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Preventing the Next Plant Invasion: Opportunities and Challenges

Kudzu, a vine well known across the southeastern United States, was introduced in the 1800s as an ornamental plant and later as forage and erosion control. The plant, native to China and Japan, spread quickly across the region and is now listed as a noxious weed in 13 states. They story of kudzu provides a cautionary tale to the dangers of an invasive plant on native lands. Photo from Rob Hainer/Shutterstock.

Introduction

Global trade has been one of the primary factors contributing to the increase in invasive species worldwide and as international trade has grown, so has the movement of non-native species across borders (Meyerson and Mooney 2007). In the past 50 years, the number of non-native species introduced outside their native range has doubled and along with climate change and habitat degradation, invasive species have been identified as major drivers of biodiversity loss worldwide, a problem that is not going away (IPBES 2019). In fact, the establishment of non-native species is projected to increase 36% globally by the year 2050 (Seebens et al. 2021). Since 1960, there have been approximately $1.26 trillion dollars in economic losses to invasive species in North America alone, averaging $21.64 billion in losses per year (Crystal-Ornelas 2021). Economic and ecological losses can occur through many mechanisms including when non-native species become weeds that reduce crop yields, negatively impact rangeland for cattle, increase fuel loads that promote fire that can damage property and alter ecosystem function, reduce biodiversity, and increase vulnerability of native ecosystems to global factors such as climate change, land use change, and pollution.

The invasion curve illustrates the control strategies for an invasive species (prevention, eradication, containment, and long-term maintenance control), depending on its extent of spread over time (Figure 1). As the area infested increases, so do the economic and ecological costs, while the likelihood of eradication diminishes. It is well-established that the economic returns on prevention and eradication early in the invasion curve far outweigh those for subsequent containment and maintenance control (Lodge et al. 2016; Cuthbert et al. 2022). As economic and ecological threats posed by invasive species become increasingly apparent, efforts to avoid

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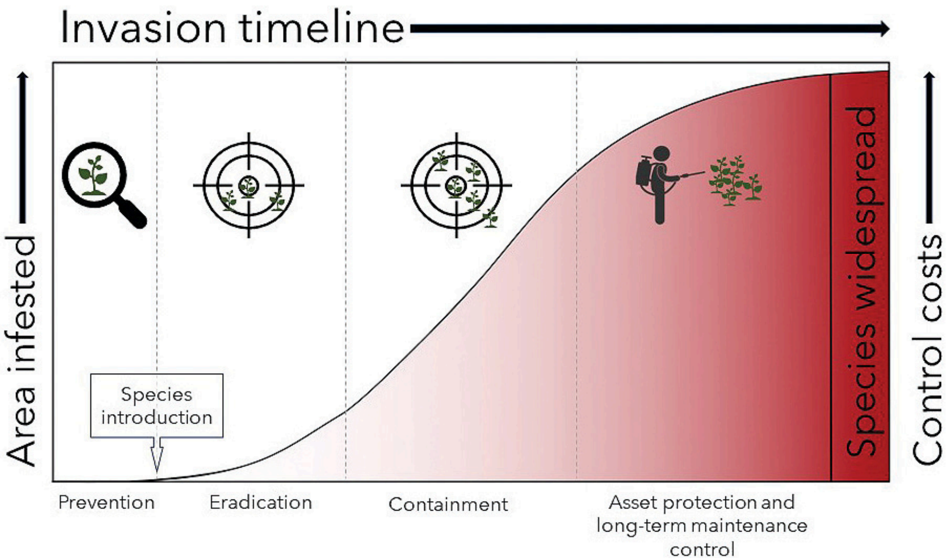


Figure 1. A generalized invasion curve illustrates four phases of invasive species management where the likelihood a species will be controlled decreases and control costs increase as the area infested grows (adapted from Victorian Government 2010).

these impacts must focus on preventing establishment of potential invaders, ideally even before the species is introduced into a new area.

The process of invasion occurs in stages – transport, introduction, establishment, and spread of non-native species (Blackburn et al. 2011). At each of these invasion stages, there may be obstacles the species must overcome to continue the process. If the obstacles cannot be overcome, the invasion process stops. For example, a plant imported from another country might be planted outdoors in the new location. If this plant has a narrow tolerance to climatic conditions (such as precipitation or temperature), it might not survive in natural areas to establish there. Other situations that might halt invasion include unsuitable habitat or inadequate soil nutrient conditions, presence of natural enemies (e.g., pathogens, herbivores), competition with native plants, and lack of specialist pollinators. Consequently, very few non-native species introduced into a new location will spread and ultimately become invasive; but those that do persist through the invasion stages will eventually exert substantial and highly detrimental impacts on their environment. In some cases, non-native species may take decades or even centuries before they begin to spread, a period of time known as the “lag phase” (Simberloff 2008). Reasons for their subsequent spread vary, but may include increased propagule pressure (e.g., repeated introductions; Lockwood et al. 2005) or increased availability of different genotypes such as commercial cultivars that can cross-pollinate in self-incompatible species (e.g., Callery pear; Culley and Hardiman 2009). Habitat disturbance through natural means (e.g., tornado or flooding) or human-induced disturbance (e.g., moving soil for building construction, urbanization) can also open areas for seed dispersal and subsequent establishment of non-native species.

The introduction of these potentially invasive, non-native species can be accidental or intentional through different pathways. Accidental introductions occur when a species is brought to a new environment inadvertently, usually due to human activities such as trade, travel, or transport. Plants and their propagules (e.g., seeds or rootable stem fragments) may be accidentally introduced through the movement of machinery, vehicles, or boats/angling equipment or may hitchhike on ships in ballast and planes in cargo (Harrower et al. 2019). By far the most prominent pathway for accidental introductions of plants, forbs and especially grasses, is arrival as seed contaminants (propagules contaminating seed shipments; Lehan et al. 2013). Thus, the U.S. Department of Agriculture Animal and Plant Health Inspection Service (USDA APHIS) and U.S. Customs and Border Protection inspectors (using APHIS' authority) are critical to prevent the entry of potential contaminants and known invasives at points of entry to the United States. As worldwide travel and commerce expands over time, the likelihood of accidental introductions will only increase. However, within recent decades, accidental introductions have been thought to be a relatively minor source of plant invasion.

The primary pathway for new invasive plants in the United States is through their deliberate introduction (Mack 2003; Lehan et al. 2013; Beaury et al. 2021b; Culley and Feldman 2023). Intentional introductions occur when a plant species is deliberately brought into a new environment for a specific purpose, such as for ornamental or horticultural use, as a food source or medicine, or for erosion control. For example, in the 1600s English colonists brought medicinal plant species like garlic mustard (*Alliaria petiolata*) and Queen Anne's lace (*Daucus carota*) with them to North America to plant around settlements so they could be readily available for medical treatment (Mack 2003; Reichard and White 2001). Kudzu (*Pueraria montana*) is perhaps the most notorious example of an intentional introduction, in this case, for erosion control (Box 1). For many of these intentional introductions, plants were imported with the best of intentions and without any foresight or knowledge that they may one day escape from cultivation and become invasive.

The ornamental plant trade is by far the largest source for invasive plant introductions (Reichard and White 2001). Approximately 86% of invasive tree, shrub, and vine taxa in the Midwestern United States are associated with past or present horticulture (Culley and Feldman 2023). In a recent study, Beaury and colleagues (2021b) determined that 61% of plants identified as invasive are still available for purchase in the United States including a substantial number listed on state (50%) or federal (20%) regulatory lists. Of particular concern is the availability of invasive plants and their propagules through e-commerce, where they can be easily purchased on internet sites such as eBay, Etsy, and other online marketplaces (Humair et al. 2015). Even when regulations are in place, it is difficult to police this online activity, especially the purchase of plants from states where they are legally sold to states where they are regulated. This under-regulated pathway is only likely to increase introductions of problematic species into the United States and enhance spread of existing species. Thus, it is imperative to identify potentially invasive introductions as soon as possible to prevent subsequent ecological and economic impacts.

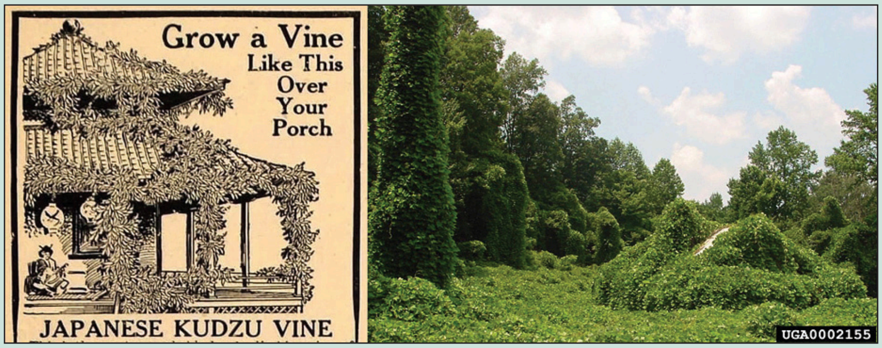
Understanding conditions associated with the invasion process and how species traits can help or hinder transition through the invasion stages can

Box 1. Kudzu, "the vine that ate the South".

A plant may be introduced for one or more purposes before it is recognized as an invasive species. Perhaps the most notorious example in the United States is the introduction of kudzu (*Pueraria montana*) in the Southeastern United States. The species is native to Japan and southeast China and was first introduced into the country in 1876 at the Philadelphia Centennial Exposition where it was featured as an ornamental vine, useful for shading Southern porches into the early 1900s (Forseth and Innis 2010). It was also recommended as a forage plant during that time period (McKee and Stephens 1948). Later, about 85 million plants were given to landowners for soil improvement and millions more were planted along roadsides and right of ways for erosion control in the southeast (Stewart 1997). By the early 1950s, kudzu's weediness was apparent, but it was not until 1970 that the USDA listed kudzu as a common weed in the south (Forseth and Innis 2010).

Although it is no longer federally regulated, it is currently listed as a noxious weed in 13 states including Florida, New York, and Pennsylvania (Loewenstein et al. 2022). Observed impacts include overtopping native plants, changes in soil chemistry through nitrogen fixation, serving as a host for agricultural pests, and increased management costs in natural, agricultural, and forestry systems (Pasiecznik 2007). Today kudzu is estimated to cover approximately 3 million acres in the Eastern United States and its introduced range continues to expand northward because of climate warming (Kovach-Hammons and Marshall 2023; Bradley et al. 2010b).

Kudzu provides a cautionary tale of a plant introduced with the best intentions that resulted in a widespread invasion causing ecological and economic impacts. Understanding the history of this invasion can help us avoid making similar errors in the future. Risk assessment is one tool we can use to identify potential invaders like kudzu before they are purposely introduced.



(Photo credits: PUBLIC DOMAIN IMAGE; Kerry Britton, USDA Forest Service, Bugwood.org.)

help predict which species are likely to become invasive, as well as where (Kolar and Lodge 2001; Fournier et al. 2019; Novoa et al. 2020). The usefulness of characteristics as predictive variables has enabled the development of accurate and efficient tools used to identify which species might become our next invader (Pheloung et al. 1999; Koop et al. 2012; D'hondt et al. 2015). In this paper, we aim to describe risk assessment as a process to determine the invasive potential of non-native plants, the benefits and consequences of using these frameworks/tools, barriers to their implementation, and how to overcome these barriers. This information is critical to protect our national economy and natural ecosystems, as plant invasions will only increase in the United States if problematic species are not identified early before their introduction or early spread.

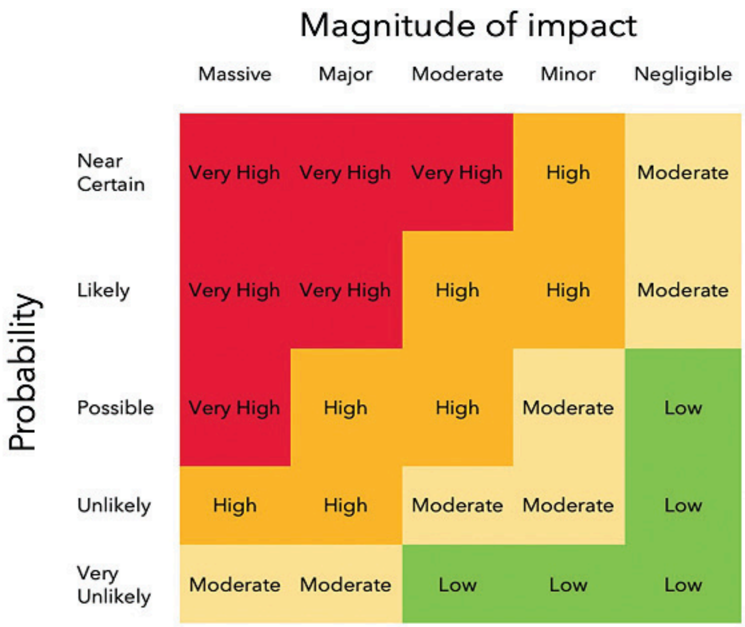


Figure 2. Risk assessment matrices are an effective way to visualize risk. As the probability a non-native species will be introduced to a new region and the severity of potential impacts increase, so does the overall invasion risk.

Risk Assessment

The purpose of risk assessment is to *predict* which non-native species are most likely to pass through successive invasion stages (transport, introduction, establishment, and spread). This process is based on the concept that specific traits of a plant (e.g., biological, ecological, physiological) can determine the success (or failure) of a species progressing through those stages. There are many common traits among successful plant invaders, including a short time to reproduction, tolerance to marginal habitats, and adaptations for long distance dispersal. In addition, drought tolerance of a plant may determine where it can survive, especially as precipitation patterns shift with climate change. Other predictive factors such as the native range and history of invasion (in adjoining geographic locations or similar climates) are also notable to consider. Alternatively, obstacles such as a mismatch of climatic conditions may prevent initial establishment, so not all introductions may result in invasion. Some species may also pass through stages of invasion at random or in proportion to the number of propagules introduced (Lockwood et al. 2005) – which often depends on traits related to reproduction and dispersal (including how humans have moved propagules around).

Identifying these traits is important for researchers, managers, and policymakers because it allows a greater understanding of biological and ecological processes that facilitate establishment and spread. If the traits of species can be understood in this way, it is possible to predict likely invaders, such as similar species with the same array of traits, but are not yet present, and to then proactively prevent those species from being introduced. Understanding how these traits also interact with climatic conditions (e.g., climate tolerance) is increasingly important when determining a species potential distribution in a new geographic area (climate matching; Pheloung et al. 1999). This is critical as continuing global change alters ranges of plant species over time (Bradley et al. 2010a).

Biosecurity and risk assessment

Risk assessment is particularly important for enhancing national biosecurity, especially as directed towards preventing the introduction, spread, and/or impact of harmful organisms. Biosecurity measures can include prohibition of entry, surveillance, quarantine, and control of species of concern. For example, in Hawai'i, port inspectors search for and intercept snakes (and educate arriving visitors) and thus far have protected Hawai'i's native biota from predation and potential extinctions due to snake invasion, such as what has already happened in Guam with the Brown Tree Snake (*Boiga irregularis*) (Rodda et al. 1992). Within the field of biosecurity, risk assessments help create species watch lists, implement pre-border regulation, and optimize limited resources to maximize the effectiveness of biosecurity measures. The process consists of identifying the probability of an organism's arrival and spread, along with potential impacts on the environment, human health, agriculture, and other socioeconomic factors (Figure 2).

Risk assessments of this type are often followed by risk mitigation (as a part of risk analysis programs) where decision-makers consider how to mitigate the risks identified (i.e., best management practices; risk management), and how these results can be best communicated to the appropriate stakeholders (e.g., state and federal regulators; risk communication; IPPC 2019). Risk analysis considers human values in order to reach decisions on appropriate action(s) or responses to a risk and can ultimately lead to decisions that prevent harm because of introduced species (e.g., prohibiting introduction, implementing targeted management).

History of risk assessment

The history of weed risk assessment can be traced back to the 1980s when concerns about the impact of invasive plant species on ecosystems and agriculture began to increase (Forcella and Wood 1984; Hazard 1988; Panetta 1993). Some of the earliest risk assessments for plants were based on informal discussions of the risks that some plants posed as crop weeds. This information was used to create simple decision support trees and other screening tools (Walton and Parnell 1996; Reichard and Hamilton 1997). These early assessments sometimes led to a noxious weed listing or other regulatory measures to eliminate or reduce economic losses to agriculture. Over time, there was greater recognition of potential harm to natural environments caused by non-native plants, and various stakeholder groups began expanding the scope of risk assessment to include consideration of natural areas. These protocols were largely based on whether a plant was identified as being invasive elsewhere (Reichard 1996; Fox et al. 2003). Because stakeholders producing these assessments and lists often had no regulatory authority, the species lists were largely non-regulatory but were used for education and management prioritization; the lists also sometimes promoted voluntary reductions in the use of certain plant species (Buerger et al. 2016). In order to reduce or eliminate the potential for subjectivity in assessing risks of non-native plants, more robust methods were subsequently developed as an alternative to earlier entirely consensus-based and simpler decsion tree methods.

The first notable framework for weed risk assessment was developed in Australia in the early 1990s (Pheloung 1996). Australia, as an island continent with unique biodiversity, faces significant challenges in managing invasive species. The initial system, known as the Australian Weed Risk Assessment (A-WRA), aimed to provide a standardized approach to assess the potential invasiveness of plant species and to make informed decisions regarding their introduction (Pheloung 1996; Pheloung et al. 1999). Over time, weed risk assessment frameworks—often based on the A-WRA—have been refined and adapted to suit other regions and to address emerging challenges (e.g., Daehler et al. 2004; Gordon et al. 2008a; Champion et al. 2010; Koop et al. 2012). These frameworks continue to evolve as new scientific research and data become available, enhancing the accuracy and effectiveness of weed risk assessments. Currently, a range of weed risk assessments are used by state and federal agencies to evaluate the potential invasiveness of plant species in different regions of the United States (e.g., USDA, Minnesota Department of Agriculture Noxious Weed Advisory Committee). Weed risk assessment plays a critical role in guiding policymakers, land managers, and environmental organizations in making informed decisions regarding the importation, cultivation, and management of plant species.

Recent efforts have shifted focus to determine the benefits of non-native species (e.g., Vimercati et al. 2020; Vimercati et al. 2022; Sax et al. 2022) with some suggesting that the assessment should include all net impacts, including favorable impacts (Sax et al. 2023). However, analysts using the most common risk assessment protocols typically do not factor in potential benefits of an introduced organism. A cost-benefit analysis does include added philosophical complexities, such as how to weigh costs and benefits that are measured in differing units, and recognize that one specific entity or interest group may experience costs while another may experience benefits. For example, a risk assessment of a non-native plant of ornamental importance only examines its potential invasiveness and possible impacts/risks within the ecosystem. It does not incorporate economic human benefits from commercial sale.

Risk assessment approaches

Risk assessments that are based on species traits can take many forms (Keller and Kumschick 2017). In this section we describe three general approaches: qualitative, semi-quantitative, and quantitative approaches. Qualitative risk assessment relies on descriptive characteristics and expert judgment to assess the likelihood and impact of potential risks. Semi-quantitative risk assessment combines elements of both qualitative and quantitative approaches, using qualitative descriptions and numerical data in a structured manner to assess risks. Quantitative risk assessment involves the use of numerical data and mathematical models to analyze risks. We discuss the advantages and disadvantages of each.

First, the invasive risk of a species can be assessed via expert opinion through a **qualitative approach**. This is most often achieved through a group of experts assembled to discuss specific plant species. Each expert brings their own knowledge and experience, and the goal is usually to produce a consensus view of the risks that a species poses (i.e., likelihood of introduction and possible impacts) (Fowler 2004; Vanderhoeven et al. 2017). This process may consider a wide range of plant traits, observations about the behavior of the plant, and any other information that is presented, such as presence on 'blacklists' in neighboring regions (Speek et al. 2013).

An advantage of this approach is that anyone present can raise any points that they feel are important. Additionally, when experts with sufficient knowledge and standing are involved, the outcomes will carry the weight of their reputation. Disadvantages of this approach are that it is often difficult to describe exactly how a decision was reached at the end of a conversation if a vote is not held. In addition, different groups of experts are likely to consider different information and may reach different conclusions (Carey et al. 2005). This latter point can be particularly problematic if, for example, a group of resource managers reaches one conclusion and a trade group reaches another. In short, the qualitative process may not be transparent to all and thus may not easily generate buy-in by all groups involved or by the general public. Another disadvantage is that this approach is very time and resource intensive. It may take several meetings for a group to reach a decision, which is not a good approach when there are many species needing to be assessed or if a timely response is needed for a rapidly spreading species (Hsu and Sandford 2007).

A second approach to risk assessment is the **semi-quantitative approach** that combines scientific data and/or information provided by experts to determine risk. This approach scores species based on traits considered by a group of experts to be important in facilitating or hindering the invasion process (Malekmohammadi and Blouchi 2014). For example, a plant that has greater seed production may be given a higher risk score than plant with intermediate or lower seed production. A single net risk score for a species can then be determined based on answers to multiple questions about the species's traits. In some cases, an answer of "Unknown" can be used if the answer to a question is not known. Many semi-quantitative approaches also require evidence from the scientific literature or expert testimony to support answers to specific questions.

The A-WRA is the best-known example of semi-quantitative risk assessment tools. It has 49 questions related to traits, not all of which need to be answered for every species. The outcome from the assessment is a final rating that links directly to management actions (e.g., Accept, Reject, Evaluate Further; Pheloung et al. 1999). Advantages of the semi-quantitative approach are that it provides a consistent and more systematic procedure to evaluate species than the qualitative method and removes many sources of bias by being explicit about the information that is necessary and sufficient to assess a species (Randall et al. 2008). The numerical scoring also makes it very clear why a species was rated the way it was. Semi-quantitative risk assessments are relatively quick to conduct. For example, it took an average of 8 hours to assess an individual species using a version of the A-WRA modified for the United States (Gordon and Gantz 2008). As long as there is sufficient data available on the species and detailed justification for answers are recorded, the assessment can be conducted by a single person with much less chance that different assessors will reach different conclusions.

A disadvantage of this approach is that the initial development of the tool (i.e., the selection of plant traits) and allocation of scores for those traits used requires substantial investment in research and testing to demonstrate that the tool makes reliable assessments of risk. Additionally, this approach considers that the traits associated with success/failure are mostly independent and additive, and any interactions among sets of traits will not be suitably incorporated. For example, a given trait such a pollination mode may promote invasion, but only when another trait is present, absent, or at a certain level such as length of the flowering season (Küster et al. 2008). Finally, while the semi-quantitative method does provide structure to the risk assessment process, it still relies on expert judgment with has its own caveats (Hulme 2012), although explicit guidelines (e.g., Gordon et al. 2010) can also help in this process. The semi-quantitative method also relies on available scientific data, which may have inherent limitations and uncertainties, and may not always be readily accessible (in the case of non-open access literature behind a paywall).

The final approach is the **quantitative approach**. This differs substantially from the first two approaches by using statistical algorithms, mathematical models, and empirical data to develop the risk assessment tool (Morin et al. 2013; Engelstad et al 2022; Pfadenhauer et al. 2022). This approach begins with experts developing a list of important traits and a list of all of the species that have transited a given invasion stage in a given region (e.g., all the species that have passed or failed to pass from "Introduced" to "Established" in California) (Griffin 2012). Data are then collected for each trait for each species, and an algorithm is used to determine which traits and/or combinations of traits are most associated with success. A large range of statistical algorithms are available, with some of the most commonly used methods being logistic regression, categorical and regression trees, random forests and neural networks (e.g., Stohlgren et al. 2010; Keller et al. 2011; Zhang et al. 2020; Engelstad et al 2022). In this approach, very few traits are usually required to identify high-risk species. This is a major advantage of the quantitative approach because the assessment of species in the future may be quite fast. Another advantage is that the development of the risk assessment tool is driven entirely by a statistical algorithm, leaving little room for bias and more transparency in the results of the assessments (Griffin 2012). Disadvantages of this approach are that the outcome may be counterintuitive to some, and there may not be a mechanistic explanation for it. Put another way, the algorithms used in this approach are very powerful and may find important traits, or combinations of traits, for which scientists are unable to explain the reasons why they are important. Because these algorithms may only be familiar to expert statisticians or coding experts, it can also be challenging to communicate results to policy-makers, managers, and the general public (Keller and Kumschick 2017).

Regulatory and non-regulatory uses of risk assessments

At the federal level, the USDA-APHIS Plant Pest Risk Analysis Laboratory plays a significant role conducting risk assessment for commodity importation (Plant Protection and Quarantine Program, PPQ), noxious weed listing, newly detected plants with limited distribution, or when a stakeholder expresses concern about a plant's risk potential (USDA APHIS 2019). There are 43 plant lists at the state level that legally regulate plants determined to be invasive (Beaury et al. 2021a), to prevent them from commercial sale and distribution, and thereby reducing spread and associated detrimental impacts. Invasive plant regulation is typically established through implementation of a noxious weed list (Lakoba et al. 2020), a state legislative pathway, or a rule-making process (Buerger et al. 2016), although in states such as Pennsylvania and Minnesota, regulation can occur through noxious weed laws. A suite of risk assessment tools that have been developed have been used for regulatory or non-regulatory (educational/informational) purposes, reflecting varying reasons why people may be interested in understanding the invasion risk of a species. Some groups (e.g., state and federal agencies) are tasked with preventing the arrival and spread of new invasive species, and they will naturally be interested in using a risk assessment with predictive features to support regulations about which species can be safely imported.

Other groups (e.g., local environmental groups, land management practitioners) may be more interested in understanding the impacts if a known invader reaches (or is already spreading within) their location, to create watch lists and educate the general public. These processes may help these groups to prepare for the arrival of the plant and to prioritize management, but it will have no regulatory influence. In all cases, these policies depend upon a transparent and widely accepted risk assessment process.

Risk assessment tools

To review available risk assessment tools, we conducted a search of scientific literature and internet sources for invasive plant or weed risk assessment tools that have been developed or adopted globally. We identified 34 screening tools used either standalone or within a more formal pest risk analysis program (e.g., European Pest Plant Organization [EPPO], USDA APHIS) and at least 12 tools in use in the United States (Table 1 and Table 2). Most assessments are comprehensive in that they consider a wide range of available information involving the introduction, establishment, and impacts of the invasive plant/weed. In contrast, some tools are designed for expedited assessment and prescreening (prioritization) to quickly identify priority species; these simple tools are typically flexible and require fewer resources (time and money) (Brunel et al. 2012). There are also associated tools used along with risk assessments, such as species distribution models (SDMs), including Climatch and Maxent, which can aid in predicting the potential future range of invasive species (Carlson et al. 2008). However, some tools have also been misapplied as risk assessments, specifically the Environmental Impact Classification for Alien Taxa (EICAT). The EICAT only classifies impacts based on the magnitude and type of environmental effects and does not consider entry potential or the likelihood to establish and spread (Kumschick et al. 2020a).

Non-native plant quantitative and semi-quantitative risk assessments in the United States are conducted primarily by USDA APHIS, some state departments of agriculture (e.g., Maryland Department of Agriculture, Michigan Department of Agriculture and Rural Development, Minnesota Department of Agriculture Noxious Weed Advisory Committee), and colleges and universities (e.g., University of Florida Institute of Food and Agriculture Sciences Assessment of Non-native Plants, University of Hawai'i Weed Risk Assessments for Hawai'i and Pacific Islands) using three prominent tools—the A-WRA, APHIS PPQ Weed Risk Assessment (APHIS PPQ-WRA), and Plant Risk Evaluator Assessment (PRE-A) specific to California. There are many other tools in use that employ simple decision support trees, evaluate risk and status simultaneously, and more. Additionally, there are a number of methods in use for specific habitats, geographic scales, and some tools are also used internationally. Sometimes conflating risk and status

Table 1. Summary of tools used for assessing the risk of invasive species in the United States.

Tool	Acronym	Taxa	Habitat	Target Region	Intended Application	Citation
United States						
Great Lakes Aquatic Non-indigenous Species Risk Assessment	GLANSRA	all taxa	aquatic	Great Lakes	species selection; prevention target ID	Davidson et al. 2017
Hawaii-Pacific Weed Risk Assessment	HPWRA	plants	terrestrial; aquatic	Pacific Islands, Hawaii, US	recommendations for use, non-regulatory	Daehler et al. 2004
Horizon Scanning Rapid Risk Assessment	HS-RRA	all taxa	terrestrial; aquatic	n/a	prevention target ID	Roy et al. 2014
Invasiveness Ranking System for Non-Native Plants of Alaska	IRS-AK	plants	terrestrial; aquatic	Alaska, US	unknown	Carlson et al. 2008
Plant Risk Assessment & Management Protocol for Minnesota	MINN-PRA	plants	terrestrial; aquatic	Minnesota, US	noxious weed listing	Minnesota Noxious Weed Advisory Committee (2020)
Plant Risk Evaluator Assessment/Tool	PRE-A/PRE-T	plants (horticulture)	terrestrial; aquatic	Western Coast, US	industry recommendations; species selection	Conser et al. 2015
Predictive Tool	PT	plants	terrestrial; aquatic	Florida, US	recommendations for use, non-regulatory	Gordon et al 2008a
US Aquatic Weed Risk Assessment	USAqWRA	plants	aquatic	United States	species selection; prevention target ID	Gordon et al. 2012
USDA PPQ Weed Risk Assessment	APHIS PPQ-WRA	plants	terrestrial; aquatic	United States	regulatory activities	Koop et al. 2012
US Weed Ranking Model	US-WRM	plants	terrestrial; aquatic	United States	noxious weed listing	Parker et al. 2007

Table 2. Summary of tools used for assessing the risk of invasive species internationally.

Tool	Acronym	Taxa	Habitat	Target Region	Intended Application	Citation
International						
Australian Weed Risk Assessment	A-WRA	plants	terrestrial; aquatic	Australia	regulatory activities; prevention target ID	Pheloung et al. 1999
Aquatic Weed Risk Assessment Model	AWRAM	plants	aquatic	New Zealand	regulatory activities; prevention target ID	Champion and Clayton 2010
Canadian Food Inspection Agency Pest Risk Assessment	CFIA-PRA	plants; invertebrates; pathogens	terrestrial; aquatic	Canada	regulatory activities; prevention target ID; species selection	Canadian Food Inspection Agency (2020)
European and Mediterranean Plant Protection Organization - Express Pest Risk Analysis	EPPO PRA	plants	terrestrial; aquatic	Europe; North Africa	regulatory activities; hazard identification	Brunel et al. 2010
EPPO's Computer Assisted Pest Risk Analysis Tool	CAPRA	all taxa	terrestrial; aquatic	Europe	regulatory activities; prevention target ID	Griessinger et al. 2012
Harmonia+	Harmonia+	all taxa	terrestrial; aquatic	Europe	management prioritization; regulatory activities; prevention target ID	D'hondt et al. 2015
Great Britain Non-Native Risk Assessment	GB-NN-RA	all taxa	terrestrial; aquatic	Great Britain	management prioritization; regulatory activities; prevention target ID	Baker et al. 2008
Great Britain Non-Native Rapid Risk Assessment	GB-NN-RRA	all taxa	terrestrial; aquatic	Great Britain	management prioritization; regulatory activities; prevention target ID	Baker et al. 2008
The UK Risk Assessment Scheme for All Non-Native Species	UK-RAS-NNS	all taxa	terrestrial; aquatic	United Kingdom	management prioritization; regulatory activities; prevention target ID	Baker et al. 2008
Risk Analysis and Prioritization (Ireland and Northern Ireland)	Ire-RAP	all taxa	terrestrial; aquatic	Ireland and Northern Ireland	management prioritization; regulatory activities; prevention target ID	Kelly et al. 2013
Risk Assessment for Alien Taxa	RAAT	all taxa	terrestrial; aquatic	South Africa	management prioritization; regulatory activities; prevention target ID	Kumschick et al. 2020

into one tool and the misapplication of current tools (e.g., using EICAT for risk assessment, conducting risk assessments for well-established species) can make it hard to know the value of outputs from each tool. Here we will cover only those tools that are specific to determining a plant's risk of invasion and do not incorporate any potential economic or other benefits.

The Australian Weed Risk Assessment (A-WRA) was developed to screen new plant taxa before importation into Australia and New Zealand (Pheloung 1996; Pheloung et al. 1999). This tool consists of 49 questions covering the biogeography (e.g., distribution, climate requirements, history of invasiveness elsewhere), undesirable traits (e.g., toxicity, forms dense stands, shade tolerance), and the biology/ecology of the plant (e.g., seed production, seed dispersal mechanisms, tolerance to mutilation/cultivation) (Pheloung et al. 1999; Gordon et al. 2010). Possible outputs from the tool are that a species is high-risk (reject from import), moderate-risk (evaluate further), and low-risk (accept for import). A secondary screening procedure was subsequently developed to reach final conclusions for species receiving intermediate scores (moderate risk/evaluate further; Daehler et al. 2004). Ths secondary screen is a decision support tree with questions targeting specific traits such as shade tolerance, wind or bird dispersal, and palatability to grazing animals (Figure 3A). When tested in Hawai'i, the secondary screening reduced the number of species in the moderate risk/evaluate further category from 22% to 12% and brought the accuracy up to 95% for major invaders and 85% for non-invaders (Daehler et al. 2004). The A-WRA has now been modified for different geographic locations and scales (e.g., Hawai'i, Bonin Islands, Japan), and overall is relatively accurate. When it is tested on species with known invasiveness, it usually correctly identified roughly 90% of major invaders and 70% of non-invaders, with an overall accuracy of 80% (Gordon et al. 2008b). There have been different derivations of the A-WRA

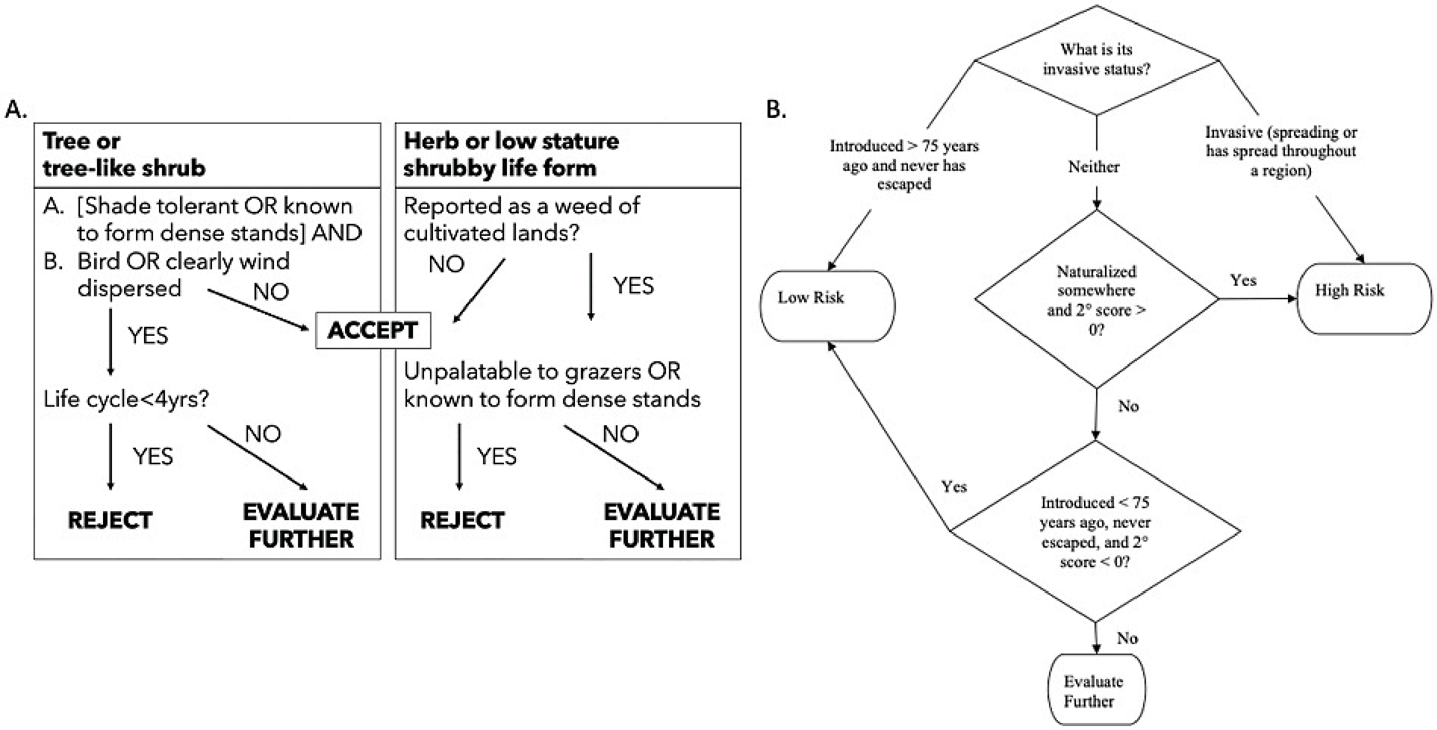


Figure 3. Secondary screening tools developed for the HPWRA (Daehler et al. 2004) (A.) and the USDA PPQ-WRA (Koop et al. 2012) (B.) to reach final conclusions for species receiving intermediate scores.

including the Aquatic WRA (Aq-WRA) for aquatic plants (Champion and Clayton 2010), the Fish Invasiveness Screening Kit (F-ISK) and its various offshoots (e.g., Aquatic Species-ISK, Freshwater Invertebrate-ISK) to evaluate various taxonomic groups in aquatic systems (Copp et al. 2013), and the USDA APHIS PPQ-WRA (Koop et al. 2012). Currently, the A-WRA is the model used the most frequently globally (Canavan and Lieurance, unpublished data).

USDA-APHIS uses the PPQ Weed Risk Assessment (PPQ-WRA) as a part of the federal risk analysis framework, with results that provide evidence-based conclusions to support management decisions (USDA 2019). The PPQ-WRA was developed to cover the entire United States and it divides assessment into two sections: (1) establishment and spread potential, and (2) negative ecological and socioeconomic impacts. Risk predictions are derived by processing responses to questions in a logistic regression model. Analysts estimate their level of uncertainty for each answer, and this is then used in a statistical model to characterize the overall uncertainty of the final conclusion (USDA 2019; Koop et al. 2012; Caton et al. 2018), a novel feature of this tool. When tested against the A-WRA, the accuracy of the PPQ-WRA was nominally higher at capturing major invaders, and there was a 38% increase in its ability to correctly identify non-invaders, with an overall accuracy that was 20% higher (Gordon et al. 2008b; Koop et al. 2012). As with the A-WRA model, the PPQ-WRA includes a secondary screening tool (Figure 3B) that reduces the percentage of species in the moderate-risk/evaluate further category by 45% (Koop et al. 2012). The PPQ-WRA also includes a simple climate suitability model known as Proto-3, which determines the geographic potential of a focal plant using plant hardiness zones, Köppen-Geiger climate classes, and mean annual precipitation bands. In this way it identifies the areas where the risk determination applies (Magarey et al. 2018; USDA APHIS 2019; Kim et al. 2023). While the PPQ-WRA is overall a semi-quantitative assessment, the logistical model, uncertainty analysis, and geopotential maps are quantitative components.

At the state level, different agencies and academic institutions also conduct invasive species risk assessments. The University of Hawai'i has developed the Hawai'i-Pacific Weed Risk Assessment (HPWRA), which is an adaptation of the A-WRA (Daehler et al. 2004). The HPWRA provides recommendations for the use of plant species in Hawai'i and the Pacific Islands. Similarly, the University of Florida Institute of Food and Agricultural Sciences (UF IFAS) utilizes the Predictive Tool (PT), another adaptation of A-WRA, to assess plant invasions in Florida (Gordon et al. 2008). Application of both tools are non-regulatory, but results from the Predictive Tool are considered in permitting decisions for biomass planting and noxious weed listing by the Florida Department of Agriculture and Consumer Services Division of Plant Industry (FDACS), and high-risk species are not to be recommended by any UF/IFAS personnel (Lieurance and Flory 2020; Lieurance et al. 2021).

There are several other state-level tools, such as the Plant Risk Evaluator Assessment (PRE-A) and the Plant Risk Evaluation Tool (PRE-T), developed by PlantRight and the California Invasive Plant Council, which provide recommendations to industry and assist in species selection in horticulture along the West-

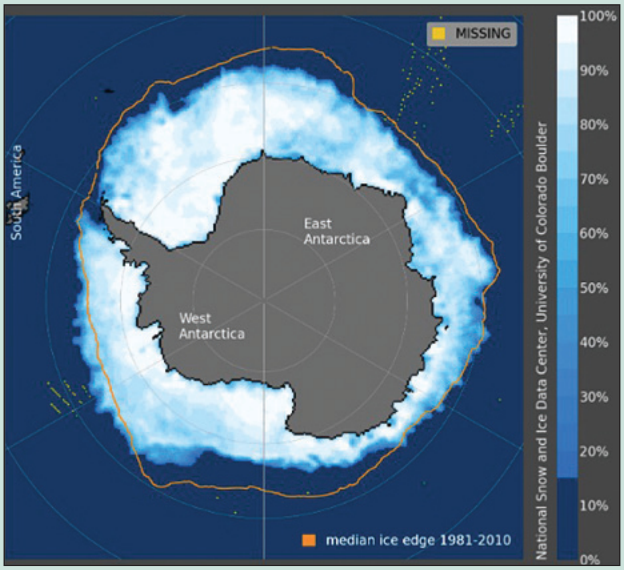
Box 2. Climate Change.

Risk assessments for non-native plants are dependent on information about species traits, current distribution, and known impacts of the species elsewhere. Because of this, the conclusions generally apply to current climate conditions. It is predicted that there will be interactive effects of invasive species and climate change including altered transportation routes, climate constraints, and changes to distributions (introduction, establishment and spread), as well as altered impacts and effectiveness of management strategies (Hellman et al. 2008). There is always some level of uncertainty within any risk assessment, but uncertainty increases considerably when we include how a plant might behave in future climate change scenarios (Bradley et al. 2010a).

Currently, few risk assessment protocols incorporate climate change when predicting invasion risk (but see Harmonia+), however it is important to consider both the current and potential future distributions of invasive plants and their interactions with changing environmental conditions. To do this, risk assessment tools and outputs can be revisited in the light of predicted climate changes (Roy et al. 2018). Another approach is to combine traditional risk assessment protocols with habitat suitability modeling using historic and future climate conditions to provide a comprehensive estimate of risk (Chai et al. 2016).

As we continue to adapt and grow risk assessment procedures, the inclusion of climate change can add to the development of watch lists and other proactive prevention efforts. Future research including testing a plant's response to simultaneous changes to environmental variables (e.g., increased temperature and disturbance), combining multiple forecasting techniques, and planning experiments around results from quantitative modeling have the potential to improve prevention efforts (Bradely et al. 2010). Overall, integrating climate change and invasive species risk assessment is crucial for understanding and managing the impacts of these two interconnected global challenges.

Altered transport



Melting sea ice is anticipated to extend shipping seasons and open novel transportation routes, potentially leading to the introduction of non-native plants, agronomic pests, and other potential invaders. For example, ice-free summers and the overall reduction of sea ice is predicted to cause significant alterations in trade patterns connecting Asia and Europe, increased maritime activitiy in the Arctic, and a considerable decrease in traffic through the Suez Canal (Bekkers et al. 2016). These projected shifts also have the potential to exert stress on an already vulnerable Arctic ecosystem. (Photo credit: NASA Natioal Snow and Ice Data Center, University of Colorado.)

Altered impacts

Extreme heat results in more evaporation from soil and vegetation. This results in the drying of trees, shrubs, grasses, and leaf litter that become highly flammable fuel that intensifies wildfires. For example, cheatgrass is an invasive grass impacting sagebrush ecosystems in the Western United States. As the climate warms, the frequency and intensity of fires will increase. Further, cheatgrass is more efficient at recolonizing burned areas than native plants, thus providing more fuel for the next wildfire. (Photo credit: Scott Shaff/U.S. Geological Survey.)

Box 2 Continued

Altered distributions of existing invasive plants

Range-shifting invasive species are species that track suitable climatic conditions and expand their range as the climate warms, either tracking northward or to higher elevation. For example, predicted species distribution areas under projected climate change scenarios suggest species such as kudzu Brazilian peppertree, and tree-of-heaven (pictured here) could shift their ranges northward as they track chanages in temperature and precipitation patterns (Wand et al. 2022). It is also important to note that tree-of-heaven is allelopathic and a host plant for spotted lanternfly, a serious invasive pest that feeds on many native and agronomic species such as grape vine, fruit trees, and native maples, oaks, and black walnut. (Photo credit: Richard Gardner Bugwood.org.)

Altered effectiveness of biocontrol

Biocontrol is an effective approach to mitigating plant invasions. Rising temperature, changes in precipitation, and increasing atmospheric CO_2 can alter dymnamics between plant hosts and biocontrol agents. or instance, increased CO2 in the atmosphere can result in higher resistance against herbivores and increased growth rates (Sun et al. 2020). For example, tropical soda apple leaf beetles feeding on tropical soda apple grown in elevated CO2 experienced longer development times and lower survivorship than those feeding on plants grown at ambient CO2 (Diaz et al. 2012). (Photo credit: Peggy Greb, USDA Agricultural Research Service, Bugwood.org.)

ern Coast of the United States (Conser et al. 2015). To develop the PRE-T, 56 questions from other weed risk assessments were considered and 19 were then selected that were determined to be the most predictive for ornamental plants. When tested, this model had an overall accuracy of 95% for horticulture species (Conser et al. 2015). The Minnesota Department of Agriculture (MDA) Noxious Weed Advisory Committee (NWAC) employs a decision flowchart-based risk assessment tool called the Plant Risk Assessment & Management Protocol for Minnesota (MINN-PRA) (Buerger et al. 2016) and there are some states currently using the PPQ-WRA, including Maryland, Michigan, and Nebraska. Other states such as Ohio have developed their own assessment protocols, often adapting questions from surrounding states, some of which can be traced back to the A-WRA (Culley, personal communication). Generally, species assessed by these tools are then considered for listing on regulatory lists under the direction of their state Department of Agriculture. Non regulatory lists in other states are often developed by volunteer organizations (e.g., Invasive Plant Councils, Exotic Pest Plant Councils).

In terms of habitat-specific assessments, the National Oceanic and Atmospheric Administration (NOAA) utilizes the Great Lakes Aquatic Non-Indigenous Species Risk Assessment (GLANSRA), a composite risk assessment tool that includes pathway analysis to coordinate multi-jurisdictional surveillance and detection of aquatic invasive species (Davidson et al. 2021). GLANSRA assesses the risks posed by various taxa in aquatic habitats (including plants) of the Great Lakes region (Davidson et al. 2022). There is also the US Aquatic Weed Risk Assessment (USAqWRA), adapted from a tool developed by New Zealand's Biosecurity Program, which follows a risk assessment approach specifically tailored for aquatic plants (Champion and Clayton 2010; Gordon et al. 2012). Although we could not find any examples of this tool being used for official purposes, it has been used experimentally to assess aquatic plants in South America (Lozano et al. 2017) and was tested for suitability to screen freshwater aquatic plants in

Canada (DFO 2014).

There are other risk assessment tools available globally that are not extensively used in the United States. One such example is Harmonia+, developed by the European and Mediterranean Plant Protection Organization (EPPO). Harmonia+ is a comprehensive tool that assesses the invasiveness of all taxa, including plants, and is widely used in Europe for regulatory activities and management prioritization (D'hondt et al. 2014; D'hondt et al. 2015). Questions address the introduction, establishment, spread, and ecological and socioeconomic impacts (D'hondt et al. 2014). This tool incorporates uncertainty (level of confidence) and results are presented in a way to represent stage-specific and general risks (D'hondt et al. 2015). There is also a sister tool, Pandora+, that specifically determines the risk of emerging infectious diseases, a topic that has become critical since the global COVID-19 pandemic (D'hondt et al. 2015; Nuñez et al. 2021).

Benefits and Consequences of Risk Assessment

Risk assessments play an important role in identifying, understanding, and managing the risks posed by invasive plant species. The use of risk assessment tools allows us to identify the potential outcomes from the importation or use of a given species. Generally, risk assessments help inform early detection and prevention measures, and can be used to protect ecosystems and agriculture systems, allocate management resources, support policy and decision-making, and facilitate research and educational activities. These assessments will have levels of confidence, either quantified (e.g., PPQ-WRA uncertainty analysis) or implied, that vary depending upon the amount and quality of data available to inform the assessment. Risk assessments also help identify knowledge gaps where data are lacking on potentially invasive species. This can be used to inform future research.

Using risk assessments to identify species with high invasive potential in a new area allows for actions to take place *before* the species has been introduced or, at least, early in the introduction. This informs management efforts so high-risk species can be excluded from import or so early control efforts can be implemented to prevent spread and minimize negative impacts (Venette et al. 2021). Prevention or early control of invasive species can lead to reduced impacts, and this is generally considered to be the most cost-effective defense against biological invasion (Lodge et al. 2016; Cuthbert et al. 2022). In fact, an economic analysis of management costs across the invasion curve by the Government of Victoria, Australia, estimated the return on investment for prevention to be 1:100 (for every dollar spent, there is a $100 return), eradication is 1:25, containment is 1:5-10, and long-term maintenance control 1:1-5. Cuthbert and colleagues (2022) estimated that since 1960, pre-invasion management spending is 25-times lower than post-invasion globally, and this estimate is four times less in North America.

Risk assessment efforts feed directly into the concepts of Prevention and Early Detection and Rapid Response (EDRR). Prevention is simply halting the introduction and establishment of a new invasive species through regulation, policies, and actions that prevent its movement and/or introduction. Quarantines, surveys, phytosanitary inspections, interdiction activities, inspections, and equipment decontamination requirements are all components that may be used to prevent the introduction of invasive species (Hallman 2007). EDRR is a concept commonly incorporated into invasive species management strategies to minimize the impact and spread of invasive species and maximize the chances of successful management (Reaser et al. 2020). Broadly speaking, EDRR includes surveying for, reporting, and verifying the presence of a non-native species before the founding population becomes established or spreads so widely that eradication is no longer feasible (early detection). Identifying high risk species through assessment allows for target lists to be developed to inform proactive prevention and EDRR efforts (Morisette et al. 2020; Reaser et al. 2020). Once detected, management activities can then be employed to eradicate the founding population of a non-native species from a specific location (rapid response) (U.S. Department of Interior 2016), such as what typically happens with giant hogweed (*Heracleum mantegazzianum*), a large herb that is phototoxic to humans.

False positives (designating a plant as invasive when it is not) are considered rare with the risk assessment tools currently in use but can occur. If that designation leads to regulation or a loss of public demand for a 'safe' species, it can have negative economic consequences and add unnecessary regulations and burdens on industry and the public. Additionally, being too risk averse (CAST 2013) and restricting the importation or use of species that have only a small chance of becoming invasive could prohibit a species that would otherwise benefit the economy, human health, or even possibly provide valuable ecosystem services (such as erosion control or flood abatement). Coupling risk assessments with incremental experimental tests (from small-scale experiments to widespread, controlled introduction) to further define risks and develop best management practices to mitigate risk is one way of increasing confidence, reducing uncertainty, and determining if the benefits of a proposed plant introduction outweigh the projected risks of invasions (Flory et. al 2012).

There is a desire for new species introductions for horticultural purposes, as alternative crops, and for biomass/biofuel plantings (Box 3). These potential introductions pose invasion risks, especially when species are selected that have traits also common in invasive species, such as broad environmental tolerance, efficient use of resources, rapid growth and establishment, short time to reproductive maturity, and high reproductive rates because of substantial blooming (Richardson and Blanchard 2011; Van Kleunen et al. 2018). There has been pushback for regulating plant species at state or local levels from some areas of the Green Industry, especially when preemptive regulations are put in place without the species having clearly demonstrated invasiveness (Li et al. 2004). This situation provides a dilemma for invasive species policy makers and managers because waiting until a species clearly shows in-

Box 3. Case Study: Cultivars.

In the nursery industry, many traits that make plants good for the landscape may also make them invasive: nursery plants are tough and adaptable, resistant to disease, produce abundant flowers, and can be unpalatable to deer and other herbivores. These traits are preserved by the nursery industry by cloning genotypes of individual plants through asexual propagation to possess one or more of these desired characteristics. An approach to reduce invasive spread of ornamental plants by drastically reducing seed production is to create sterile cultivars (Gagliardi and Brand 2007).

Infertile versions can be created in several ways, such as converting reproductive organs of flowers into extra petals or producing triploid individuals that are unable to cross with other plants. However full sterility, defined as the absence of seeds and functional pollen over the lifetime of a plant, can be challenging to achieve as sterility may break down over time. Therefore, plants producing very low levels of seeds may be viewed as sufficiently "sterile" by the nursery industry and may be excused from regulation — as in Oregon, where approved cultivars must produce 2% or less of viable seed (Oregon Department of Agriculture 2023). But even low seed production can trigger invasive spread (Knight et al. 2011) and cultivars of some species such as *Berberis* are known to increase seed production in later years (Brand et al. 2012).

In Florida, several seed-sterile cultivars of *Lantana* have been approved for commercial release, with the assumption that these cultivars are triploid, they do not produce seeds, the pollen is not viable, and sterility will continue to persist. In addition, some self-sterile cultivars might nonetheless be fully cross-compatible with other genetically different cultivars. For example, the original cultivar of *Pyrus calleryana* known as 'Bradford' initially did not produce any fruit as it is self-incompatible, but years later set copious fruit in the presence of pollen from other cultivars (Culley and Hardiman 2007).

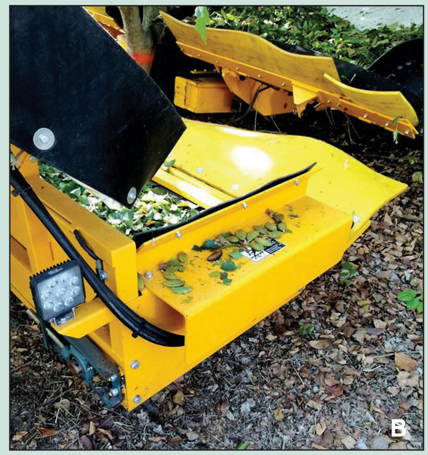
Consequently, the concept of "sterility" still needs to be defined in risk assessments amid the need of a national cultivar standard, with greater attention to changes in sterility due to plant age and across generations during global climate change.

Planted cultivars of Callery pear (Pyrus calleryana) along a residential street (top), a wild population growing in a gulch next to a bridge in urban Cincinnati (above), and wild pear along an interstate freeway (left). (Photo credit: Theresa Culley.)

Box 4. Case Study: Biomass.

Biomass species are renewable crops grown at large scales typically for biofuel, but sometimes for other purposes including biochar, paper pulp, medicinal purposes, and fiber. Like horticulture species, biomass plants and invasive plants share many common traits including rapid growth, high reproduction, tolerance to a wide variety of habitats, efficient resource utilization, and a lack of natural enemies (Raghu et al. 2006). Crops such as giant miscanthus (biofuel-ethanol), industrial hemp (fiber, CBD oil), eucalyptus (landscaping mulch, fiber, biofuels), and bamboo (paper pulp, biochar) are being planted on more and more acres, often with best management practices (BMPs) defined to mitigate escape, but little regulation to enforce these BMPs.

In 2008, the U.S. Farm Bill, or the Food, Conservation, and Energy Act, included a program that incentivized growing bioenergy crops by providing up to 75% of the start-up costs for planting and providing annual payments for farms enrolled in the program (Barney 2014). Two species, giant reed (*Arundo donax*) and elephantgrass (*Pennisetum purpureum*) are now eligible for credits from the Environmental Protection Agency (EPA) that can be traded in an open market (Barney 2014). After a contentious public comment period regarding these two species, the EPA required precautions including proof that the planting will not spread, that growers supply a Risk Mitigation Plan to reduce potential escape, and that there is a plan to eradicate the crop if land is abandoned (Barney 2014). Some states including Florida, Mississippi, and Oregon have regulations that require permitting, BMPs, and the deposit of surety bonds (Quinn et al. 2013; Quinn et al. 2015). In Florida, the state's department of agriculture also requires a risk assessment in the permitting process and at this point, the application can be (1) rejected if the risk for invasion is too high, (2) permitted and monitored with specified BMPs defined and a surety bond for eradication, or (3) be exempted from permitting if the species does not present a significant invasion risk (Lieurance et al. 2021).



The *dos* and *don'ts* of invasion risk mitigation for biomass crops. A. *Do* – implement 25+ foot buffers around plantings and install silt fences to prevent movement of propagules (seeds and stem fragments) into nearby waterways and canals (Credit: Trevor Smith, Florida Department of Agriculture and Consumer Services, Division of Plant Industry). B. *Do not* – move planting or harvesting equipment with accumulated propagules on the machinery which may escape during transport without implementing proper decontamination methods. (Photo credit: Michael Sthreshley, UF/IFAS.)

Barney (2012) outlined BMPs for non-native biomass planting including proper crop selection, proper field management to mitigate escape (e.g., buffer zones, avoid planting along major dispersal corridors), and proper harvesting, transport, and storage to ensure propagules are not accidentally introduced outside of production areas. Risk assessment is an important step in species selection where screening species both pre- and post-introduction for invasion risk can include climate matching, trait-based risk assessment, and incremental experimental evaluations from small-scale experiments to widespread, controlled introductions (Cousens 2008; Flory et al. 2012). Invasive species prevention efforts can be enhanced by continued innovations in risk assessment such as more precise climate matching, uncertainty analysis to identify research gaps, and incorporating climate change into the assessments to screen for present and future climate conditions (Roy et al. 2018).

As the climate continues to warm, the popularity of green solutions to carbon emissions will grow as farmers look towards alternative crops as traditional yields decline from climate change and invasive pests. Thus, a precautionary approach to the introduction and mass production of non-native species can prevent future invasions. Furthermore, integrating new advances in screening approaches can improve our predictive accuracy to assure that either economically valuable species are not erroneously rejected, or an approved species does not become a major invader (Davis et al. 2010).

vasive tendencies is likely much too late for any type of effective rapid response to avoid a substantial economic cost.

Development and assessment of cultivars

The U.S. nursery industry is an important part of the national economy, producing nearly $13.8 billion in horticultural sales in 2019 (USDA APHIS 2019). Ornamental plant sales are partly driven by consumer demand for novel, often non-native species or cultivars (Brand and Leonard 2001). These market forces make it difficult for growers and landscapers to quickly change their approach to the production and use of invasive species. There are many complexities affecting transition to the production of less- or non-invasive horticulture selections that fall outside the scope of this paper, including associated economic costs and reluctance to share proprietary information. Here we will focus on the development of alternatives to invasive ornamental plants and how current risk assessment protocols address these cultivars (Box 4).

The ornamental plant industry may support bans on plants that have been clearly demonstrated to be invasive. Enthusiasm for plant bans is less robust when the species in question has a high economic value and are in strong demand for horticultural use. In cases of economically important plants, a more measured approach is sought. For example, there has been significant industry resistance to prohibition of Japanese barberry (*Berberis thunbergii*) because it has high economic value and there are few alternative plants that can replace its utility and ornamental characteristics. But annual sales of barberry dropped by approximately $10.5M USD between 2007 and 2017 (USDA 2009), likely attributed to state-imposed legal bans on barberry in several New England states that occurred during this time period.

One potential solution is the development of sterile forms of cultivated varieties (cultivars) of invasive ornamental species (Gagliardi and Brand 2007). Cultivars are individual genotypes of plants that are cloned (asexually propagated) by the nursery industry to preserve unique and desirable characteristics of a plant that would usually be lost through seed production (sexual propagation). Several university researchers and nursery operations are now breeding and developing sterile forms of invasive ornamental genera such as *Buddleia, Euonymus, Lantana, Ligustrum, Miscanthus, Pennisetum,* and *Pyrus.* As invasive horticultural plants are regulated, exemptions may allow for legal use of sterile forms. For example, in Florida, small-leaved privet (*Ligustrum sinense*) is regulated by the Department of Agriculture and Consumer Services with an exemption for the cultivars 'Variegatum' and 'Sunshine' (FAC 2020). In Wisconsin (Wisconsin Department of Natural Resources 2023) and Minnesota (Minnesota Department of Agriculture 2023), a slightly different approach has been adopted in the case of barberry, where the wild type species, along with other reproductive cultivars, are illegal to sell, but all other unspecified cultivars with low fertility, or undetermined fertility, remain legal to grow and use. This legislation draws upon an extensive controlled research dataset developed for barberry reproduction over many years (Brand et al. 2012).

Sometimes when states establish cultivar exemptions, they require evidence that the genotype in question has a low level of fertility. The information would most often be provided by the "owner" of the cultivar name, such as the breeder, patent holder, or brand owner. Information that is typically required includes how the plant was created, its pollen viability and hybridization potential, how prolific is the seed production, what is the seed germination rate and vigor of resulting seedlings, how it can be distinguished from the parent species, whether any vegetative spread occurs, and what hardiness zone the plant was studied in. The most universally acceptable evidence used to support the exemption of a cultivar is refereed journal articles, where methodology and sterility data are peer-reviewed. Affidavits from experts have also been accepted, documenting the non-invasive qualities of cultivars. These are best provided by plant breeders, industry professionals, botanical gardens, arboreta, or academic institutions.

There are few risk assessments that apply specifically to the horticulture industry, and even less that address cultivars. The Plant Risk Evaluation tool specifically screens horticulture species but was not designed to screen cultivars (Conser et al. 2015). In Florida, the UF/IFAS Assessment of Non-native Plants uses a separate cultivar assessment tool to determine if a cultivar is a lower risk than the parent species. These assessments are used internally in the University of Florida's cultivar release process and to determine if a species should be exempted from the state's Noxious Weed List (Lieurance and Flory 2020). If there are adequate data for a cultivar, more traditional risk assessment tools that involve specific character-based questions may be applied. However, this type of data is often not available, typically because cultivars may only be studied for marketable traits and in many cases, relevant information is withheld by breeders as proprietary data. There is now a need for a universal, national cultivar assessment tool, a mechanism to share data from the nursery industry so assessments can be completed, and widespread screening of plants in trade to identify species with high invasive potential that would benefit from the development of new cultivars (Conser et al. 2015). Additionally, collaboration between industry and universities can help facilitate research to determine sterility and other measures of reduced invasiveness.

Barriers to the development and implementation of risk assessment

The ultimate goal of risk assessment is to prevent the introduction, establishment, spread, and subsequent detrimental impacts of plant invasions, but there are several barriers to developing new methods and implementing risk assessment protocols. These include data limitations, insufficient communication among different assessment programs, lack of harmony in assessment methodology (i.e., too many individual tools), matching the regionality of invasion with the scale of the tools, and incorporating range shifts due to climate change.

A strength of risk assessments but also a potential limitation is their dependence on accurate and comprehensive data to predict risk of non-native species. Limited availability of these data can hinder the ability to make informed decisions, leading to incomplete or inaccurate assessments, often resulting in uncertainty. Quantitative data, information from multiple independent sources, and the addition of expert information reduces this uncertainty and incorrect assumptions (Matthews et al. 2017; USDA APHIS 2019; Clarke et al. 2021). There are two types of data limitations: (1) relevant data may be completely lacking (i.e., a gap), or (2) data may not be readily available. Targeted research can fill data gaps identified during a risk assessment (Hulme 2012), but it takes time and effort to accomplish. Data useful for risk analysts (e.g. seed longevity, time to reproductive maturity) may have been previously obtained during a study but may not be included in a published paper if it is not considered relevant to the main study question. Addressing barriers to data accessibility is a different challenge as peer-reviewed information is often kept behind paywalls by publishers, requiring subscriptions that may be too high for programs with tight budgets. Open access publishing models now circumvent this problem, but efforts are still needed to share relevant literature among programs assessing the same species, while still adhering to the required distribution policies of publishers.

To date, many risk assessment tools have operated in isolation as uncoordinated silos within the risk assessment community. This can create redundancy in efforts to not only collect data for individual species assessment, but also in developing tools with comparable procedures and accuracy. This waste of time and effort could be rectified through better communication across risk assessment programs and the creation of shared data repositories (currently under construction) for source information and completed assessments. Given the large number of different risk assessment methods currently being used by different entities (see Table 1), there also needs to be a general agreement for all risk assessment programs to strive to meet international standards (e.g., International Standards for Phytosanitary Measures, ISPM 2). Standardizing approaches would help reduce variability among assessment tools and help overcome challenges comparing assessments of individual species (Roy et al. 2018).

When thinking about conducting an assessment, it is important to remember the regionality of plant invasions and determine if the tool being used is appropriate for the job. For example, the USDA-PPQ WRA predicts risk at a continental scale and the resulting species distribution maps predict the areas in the United States suitable for establishment by the taxon. In contrast, the A-WRA has been modified multiple times to predict risk in more specific and often smaller regions (e.g., Florida, Hawai'i). Applying an incorrect tool, or a tool at the wrong scale, or using data that would not apply to the region of interest can result in an inaccurate result, potentially misdirecting prevention efforts.

Finally, risk assessments must address the reality that plant species react to their immediate surroundings and adapt over evolutionary time to changes in their environment (Box 2). Given warming climatic temperatures and projected increases in extreme weather events (Jay et al. 2018; National Academy of Sciences 2020) that can disrupt native vegetation and facilitate invasion (Bradley et al., 2010a; 2010b), risk assessments should incorporate climate projections and stochastic events into their processes. In many cases in the US, plant species are already moving northward as temperatures shift, and invasive species will be no different (Hellman et al. 2008; Pyke et al. 2008; Wang et al. 2022; Osland et al. 2023). As such, quantitative risk assessments will likely increase in use as they are nimbler and more reactive to recent changes and can be modified to incorporate landscape- and local-level climatic data to predict potential range shifts of non-native species.

Recommendations

Given that global commerce continues to increase the potential for non-native species to arrive in the US, risk assessments are needed to identify potentially problematic species before they cause substantial economic and ecological costs associated with extensive spread. Invasive plant regulation is typically reactionary, addressing species that are already well established and causing negative impacts. Because prevention can save billions of dollars in avoided economic losses and management costs (Lodge et al. 2016; Lakoba et al. 2020; Cuthbert et al. 2022), we recommend more proactive action to control plants before they become invasive – and risk assessment is a critical part of this process. To be most effective, risk assessments should consider the following recommendations:

- **The risk assessment method must match the needs of a particular application.** For example, if the purpose is to look at invasion risk to the environment, a tool should not incorporate economic benefits. Some tools have even been misapplied as risk assessments, such as the EICAT (see above).
- **All tools should meet best practices for risk assessment**, such as the incorporation of uncertainty or confidence (such as in the APHIS-PPQ-WRA) and climate change (Harmonia+). Assessment must also be fully transparent (Roy et al. 2018), including all responses to assessment questions and certainty levels for each question.
- **A national library of protocols, tools, completed assessments, and supporting sources should be established so states can work together** for semi-quantitative and quantitative assessments. This includes coordinating which species are being assessed (especially by adjoining states or those in the same growing zone). Individual states can increase their efficiency by not replicating the same process, but instead can choose to modify an existing approach or assessment for their own purpose and geographic location.
- **A national cultivar assessment tool must be developed** as several individual states are currently working on this issue in isolation.
- **Comparisons among qualitative, semi-quantitative, and quantitative risk assessment approaches would be helpful** to examine their relative conclusions regarding the same species.
- **Better information is needed regarding the introduction history of non-**

native species, especially those that have been accidentally introduced. To this end, more effort and resources are needed at ports of US entry, such as increased APHIS screening.

- **Impacts of ongoing global climate change need to be incorporated into risk assessments.** This could include expected shifts in species ranges with time, such as movement northward with increasing temperatures, production of biomass/biofuel species in agriculture to attempt to mitigate rising carbon dioxide emissions, or sea ice melt causing changes to existing shipping routes or the emergence of new shipping routes. Furthermore, estimates of uncertainty may need to be adjusted over time, as impacted by ongoing climate change.
- **Proactive approaches such as horizon scanning of species before they are introduced into the United States should be made a priority.** This approach has the potential to greatly reduce future invasions by eliminating species that have been found to be invasive elsewhere, but a funding mechanism to conduct the scanning needs to be developed.
- **More research needs to be directed towards information gaps identified in risk assessments.** This approach of using experimental or survey data (Hulme 2012) is currently being applied to industrial hemp in Florida where experiments have been conducted on establishment and persistence at multiple sites and seed viability over time (Canavan et al. 2020).
- **Overall consistency and comparability of risk assessments across regions could be improved by coalescing the large number of tools currently used in the United States, adding in international tools, and adopting international standards**. This will require coordination and standardization across several entities (including agencies, academic institutions, and international organizations) to increase efficiency of the process. This could result in the development and implementation of effective risk assessment strategies across U.S. states and international borders.

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