., 2008; Koop et al., 2012), the continued refinement of these tools remains a high priority in the field of invasion ecology (Keller & Kumschick, 2017; Kumschick & Richardson, 2013)

There is no singular, globally adopted approach to conducting risk assessment (McGeoch et al., 2016; Vanderhoeven et al., 2017). Risk assessment tools have been developed for many different scenarios – a recent publication approximates that 70 unique risk assessment tools have been developed (Roy et al., 2018), while an older publication states that over 300 risk assessment tools have been developed for invasive species (Leung et al., 2012). Many types of risk assessment tools exist because they have been developed by various stakeholders whose interests and constraints differ. Risk assessment tools for invasive species are applied in all parts of the world, by various different organizations with different goals and priorities. Some risk assessment processes are more detailed and comprehensive, while others are used for screening or identifying hazards (J. Hill et al., 2020). Because the results of these risk assessments are often poorly catalogued (Reaser et al., 2020), we still lack a detailed picture of precisely where, why, and how most risk assessment tools are typically used. A clearer understanding of how risk assessment is successfully applied in different scenarios could help assessors select the correct tool for their situation (Srebaliene et al., 2019; Vanderhoeven et al., 2017).

Additionally, we know little about how contextual factors may influence the implementation of risk assessment. At least six contextual factors may influence which tool is selected by an assessor (Figure 1). The first contextual factor is where risk assessment is being conducted. An assessor's capacity to carry out risk assessment may depend on their geographic location, as many risk assessment methodologies are prohibitively resource-intensive for countries with a lower human development index (Early et al., 2016; Faulkner et al., 2014). Furthermore, risk assessment tools frequently are developed for specific countries or regions, meaning that an assessor's choice of risk assessment tool is likely often dependent on where they are from (Bindewald et al., 2020; Early et al., 2016; Matthews, Velde, et al., 2017). A second contextual factor is the assessor's professional affiliation. The organization for which an assessor works could influence their choice of risk assessment tool because many tools were designed by and for particular agencies (Koop et al., 2012; Meyers et al., 2020; Reaser et al., 2020). A third contextual factor includes the priorities and needs of stakeholders and the specific reason(s) why an assessment is undertaken. For example, regulatory officials and resource managers have

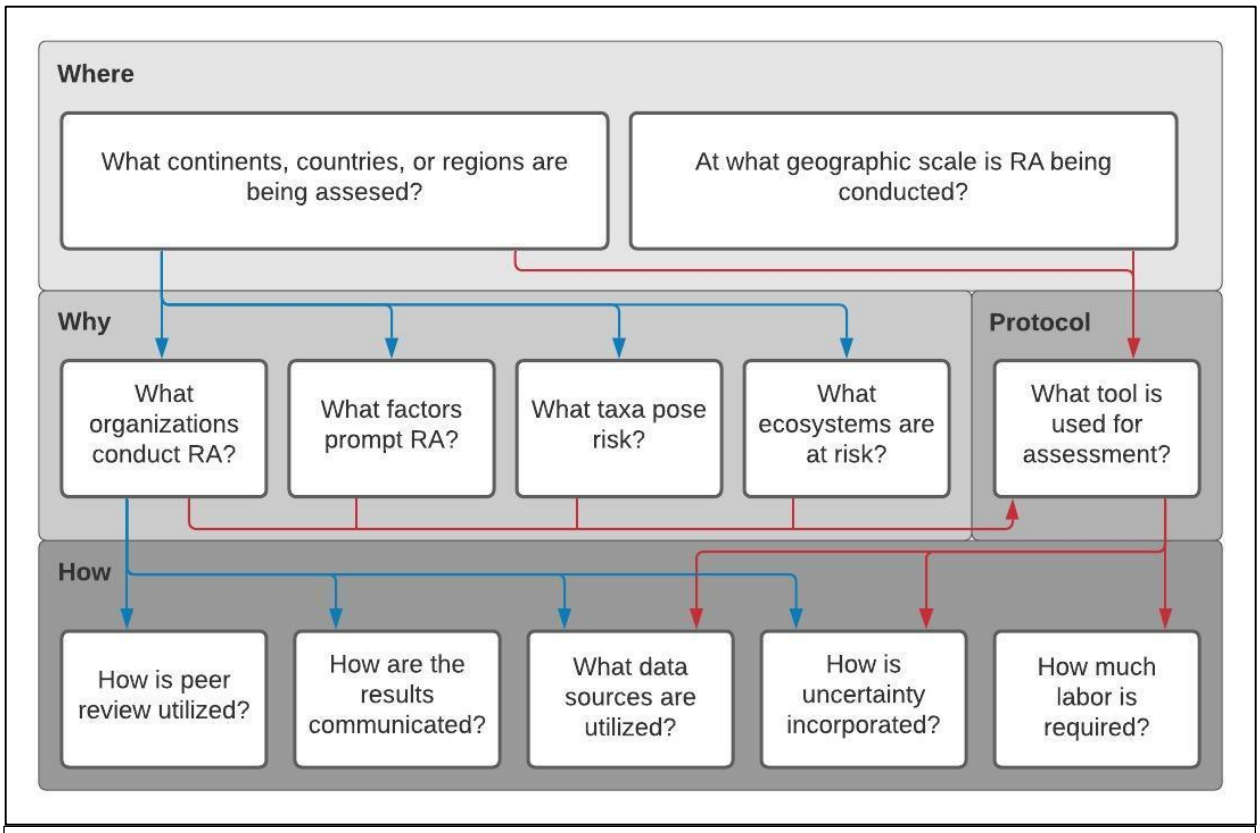

Figure 1. The geographic and sociopolitical context in which risk assessment is conducted affects which assessment tool a user will choose. Additionally, the details of how risk assessment is conducted depend both on these outlying factors and on the tool that is used. Blue arrows show potential relationships driven by situational factors such where risk assessment is being conducted, what organization is overseeing the process, what taxa are being assessed, and why risk assessment is being conducted. Red lines show potential relationships driven by built-in features of the chosen risk assessment tool.

developed risk assessment protocols independently from each other and with different purposes in mind, creating a distinction between pre-border screening tools and post-border prioritization tools (Devorshak, 2012; Křivánek & Pyšek, 2006; McGeoch et al., 2016). Also, because there is an inherent trade-off between the amount of time taken and the amount of detail included in a risk assessment (Keller & Kumschick, 2017), different tools might be selected based on whether speed or precision is more crucial in a given situation. The fourth contextual factor is the type of taxa that is being assessed, and the fifth is the type of ecosystem that is being assessed. These oft-related contextual factors matter because many risk assessment tools are not transferrable between different taxonomic groups or ecosystems (Kumschick & Richardson, 2013). Finally, the geographic scale at which risk assessment is being conducted is also an important contextual factor, because tools are often designed to be implemented exclusively at a particular geographic scale (Dahlstrom et al., 2011).

In addition to influencing which risk assessment tool is used by an assessor, these contextual factors may also place constraints on other aspects of the risk assessment process. Specifically, the amount of funding or access to data may differ between particular regions or organizations or between taxonomic groups (Beaury et al., 2020; Early et al., 2016; Matzek et al., 2014; Turbelin et al., 2017), potentially affecting the outcome of risk assessment. As another example, items such as uncertainty, peer review, or public participation may be incorporated into

risk assessment differently (or not at all) depending on what organization is responsible for overseeing the process (Matthews, Velde, et al., 2017; Reaser et al., 2020). Additionally, the risk assessment tool itself may dictate how much time, experience, and data is necessary to complete a risk assessment (Keller & Kumschick, 2017; Roy et al., 2018; Verbrugge et al., 2012). Also, some components of risk assessment such as uncertainty and peer review are inherently ingrained into some tools more so than others (Roy et al., 2018; Vanderhoeven et al., 2017; Verbrugge et al., 2012). Because of this, it has been difficult to disentangle how these contextual factors and the selected protocol combine to influence the outcome of risk assessments.

To address biological invasions at a global scale, we need a better understanding of where, why, and how risk assessment tools are applied, as well as how the application of risk assessment varies situationally. Toward this end, I developed and administered the first survey of invasive species managers with experience in risk assessment, asking them questions about where, why, and how they implement risk assessment. My goals were 1) to attain a clearer picture of where risk assessment is being conducted, what taxa are being assessed, what tools and data are being used, and how the results are being implemented, and 2) to explore possible patterns among assessors that might explain how contextual factors influence the risk assessment process.

Methods

Ethics

Throughout the data collection process, I followed standard procedures of survey design, which have been used in similar studies (Beaury et al., 2020; Gozlan et al., 2013; Matzek et al., 2014). Participants were made aware that the survey was confidential, that their anonymity would be maintained, that their cooperation was voluntary and that they could drop out of the study at any time. Participants were given the option to share their email address if they wished to receive updates about the study, but otherwise no personally identifying information was solicited. My survey was approved by the University of Florida's Institutional Review Board, ID #202001808.

Surveyed population and questionnaire

My goal was to survey assessors of all regional, professional, and taxonomic contexts. The questionnaire was distributed through two listservs, Ecolog and Aliens-L. At the time the questionnaire was distributed, Ecolog had approximately 27,000 subscribers and Aliens-L had 1,470 subscribers; however, since the topical scope of each listserv extends far beyond risk assessment, there is no precise way of knowing how many assessors the questionnaire reached. To bolster the response rate from regions with fewer listserv subscribers, I also sent invitations directly to authors of peer reviewed papers about invasive species risk assessment from underrepresented regions. The questionnaire was open from December 2020 to March 2021. The questionnaire asked participants to share where, why, and how they completed risk assessments, using a mixture of list-all-that-apply, check-all-that-apply, Likert-scaled, multiple choice, and open-ended questions (Table 1). The questionnaire contained 30 questions and took an estimated 10-15 minutes to complete. All data was collected through Qualtrics software.

Table 1. Questions and response options included in a survey of invasive species managers with experience in Risk Assessment. Our survey was designed to elucidate where, why, and how Risk Assessment for invasive species takes place.

Q#	Question (number of responses)	Response type	Response options
	Questions about your Risk Assessments - Basics		
Q1	Which Risk Assessment tool(s) have you used? (88)	Fill in the blank	
Q1a	What Risk Assessment tool do you currently use most frequently? (88)	Fill in the blank	
Q2	What continents at risk have you conducted Risk Assessments for? (88)	Select all that apply	Africa, Asia, Australasia, Europe, North America, South America, Other
Q2a	For what regions have you conducted Risk Assessments? (Answer this question only if you selected 'Other' for the previous question.) (9)	Open-ended	
Q3	Please list the specific countries/regions/areas for which you have completed Risk Assessments. (79)	List all that apply	
Q4	To what geographic scale do most of the Risk Assessments you have completed apply? (88)	Select all that apply	Continental, Country, Regional (state, province, territory, county), Other
Q4a	To what geographic scale do your Risk Assessments apply? (Answer this question only if you selected 'Other' for the previous question.) (9)	Open-ended	
Q5a	How often have you evaluated the following taxonomic groups? (Select all that apply.) - Plants (88)	Likert	Never, Sometimes, Half, Most, All
Q5b	How often have you evaluated the following taxonomic groups? (Select all that apply.) - Birds (88)	Likert	Never, Sometimes, Half, Most, All
Q5c	How often have you evaluated the following taxonomic groups? (Select all that apply.) - Mammals (88)	Likert	Never, Sometimes, Half, Most, All
Q5d	How often have you evaluated the following taxonomic groups? (Select all that apply.) - Reptiles/Amphibians (88)	Likert	Never, Sometimes, Half, Most, All
Q5e	How often have you evaluated the following taxonomic groups? (Select all that apply.) - Invertebrates (88)	Likert	Never, Sometimes, Half, Most, All
Q5f	How often have you evaluated the following taxonomic groups? (Select all that apply.) - Fungi (88)	Likert	Never, Sometimes, Half, Most, All
Q5g	How often have you evaluated the following taxonomic groups? (Select all that apply.) - Algae (88)	Likert	Never, Sometimes, Half, Most, All
Q5h	How often have you evaluated the following taxonomic groups? (Select all that apply.) - Microorganisms (bacteria, viruses, etc.) (88)	Likert	Never, Sometimes, Half, Most, All
Q5i	How often have you evaluated the following taxonomic groups? (Select all that apply.) - Other (88)	Likert	Never, Sometimes, Half, Most, All
Q5j	How often have you evaluated the following taxonomic groups? (Select all that apply.) - Other - Text (21)	Open-ended	
Q6a	What ecosystems have you conducted Risk Assessments for? (Select all that apply.) - Terrestrial (88)	Likert	Never, Sometimes, Half, Most, All
Q6b	What ecosystems have you conducted Risk Assessments for? (Select all that apply.) - Marine (88)	Likert	Never, Sometimes, Half, Most, All

Q6c	What ecosystems have you conducted Risk Assessments for? (Select all that apply.) - Freshwater (88)	Likert	Never, Sometimes, Half, Most, All
Q6d	What ecosystems have you conducted Risk Assessments for? (Select all that apply.) - Other (88)	Likert	Never, Sometimes, Half, Most, All
Q6e	What ecosystems have you conducted Risk Assessments for? (Select all that apply.) - Other - Text (6)	Open-ended	
	Questions about your experience conducting Risk Assessments		
Q7	How many years have you been conducting Risk Assessments? (87)	Multiple choice	Less than one year, At least one year but less than three years, At least three years but less than five years, At least five years but less than ten years, At least ten years
Q8	Over the last 3 years, how many Risk Assessments have you done? (86)	Multiple choice	10 or less, 11-50, 51-100, over 100
Q9a	Which factors typically prompt you to initiate a new Risk Assessment? - Academic exercise (88)	Likert	Almost never, Rarely, Sometimes, Often, Almost always
Q9b	Which factors typically prompt you to initiate a new Risk Assessment? - New species proposed for import or use (88)	Likert	Almost never, Rarely, Sometimes, Often, Almost always
Q9c	Which factors typically prompt you to initiate a new Risk Assessment? - Newly detected species (recent introductions and expanding range) (88)	Likert	Almost never, Rarely, Sometimes, Often, Almost always
Q9d	Which factors typically prompt you to initiate a new Risk Assessment? - Identify potential threat to the region (from a horizon scan or similar tool) (88)	Likert	Almost never, Rarely, Sometimes, Often, Almost always
Q9e	Which factors typically prompt you to initiate a new Risk Assessment? - Concern of risk to the region (directly from stakeholders) (88)	Likert	Almost never, Rarely, Sometimes, Often, Almost always
Q9f	Which factors typically prompt you to initiate a new Risk Assessment? - Review of species currently under regulation/review of current policy (re-assessment) (88)	Likert	Almost never, Rarely, Sometimes, Often, Almost always
Q9g	Are there any other factors that typically initiate a new Risk Assessment not mentioned above? Please explain. (16)	Open-ended	
Q10	For the Risk Assessment tool you use most commonly, how long does it take you to compete the whole review process for a Risk Assessment of a species? (88)	Multiple choice	An hour or less, At least an hour but less than a day, At least a day but less than a week, At least a week, but less than a month, At least a week
Q11	What organization(s) do you report back to with your completed Risk Assessments? (87)	Select all that apply	Government agency, University of research institutions, Private consultancy, Non-profit/non-governmental organizations, Other

Q11a	If you selected 'Other', please explain. (11)	Open-ended	
	Questions about your opinions regarding who is qualified to conduct RA's		
Q12	What do you think is the minimum level of education required for an assessor to proficiently conduct a Risk Assessment? - Selected Choice (88)	Multiple choice	Secondary or high school, Some college but no degree, Associate's degree, Bachelor's degree, Master's degree, Doctorate degree, Other
Q12a	What do you think is the minimum level of education required for an assessor to proficiently conduct a Risk Assessment? - Other - Text (8)	Open-ended	
Q13	What is your level of education? - Selected Choice (87)	Multiple choice	Secondary or high school, Some college but no degree, Associate's degree, Bachelor's degree, Master's degree, Doctorate degree, Other
Q13a	What is your level of education? - Other - Text (3)	Open-ended	
Q14	How many hours' worth of training do you think are required to become proficient at conducting a typical Risk Assessment? (88)	Multiple choice	1-3 hours (half a day), 4-8 hours (full day), 9-16 hours (up to two days), 17-40 hours (up to a week), 40-160 hours (up to a month), >160 hours (more than a month)
Q15	Do you feel that the completion of a training/certification program should be a pre-requisite for conducting Risk Assessments? (67)	Multiple choice	Yes, No, Unsure
	Questions about how you source data used in RA's		
Q16	Please select up to three online databases you most frequently use to find taxonomic data for Risk Assessments from the options below. If your most frequently used database(s) are not listed please list them in the section below. (85)	Select up to three	None of these, Algaebase, Amphibian Species of the World, ASM Mammal Diversity Database, Avibase, Eschmeyer's Catalog of Fishes, FishBase, Global Lepidoptera Names Index, Index Fungorium, Index Herbarium, International Plant Names Index, ITIS-Integrated Taxonomic Information System, MycoBank,

			Nomenclator Zoologicus, PESI- Pan-European Species directory Index, The Consortium for the Barcode of Life project, The Reptile Database, TROPICOS, WCSP- World Checklist of Selected Plant Families, Wilson & Reeder's Mammal Species of the World, World Flora Online, WoRMS- World Register of Marine Species, ZooBank
Q16a	Specify database(s) if not listed above. (60)	Open-ended	
Q17	Please select up to three online databases you most frequently use to find general data for Risk Assessments from the options below. If your most frequently used database(s) are not listed please list them in the section below. (86)	Select up to three	None of these, Aquatic Invasive Alien Species Web portal for ASEAN countries, BioNET's regional networks, CIESM- Atlas of Exotic Species in the Mediterranean, DAISIE- Delivering Alien Invasive Inventories for Europe, EPPO- European Plant Protection Organisation, EASIN- European Alien Species Information Network, FISNA- Forest Invasive Species Network for Africa, GISD- Global Invasive Species Database, Inter-American Biodiversity Information Network, NAPPO-PAS- The North American Plant Protection Organization- Phytosanitary Alert System, NIMPIS- National Introduced Marine Pest Information System, NOBANIS- The North European and Baltic

			Network on Invasive Alien Species, RBIC- Regional Biological Invasions Centre, GCW- Global Compendium of Weeds, CABi ISC- Invasive Species Compendium, EDDMaps, APFISN- Asia-Pacific Forest Invasive Species Network
Q17a	Specify database(s) if not listed above. (45)	Open-ended	
Q18	Please select up to three online databases you most frequently use to find occurrence data for Risk Assessments from the options below. If your most frequently used database(s) are not listed please list them in the section below. (87)	Select up to three	None of these, ALA- Atlas of Living Australia, AquaNIS, BISON- Biodiversity Information Serving Our Nation, BONAP- Biota of North America Program, CABi ISC- Invasive Species Compendium, EASIN- European Alien Species Information Network, eBird, EDDMaps, eDNAtlas database, GBIF- Global Biodiversity Information Facility, GloNAF- Global Naturalized Alien Flora database, GRIIS- Global Register of Introduced and Invasive Species, iDigBio, iNaturalist, Map of Life, National Exotic Marine and Estuarine Species Information System (NEMESIS), OBIS- Ocean Biogeographic Information System, VertNet
Q18a	Specify database(s) if not listed above. (38)	Open-ended	
Q19	What Risk Assessment-related data do you have the most difficulty finding? (69)	Open-ended	
Q20	How much of your data comes from peer-reviewed sources? (88)	Multiple choice	None - all from grey literature and/or expert opinion, A small amount, A moderate

			amount, A large amount, All data comes from peer-reviewed sources
Q21	How much of your data comes from expert opinion? (88)	Multiple choice	None - all from published sources (either grey literature or peer-reviewed publications), A small amount, A moderate amount, A large amount, All data comes from expert opinion
	Questions about how you implement completed RA's		
Q22	Is there a peer-review process in place for your Risk Assessments? (88)	Multiple choice	Always, Sometimes, Rarely, No, Unsure
Q23	If there is a peer-review process in place, is it internal review or external review? (82)	Multiple choice	Internal, External, Both, Neither
Q24	Do you incorporate uncertainty or confidence into your Risk Assessments? (88)	Multiple choice	Always, Sometimes, Rarely, No, Unsure
Q25	At some point of the process, are your Risk Assessments open for public comment? (88)	Multiple choice	Always, Sometimes, Rarely, No, Unsure
Q26	Are the results of your Risk Assessments accessible to the public? (88)	Multiple choice	Always, Sometimes, Rarely, No, Unsure
Q27	Where are your Risk Assessments published? (36)	Open-ended	
Q28	How are the results of your Risk Assessments used in policy and regulatory measures? (79)	Open-ended	
	Final things		
Q29	If you would like to share any other information about your experience conducting Risk Assessments, feel free to use the space below to do so. (24)	Open-ended	
Q30	If you would like to receive updates on the results of our study, please provide your contact information in the space below. Thank you again for completing our survey! (52)	Open-ended	

Data analysis

Questionnaires with less than 80% of the questions answered, as well as questionnaires where the respondent indicated that they did not personally have experience with risk assessment, were dropped from the study. Eighty-eight surveys were completed sufficiently. Because some questions had a response rate of less than 100%, sample size for each question varied throughout the survey. Because some questions included list data or multiple answers, the results are reported as proportions of the total number answers for each question, and proportions add up to over 100% for some questions.

Because the dataset included variables with two or three categorical responses, I used Chi-squared tests of independence with simulated p-values to explore whether or not correlations between variables existed. I additionally calculated Cramer's V values to assess the relative

strength of the correlations I found. Cramer's V values of >0.15 can be interpreted as strong correlations, and values of >0.25 can be interpreted as very strong correlations (Akoglu, 2018).

For the sake of data analysis, respondents were grouped into two categories based on whether they had conducted risk assessments in one of the regions from which results of risk assessments are commonly reported. These regions are primarily western and industrialized, including Europe and the United Kingdom, Canada, the United States, South Africa, Australia, and New Zealand. Respondents who have conducted risk assessment primarily in one of these regions were placed into the first category and all other respondents were placed into the second category. My reason for doing this was to contrast and compare the regions where risk assessment is less well-studied with the regions where more literature about risk assessment has been published. I also grouped the A-WRA and the -ISK family of tools (FISK, AS-ISK, and FI-ISK) together for data analysis. I had multiple reasons for doing this; they are very similar species-based trait-scoring tools (the FISK tool was based directly on the A-WRA), and they represent the two most widely used risk assessment tools for invasive species, based on previous reports (Copp et al., 2016; Kumschick & Richardson, 2013; Lawson et al., 2013).

Results

Descriptive results

I received responses from all continents except Antarctica (Figure 2). However, response rates from certain regions were notably higher than others. All respondents listed at least one continent for which they have conducted risk assessment (n=88). I found that 45% have conducted risk assessment in North America (n=40), 28% have conducted risk assessment in Europe (n=25), 26% have conducted risk assessment in Asia (n=23), 19% have conducted risk assessment in Africa (n=17), 8% have conducted risk assessment in Oceania (n=7) and 8% have conducted risk assessment in South America (n=7). Many (though not all) respondents provided further information about the specific countries and regions for which they have conducted risk assessment. Countries with the highest percentages of respondents included the US (30%, n=26), Canada (11%, n=10), and Australia (9%, n=8). All other countries were represented by four or fewer respondents. 77% of respondents (n=68) were from the western industrialized regions, including the European Union, the United Kingdom, the United States, Canada, Australia, New Zealand, and South Africa. In response to the question about the scales at which assessors conduct risk assessment (n=88), I found that 17 conducted risk assessment at a continental scale (n=15), 57% conducted risk assessment at national scale (n=50), 49% conducted risk assessment at a regional scale (n=43), and 23% conducted risk assessment at a scale that aligned with other geographic or geopolitical borders (n=20).

Most participants (98%) answered the question about the organizations to which they report (n=86; Figure 3). Of these assessors, a majority were associated with government agencies (73%, n=63). A large contingent of assessors were also associated with a research institution (43%, n=38). Smaller percentages were affiliated with nonprofits/NGO's (19%, n=16), private consultancies (8%, n=7), or other organizations (11%, n=10). Among the assessors, the most common reason for conducting risk assessment was to scanning for future threats (41%, n=36), followed by concern from stakeholders (33%, n=29), policy review (30%, n=26), early detection (27%, n=24), academic exercise (24%, n=21), and proposed imports (22%, n=19). 57% (n=50) of respondents indicated that they primarily assessed plant species, 19% (n=16) primarily

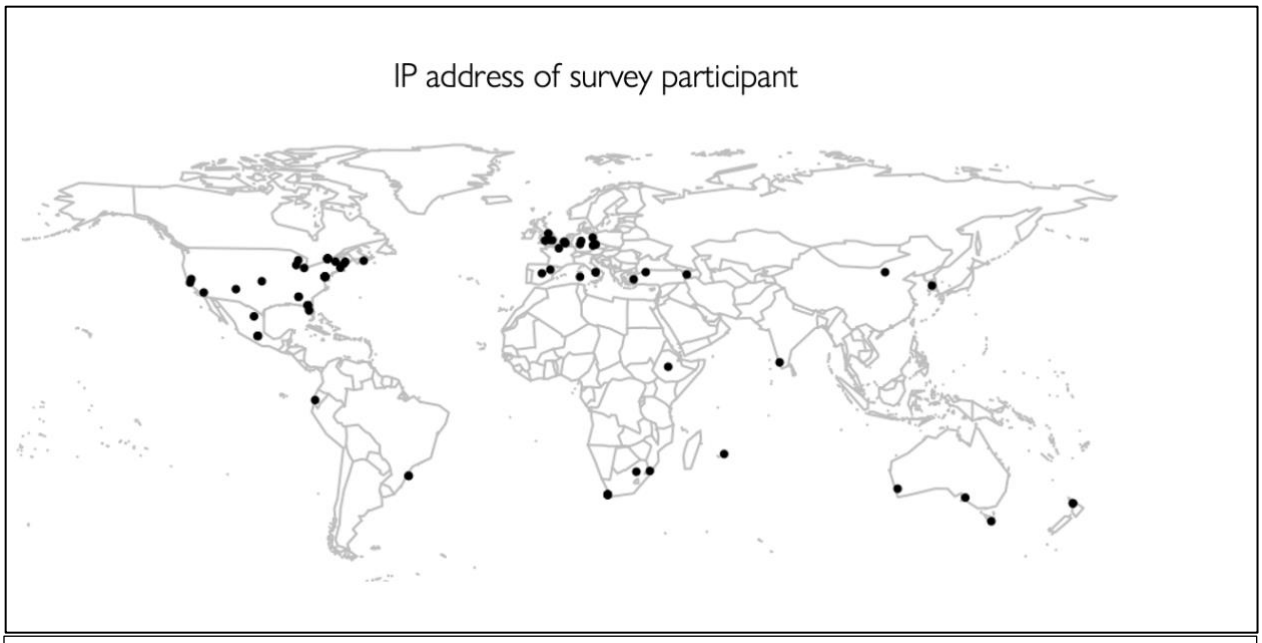

Figure 2. Locations of the individuals who responded to my survey.

assessed invertebrates, 11% (n=10) assessed fishes, 9% (n=8) assessed terrestrial vertebrates, and 11% (n=10) assessed other taxonomic groups including fungi, algae, and microbes. Out of those who responded to the question about what types of ecosystems they assess, 77% (n=67) assess terrestrial ecosystems at least half of the time and 33% (n=29) assess aquatic ecosystems at least half the time.

Details of how risk assessment was applied by assessors varied widely. Respondents reported using over fifty different risk assessment tools, and the majority were used by only a small proportion of respondents. Notable exceptions include the Australian Weed Risk Assessment (A-WRA, Pheloung et al., 1999), the Fish Invasiveness Scoring Kit (FISK, Copp et al., 2009; Lawson et al., 2013), the Aquatic Species Invasiveness Scoring Kit (AS-ISK, Copp et al., 2016), and the Plant Protection and Quarantine Weed Risk Assessment (PPQ-WRA, Koop et al., 2012). 30% of respondents (n=26) reported that they primarily used either the A-WRA or one of the -ISK tools (Figure 4).

Similarly, I found that many databases were listed by respondents but that many of these were used only by a narrow audience. I found a similar trend among the databases which were listed by respondents. The Integrated Taxonomic Information System (ITIS) was by far the most widely used database for retrieving taxonomic information. The Global Biodiversity Information Facility (GBIF) was the most popular database for finding occurrence data, and the Centre for Agriculture and Bioscience International Invasive Species Compendium (CABI-ISC) was widely used to obtain both occurrence data and general data about the species being assessed. Approximately two-thirds of respondents indicated that a large amount of their data came from peer-reviewed sources, while less than 10% of respondents said that a large amount of their data came from expert opinion. With regards to the frequency and method of peer review, over 60% of respondents said that they always apply peer review to their assessments, and 40% said that they apply both internal and external peer review. Over three-quarters of respondents indicated that they always incorporate uncertainty into their assessments. Just 20% of respondents said that members of the public always had opportunities to make comments during the risk assessment

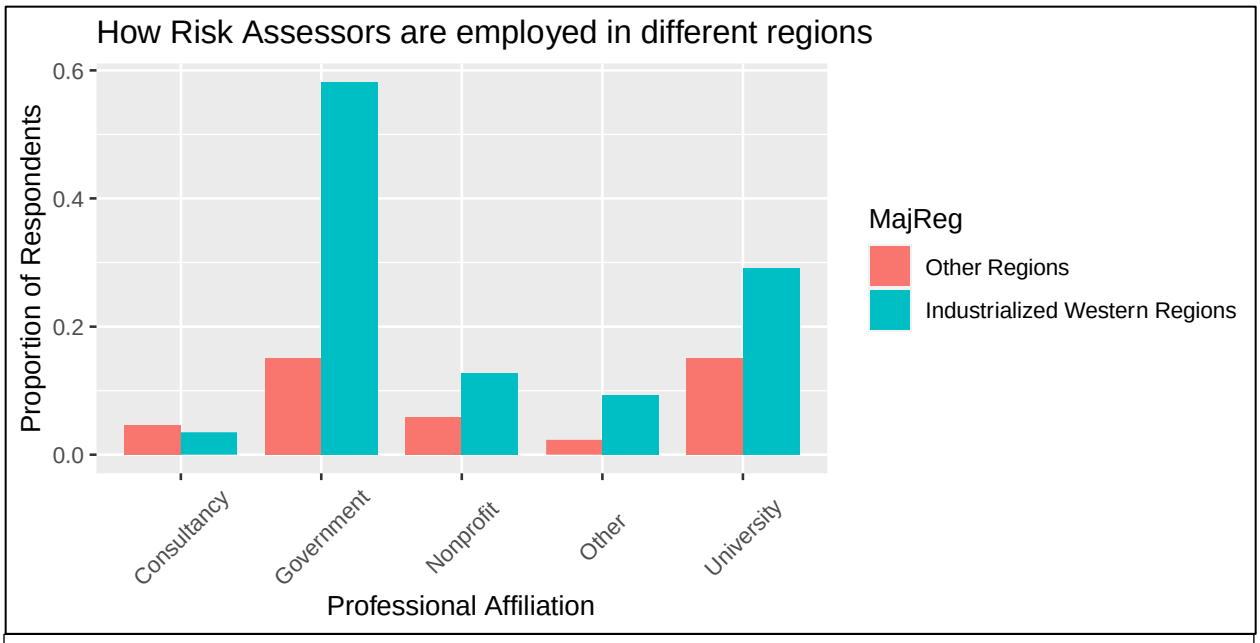

Figure 3. Types of organizations that oversee the Risk Assessment process, both in western industrialized nations and in other parts of the world.

process, and 43% said that the results of their assessments were always made available to the public (Figure 5).

The amount of experience held by respondents varied considerably. I found that out of 86 assessors who shared how many years they had been conducting risk assessment, 36% (n=31) had less than five years of experience, 27% (n=23) had between five and ten years, and 37% (n=32) had over ten years. Out of those who shared how many assessments they had completed in the last three years, 41% (n=35) had completed less than ten, 36% (n=31) had completed between ten and fifty assessments, and 22% (n=19) had completed more than fifty. The largest proportion of respondents take between a day and a week to complete a single risk assessment, although some take less than an hour and others take over a month. Over 60% of respondents held doctorates, but most respondents mostly agreed that risk assessment could be conducted by those with either or Bachelor's or Master's degree. Respondents varied widely in how much training they felt was necessary to conduct risk assessment. Some indicated that less than a day or training would suffice while others thought that over a month was necessary, but respondents most commonly answered that more than a couple days but less than a week was an appropriate amount of training. Over 70% of respondents indicated that they thought a certification program could serve as a useful prerequisite for conducting risk assessment.

Correlations between variables

The results of my Chi-squared tests indicated several tentative correlations between variables. I found that the organizations responsible for overseeing risk assessment and the assessor's reasons for conducting risk assessment were often correlated with the region where risk assessment took place. Respondents from western industrialized nations were less likely to work for a research institution (V=0.27) or a consultancy (V=0.27), and more likely to conduct risk assessment for the purposes of academic exercise (V=0.21) or early detection (V=0.28) than

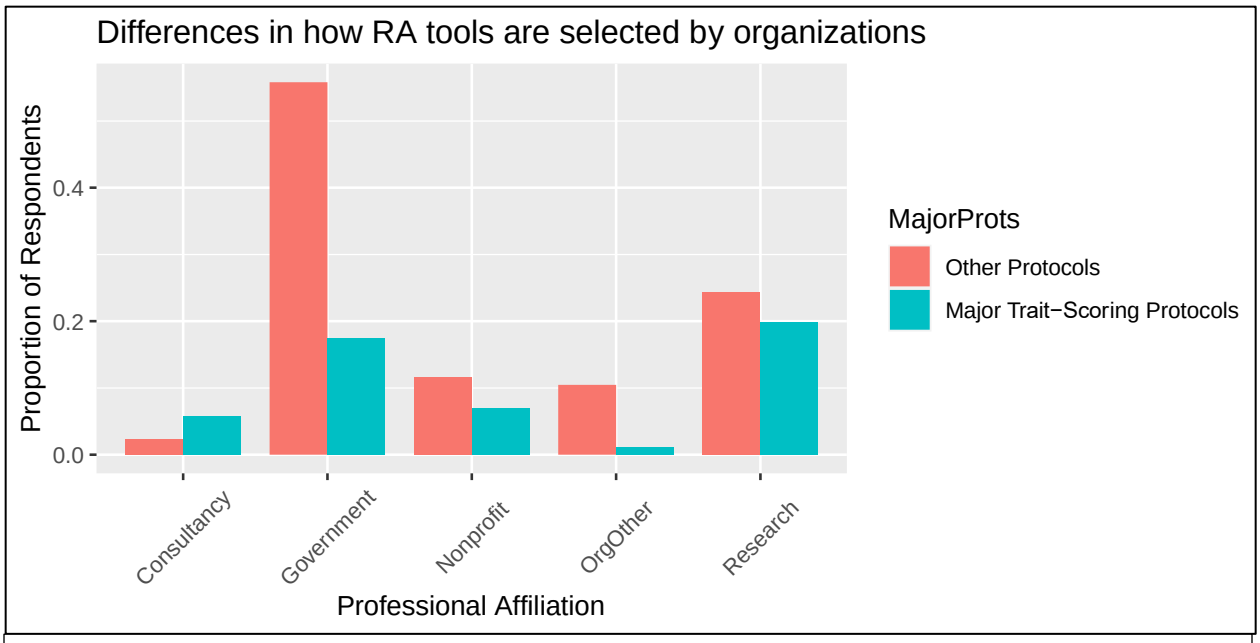

Figure 4. The types of Risk Assessment protocols that are selected by employees of different types of organizations.

respondents who were from other regions. I also found correlations between where risk assessment was conducted and the type of risk assessment protocol that was chosen. Those from the western industrialized regions were more likely to have adopted the niche tools that are less widely used (V=0.18), while those from other regions were more likely to primarily use either the A-WRA or FISK. These tools were also more likely to be used to conduct risk assessment at a regional scale (V=0.21) than other types of tools. The type of organization an assessor worked for was also often correlated with the type of risk assessment tool that they used. Respondents were less likely to primarily use either the A-WRA or FISK if they worked for government agencies (V=0.20), but were more likely to primarily use one of these tools if they were employed by consultancies (V=0.28) or research institutions (V=0.31).

The extent to which uncertainty, peer review, and public accessibility were included in risk assessment was often strongly correlated with the organization that was responsible for overseeing the process and the type of risk assessment tool that was used. Government employees were more likely to always apply peer review (V=0.27) and to apply both internal and external peer review (V=0.32) than those who did not work for government agencies. They also tended to have more experience (V=0.53) and tended to have completed more risk assessments over the last three years (V=0.38). On the other hand, employees of research institutions were less likely to incorporate peer review (V=0.32) or uncertainty (V=0.22) into their assessments than those who did not work for research institutions, and tended to have fewer years of experience (V=0.51). Assessors who worked for nonprofit organizations were less likely to utilize peer review (V=0.29) or measure uncertainty (V=0.20) than those who did not work for nonprofits. These assessors were also more likely to rely on expert opinion as a data source (V=0.21) and to spend less than a week working on any given risk assessment (V=0.22). Similarly, employees of consultancies were relatively likely to rely on expert opinion as a data source (V=0.27) and were relatively unlikely to incorporate peer review (V=0.28) compared to those who did not work for consultancies.

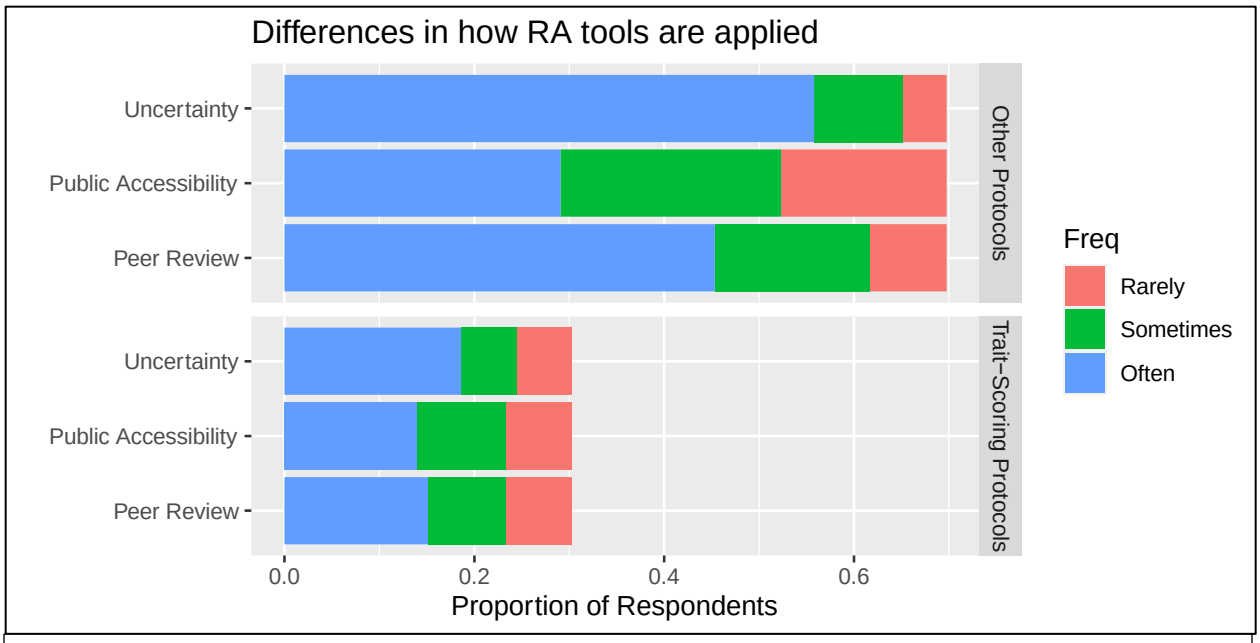

Figure 5. How respondents incorporate uncertainty, public accessibility, and peer review, both when they use common the trait-scoring tools A-WRA and FISK and when they use other tools.

Finally, I found that the type of tool that was chosen also had effects on how risk assessment was applied. Assessors who primarily utilized either the A-WRA or FISK were less likely to incorporate uncertainty into their risk assessments (V=0.22), and they were more likely to use expert opinion as a data source (V=0.27). They also were much less likely to spend longer than a week working on a single risk assessment (V=0.33). The amount of experience necessary, the frequency and type of peer review, and the accessibility of results were not correlated with the type of protocol that was used.

Discussion

Where, why, and how risk assessment tools are being used

Previous authors have suggested that risk assessment takes place primarily in industrialized western nations (Early et al., 2016), at national or regional scales (Bindewald et al., 2020; Matthews, Beringen, et al., 2017), for government agencies (Meyers et al., 2020), and for plant taxa in terrestrial ecosystems (Kumschick & Richardson, 2013). By actually sampling the population of invasive species risk assessors, I have provided the strongest evidence yet for these claims by proving that these are in fact the contexts where risk assessment is most frequently conducted. I also uncovered considerable variation among assessors regarding the reasons why they conduct risk assessment. Scanning for potential threats was the most common reason why people conducted risk assessments, suggesting that risk assessment is often used in a proactive way.

My study shows that a surplus of risk assessment protocols are available, further demonstrates the widespread popularity of trait-scoring approaches such as the A-WRA and FISK (Keller & Kumschick, 2017), and suggests that few of the risk assessment tools in existence are used in a wide variety of contexts (Bindewald et al., 2020; Meyers et al., 2020). I

found several correlations within the dataset which suggest that contextual factors may partially determine what risk assessment tools are used and how they are applied. For example, I found that the common trait-scoring approaches (A-WRA and FISK) were more widely used by assessors from less industrialized nations. The A-WRA and FISK have become widely popular because they are both quite intuitive and adaptable while also maintaining a high rate of accuracy (Copp, 2013; Gordon et al., 2008; Kumschick & Richardson, 2013). Therefore, it makes sense that their use is especially prevalent in regions with fewer resources to allocate towards risk assessment. These trait-scoring approaches seem to be widely adopted by consultancies and research institutions, but they are less widely used by employees of government agencies. This is possibly because employees of government agencies may be required to use more comprehensive risk analysis tools, or they may be more likely to have opportunities to develop their own resources. For example, though the A-WRA has been widely used for over twenty years, researchers have often cited its shortcomings and have searched for ways to improve it (Hulme, 2012; Koop et al., 2012; McGregor et al., 2012). On the other hand, I found less diversity among protocols used for aquatic ecosystems. It seems that those who assess aquatic ecosystems have widely adapted the -ISK family of protocols (Vilizzi et al., 2019), and have not developed as many alternatives.

It could be that perceived flaws in these screening tools have led researchers to explore more comprehensive risk analysis approaches, or other more robust risk assessment tools such as the Risk Analysis for Alien Taxa (RAAT, Kumschick et al., 2020) or Harmonia+ (D'hondt et al., 2015). These tools are less widely used, likely because they have been developed more recently. These tools differ from the A-WRA and FISK because they can be fine-tuned to produce risk scores that align more closely with an assessor's priorities and definition of risk (D'hondt et al., 2015). Additionally, items such as uncertainty and communication are more thoroughly ingrained in the structure of these tools (D'hondt et al., 2015; Kumschick et al., 2020), ensuring that they will be included consistently regardless of who conducts the risk assessment. The downside is that their complexity endows them with a steeper learning curve (Keller & Kumschick, 2017), which may prevent assessors with less training or fewer resources from using them. However, I found little evidence for a correlation between what tool was used and how much experience was required to use it, and tools such as Harmonia+ and RAAT could probably be used more widely if assessors were provided with the proper training.

The results of my survey also show that the way in which uncertainty, peer review, and public accessibility are applied often depend both on what organization is overseeing the assessment and on what tool is used to conduct the assessment. Also, an assessor's employment status (whether they were employed by a government agency, research institution, nonprofit organization or consultancy) often makes a difference in terms of what data they were likely to incorporate into their assessments. Studies by Matzek et al. (2014) and Beaury et al. (2020) also revealed that managers of invasive species may use different types of data depending on who employs them, with members of some agencies being more likely to use peer-reviewed data than others.

Additionally, I found that assessors who primarily use the trait-scoring tools A-WRA or FISK were less likely to spend longer than a week working on a single assessment, and less likely to incorporate uncertainty into their analyses. These observations seem to reflect both the advantages and disadvantages of these tools (Koop et al., 2012). These assessors seemingly were more likely to rely on expert opinion as a data source. This could indicate that these tools have fewer data limitations than other tools, or that these tools are more likely to be used in situations

where peer-reviewed data are scarce. However, conclusions should be drawn carefully because my sample size is scant and respondents may not always be entirely accurate.

Considerations for risk assessment

In many ways, assessors seem to be meeting the standards for risk assessment which were proposed by Roy et al. (2018). For example, my finding that the majority of assessors always incorporate uncertainty into their assessments was pleasantly surprising, because previous reviews of risk assessment have suggested that many tools do not formally quantify uncertainty (Devorshak, 2012; Roy et al., 2018). The majority of assessors also frequently implement some type of peer review process, which is encouraging because peer review counterbalances subjective biases and makes the application of risk assessment more consistent (Vanderhoeven et al., 2017). Another positive thing I found is that risk assessment is often conducted proactively, which increases the chances that invaders can be detected and eradicated early (Early et al., 2016; Martinez et al., 2020). Additionally, I found that dozens of databases are utilized by assessors, and my results suggest that assessors are typically able to rely on high-quality, peer-reviewed data for the majority of their risk assessments.

I also found that there are dozens of tools available to assessors. Such a diversity of tools helps to ensure that needs of all stakeholders can be accommodated. However, with the advent of tools such as Harmonia+, which can be applied to any region or taxa, it may be time to consider whether so many tools are necessary. Though tools with a narrower scope may still sometimes be the most accurate option for specific situations, risk assessment could perhaps be streamlined if assessors were encouraged to use more broadly applicable tools or if training opportunities were more accessible. The results of the survey suggest that adaptable and intuitive tools such as the A-WRA and FISK are relied upon most heavily in regions where resources are limited and convenience is important. Risk assessment capabilities in such regions could potentially be enhanced if these trait-scoring tools were supported with more advanced climate-matching techniques and estimates of propagule pressure. Alternatively, a robust and comprehensive tool such as Harmonia+ could potentially be used to make consistent predictions across regions if users could be helped over the learning curve with more extensive training.

The use of risk assessment could perhaps be more standardized if fewer tools were used. Studies have found that the most widely used risk assessment tools often achieve consistent results (Copp, 2013; Gordon et al., 2008; Vilizzi et al., 2019), and guidelines explaining how risk assessment tools should be used (e.g., Gordon et al., 2010) have become the norm (Kumschick et al., 2020; Roy et al., 2018). However, other studies have found inconsistent classifications of risk when the same taxa is assessed with different tools (Bindewald et al., 2020; Magarey et al., 2018; Matthews, Velde, et al., 2017). A large amount of variation among classifications is due to the fact that risk assessment tools weigh components of risk differently (Leung et al., 2012), or that they have different definitions of what constitutes a high level of risk. For instance, invasiveness may be interpreted from any of several demographic factors (Catford et al., 2016; Speek et al., 2013), such as local abundance, geographic range, environmental range, or spread rate. Risk assessment tools are typically unclear about specifically what type of invasion risk they aim to quantify, and this lack of clarity may hinder comparisons among tools. Some risk assessment tools place greater importance on the abundance and/or spread of an invader, while others may have greater consideration for its impacts (Daehler & Virtue, 2010; Hulme, 2012). Different risk assessment tools may also consider some types of impact to be more important than others.

Inconsistency in risk classification can also arise from conflicts between data sources. When assessors prefer different data sources, as was sometimes the case in this study, the data that informs risk assessment may be inconsistent, leading to diverse and uncertain outcomes. Finally, inconsistency may also stem from differences in subjective opinion or bias held by assessors, or by the organizations for which they work (Hulme, 2012).

To make risk assessment a more consistent discipline, all sources of inconsistency (including assessors, tools, and data) must be addressed. I found that assessors are already taking several steps to ensure that their output is consistent, such as incorporating measurements of uncertainty and utilizing peer review. Perhaps the most obvious next step that could be taken towards making risk assessment a more consistent discipline would be enabling assessors to share their results more easily. My survey highlighted the reality that the results of risk assessment are infrequently shared with the public. Previous authors have called for the development of databases or clearinghouses where the results of risk assessments could be stored (J. Hill et al., 2018; Meyers et al., 2020; Reaser et al., 2020). A clearinghouse containing the results of risk assessments could make it simple to see what taxa have been assessed, what areas the assessments apply to, and what tools and information were used in the assessments. The potential benefits of a clearinghouse such as this are obvious. Fewer assessments would need to be conducted if results were more openly shared, which would ease the burden on regions or organizations with a limited capacity to conduct risk assessment. Additionally, a clear summary of the risk classifications that have resulted from assessing taxa with different tools could make it much easier to make comparisons between tools and further explore differences in how different tools produce different classifications. By publishing the results of risk assessments more frequently, scientific journals could also provide an independent source of external peer review and increase their accessibility.

This study has provided a clearer understanding of what tools are used by assessors, as well as what situations these tools are used in and what resources are required to use the tools. The study has also suggested that the incorporation of uncertainty, peer review, and public accessibility (and therefore the overall quality of risk assessment) may be affected by the context in which risk assessment takes place and the tools which are used to conduct it. Future studies should investigate whether inconsistency can be reduced by making uncertainty, peer review, and risk communication standard practices in risk assessment, or whether inconsistency could be more effectively managed by developing and supporting a robust, flexible, and user-friendly protocol that can be applied to all contexts and reducing the usage of redundant tools. These steps will be important in making risk assessment a more unified discipline.

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