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# A participatory method for prioritizing invasive species: Ranking threats to Minnesota's terrestrial ecosystems

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ABSTRACT

Terrestrial invasive species threaten the integrity of diverse and highly-valued ecosystems. The Minnesota Invasive Terrestrial Plants and Pests Center (MITPPC) was established by the state of Minnesota to fund research projects aimed at minimizing harms posed by the most threatening terrestrial invasive species to the state's prairies, wetlands, forests, and agriculture. MITPPC used the Analytic Hierarchy Process (AHP) to identify and prioritize diverse invasive species threats. We describe how MITPPC tailored AHP to establish its research priorities and highlight major outcomes and challenges with our approach. We found that subject matter experts considered factors associated with the severity of impact from invasion, rather than the potential for invasion, to be the greatest contributors in identifying the most threatening species. Specifically, out of the 17 total criteria identified by the experts to rank species, negative environmental impact was the most influential threat criterion. Currently, narrowleaf cattail, mountain pine beetle, and the causative agent of Dutch elm disease are top threats to Minnesota terrestrial ecosystems. AHP does not handle data-poor situations well; however, it allows for easy incorporation of new information over time for a species without undoing the original framework. The MITPPC prioritization has encouraged interdisciplinary, cross-project synergy among its research projects. Such outcomes, coupled with the transparent and evidence-based decision structure, strengthen the credibility of MITPPC activities with many stakeholders.

## 1. Introduction

Terrestrial invasive species threaten the integrity and functioning of diverse agricultural and natural ecosystems (e.g., Beck et al., 2008; Carruthers, 2003; Charles and Dukes, 2007; Olson, 2006; Pimentel et al., 2005). Though the economic impact from the establishment of these species in new areas is difficult to capture, costs well exceed $150 billion annually in the United States due to lost productivity and increased management (based on Pimentel et al. (2005), accounting for inflation). Research is needed to develop new technologies and techniques to mitigate impacts from these species and manage future threats. Research that assesses the effectiveness of management goals is also vital. However, funding needs for research on terrestrial invasive species far exceed the resources currently available. This gap will only worsen as more species undoubtedly arrive in the future.

In Minnesota (U.S.), over 300 terrestrial invasive species are estimated to occur,[1] many of which significantly harm the diverse terrestrial systems across the state (e.g., Asplen et al., 2015; French and Juzwik, 1999; Hale et al., 2006; Melchior and Weaver, 2016; Ragsdale et al., 2010; Rosenberger et al., 2018; Van Riper et al., 2010). To address the need for invasive species research, the Minnesota Legislature established the Minnesota Invasive Terrestrial Plants and Pests Center (MITPPC) in 2014, with the mandate to, "research and develop effective measures to prevent and minimize the threats posed by terrestrial invasive plants, other weeds, pathogens, and pests in order to protect the state's prairies, forests, wetlands, and agricultural resources" (MN, 2014). The primary financial support for the MITPPC comes from the Environmental and Natural Resources Trust Fund, a constitutionally-dedicated state fund composed of Minnesota State Lottery proceeds and investment income (https://www.lccmr.leg.mn). To achieve its mandate, three primary activities of MITPPC are to prioritize the terrestrial invasive species threatening Minnesota, administer a competitive research grant program for University of Minnesota faculty to address those prioritized species, and ensure the findings of the research it supports are publicly

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[1] Estimate based on profiles and assessments from the Minnesota Invasive Species Advisory Council (mninvasives.org).

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accessible. Of note, the prioritizations of the MITPPC do not supersede regulatory lists or management priorities set by county, state, tribal or other national agencies.

Prioritizing invasive species is a common organizational challenge. Indeed, dozens of protocols have been developed to characterize and assess invasive species for awareness, regulation, survey, or management (e.g., Blackburn et al., 2014; reviewed in Buerger et al., 2016 and McGeoch et al., 2016; Koop et al., 2012; Warner et al., 2003; Randall et al., 2008). Pest risk (*sensu* Orr et al., 1993) is frequently an organizing framework for prioritization, with specific evaluation criteria and processes being dictated by the ultimate purpose for prioritizing. Prioritization schemes may be structured to target pathways or sites associated with invasive species, but the majority order species themselves based on risk (McGeoch et al., 2016). An organization may seek to assess species for management or public education, whereas another may be tasked with making regulatory decisions (Buerger et al., 2016; Randall et al., 2008). Criteria for prioritization of invasive species vary widely and may include factors associated with the likelihood of successful invasion or impacts from invasion, such as threats to economies, biodiversity, human health, or cultural values. Frequently, qualitative ratings or associated point scores are given to each criterion. These individual ratings are then aggregated to define a final overall rating (e.g., high, medium, or low risk) assigned to the species based on a standard rubric, typically with an unlimited number of members within each final rating category (e.g., Weiss and McLaren, 2002). Such binned outcomes are sufficient in some circumstances, but the number of "high risk" (or equivalent) species may eventually exceed the resources available to address them. For applications like the MITPPC, where limited funds are available, a need exists to rank species to identify which species pose the greatest relative threat to the state. The nature of the MITPPC also requires a prioritization process that is scalable (i.e., allows additional species to be continually added) and can be updated whenever new scientific information becomes available.

This paper serves two purposes. First, it provides a detailed technical description of the prioritization process used to engage diverse experts and rank some of the greatest terrestrial-invasive-species threats to Minnesota. A whitepaper has been drafted previously as an overview of the process (Venette, 2020). Second, by describing the process and experiences of MITPPC, we hope to offer a transparent, consistent, and responsive framework for prioritizing efforts related to invasive species. As such, MITPPC's approach could be informative for other entities with similar needs focused on prioritization. At present, the ranking of terrestrial invasive species by MITPPC is one of the most extensive (i.e., provides a relative ranking for the largest number of species) regionally and nationally.

## 2. Prioritization using the analytic hierarchy process

In 2015, MITPPC used relevance selection (Butler et al., 2015) to assemble a panel of 15 subject matter experts with experience in the study or management of invasive species (i.e., species that are not indigenous to an area and whose introduction causes or is likely to cause harm). Expertise was solicited on invasive plants, plant pathogens, and phytophagous insects. Six subject matter experts were university faculty (Departments of Entomology, Plant Pathology, Agronomy and Plant Genetics, and Forest Resources), and nine were from two state agencies (Departments of Natural Resources and Agriculture) with major responsibilities associated with invasive species management. Experts were guided through the analytic hierarchy process (AHP), the method used to compare and rank terrestrial alien invasive species that threaten Minnesota. Here, we first provide an overview of AHP, then detail how AHP was tailored to MITPPC's application. We emphasize that our overview of AHP is not intended to re-establish the mathematical and theoretical details of the method, but rather briefly introduce key components that give context to MITPPC's usage of the analysis.

AHP is a type of multi-criteria decision analysis that systematically structures a decision (or series of decisions) among a set of alternatives. The decision structure is hierarchical and based on independent decision criteria that (may) differ in importance (Saaty, 1977, 2008). AHP uses expert judgement to inform the relative importance of each criterion for the decision in question, and has been applied in myriad organizational settings where complex decision-making is needed (Saaty, 2008), including decisions related to invasive species. For example, AHP has been used to spatially prioritize invasive plant management across a defined landscape (Skurka Darin et al., 2011; Hohmann et al., 2013; Nielsen and Fei, 2015). A weed risk assessment framework for the Australian state of Victoria utilized AHP to categorize plants into one of four rankings based on their potential invasiveness (Weiss and McLaren, 2002). Schaad et al. (2006) used AHP to prioritize non-native crop pathogens for future detection efforts. Similarly, the U.S. Department of Agriculture Animal and Plant Health Inspection Service (USDA-APHIS) used AHP to select ~50 non-native plant pests to be targeted by the Cooperative Agricultural Pest Survey (Devorshak, 2012; Magarey et al., 2011), an application most akin to MITPPC's use of AHP. AHP can incorporate multiple lines of quantitative and qualitative evidence that vary in their degree of certainty, a much-needed flexibility in working with invasive species.

A unique aspect of AHP is the process by which the importance of each decision criterion is set. Importance is inherently relativistic. Mathematically, establishing importance using AHP occurs as follows (Saaty, 2004, 2008): Given a set of decision criteria, $s_i$, $i = 1 \ldots S$, AHP defines a matrix $A$ with elements $a_{i,j}$ representing pairwise comparisons of the relative importance of criterion $s_i$ with $s_j$, $j = 1 \ldots S$. Each comparison follows what Saaty (1977) calls "the fundamental scale of absolute numbers," an ordinal, quasi-interval rating scale (i.e., the numerical distances between values are not necessarily proportional in their meaning) with integer values, $v$, from 1 to 9, with 1 indicating equal importance, 5, strongly greater importance, and 9, extremely greater importance. To populate matrix $A$, reciprocal elements $a_{i,j}$ are used, where if $s_i$ is more important than $s_j$, $a_{i,j} = v$, else $a_{i,j} = 1/v$ (Saaty, 1977, 2004). By definition, $a_{j,i} = 1/a_{i,j}$, and when $i = j$, $a_{i,j} = 1$ (Saaty and Sodenkamp, 2008). Thus, $S(S\text{-}1)/2$ comparisons are needed to populate matrix $A$. Weights for each criterion ($w_i$) can be determined from the principal eigenvector of $A$ or by normalizing each cell of $A$ against the sum of its associated column and averaging within the row (Saaty, 2004). (Note that $\Sigma\, w_i = 1$). Consistency is, in part, a measure of the degree to which all elements of $A$ follow the transitive property: if $a_{1,2} > a_{1,3}$ and $a_{1,3} > a_{1,4}$, then $a_{1,2} > a_{1,4}$. A consistency ratio can be calculated for a comparison matrix, wherein values of 0 indicate perfect consistency and values of 1 indicate random judgements (i.e., the matrix is inconsistent). Consistency ratios $\leq 0.05$, 0.08, and 0.10 are considered acceptable for $3 \times 3$, $4 \times 4$, and $5 \times 5$ matrices, respectively (Saaty and Sodenkamp, 2008; Saaty, 2000). Further detail on the theory and estimation of consistency is well described elsewhere (e.g., Alonso and Lamata, 2006; Lin et al., 2013; Saaty 2000). Lastly, AHP allows for "child" (and, subsequently, "grandchild") criteria to be included that elaborate on a "parent" criterion. Child criteria should be independent of each other, but not the parent. Weights for child criteria are determined as for parents, but each child weight is multiplied by the weight of its parent (and grandparent, if applicable). Child criteria are not compared to any parents or child criteria of other parents, and the contribution of each child to the overall decision cannot exceed the weight of their parent.

MITPPC's application of AHP had six steps, approximately following Saaty (2008) and Devorshak (2012): (1) problem definition (i.e., what is the goal of the decision in question); (2) species selection (i.e., what are the alternatives from which to choose); (3) identification, organization, and weighing of the decision components into a hierarchy (i.e., what decision criteria should factor into the decision and which criteria are most important); (4) definition of consistent measurement standards for each criterion (i.e., what does each criterion mean and what levels equate to meaningful differences); (5) reviewing information sources to assign a rating to each criterion for each species; (6) analysis of the criteria ratings to determine a relative ranking for each species. In the sections below, we discuss these steps in more detail, identifying where the variables and analyses mentioned above apply to our process.

### 2.1. Problem definition

The decision problem faced by MITPPC was to identify the terrestrial invasive species that pose the greatest threat to Minnesota in the absence of management. The species of concern need not be established or present in the state. MITPPC disregarded management considerations in its decision-making because management scenarios for species not yet present in the state were deemed too speculative. For MITPPC, 'terrestrial' species are considered those that dwell primarily on land, but some may readily move in or along water, such as those species that inhabit wetlands. 'Invasive' refers to species that are not native to Minnesota's ecosystems and have the potential to cause economic, environmental, or social harms. More specifically, MITPPC focused on invasive plants, pathogens, insects, earthworms, mites, and mollusks that have the potential to harm the abundance or health of valued plants. For MITPPC's purposes, pathogens included viruses, phytoplasmas, bacteria, fungi, nematodes, and parasitic plants. Non-native species that primarily harm human or animal health are beyond the scope of MITPPC.

### 2.2. Species selection

The 15 expert panelists were divided into three teams of five based on disciplinary expertise (i.e., plants, plant pathogens, or invertebrates). Each team was asked to use their professional judgement to nominate the 40 most-threatening terrestrial invasive species (within their discipline) to Minnesota's agriculture, forests, wetlands, or prairies. Additional criteria for nominating a species were not specified to the panelists. From these discussions, 124 total species were submitted.

In 2017, MITPPC issued a general call for additional nominations of terrestrial invasive species of concern. Approximately 85 unique species nominations were received, primarily from land managers. Most nominated species had not been previously considered by MITPPC and included the first nomination of jumping worms (*Amynthas* spp.), cyst nematodes (*Globodera* spp. and *Heterodera* spp.), and cattails (*Typha* spp.). By January of 2020, 167 total species had been evaluated in the prioritization process.

### 2.3. Identification, organization, and weighting of the decision criteria

The expert panel convened for a half-day, facilitated discussion about criteria that could be used to assess the "unmanaged biological threat" that an invasive species posed to Minnesota. Discussions were prompted by a brief introduction to the definition of risk from invasive species as defined by Orr et al. (1993), that is, the potential of invasion

**Box 1**

An example calculation of the overall threat posed by Japanese beetle, *Popillia japonica*, to Minnesota. Japanese beetle, native to Asia, was first detected in North America in 1916 and was found in Minnesota by 1998 (Potter and Held, 2002). Outbreaks within the state, primarily on ornamental plants, have become more severe over the past 10 years. The 17 decision criteria and their associated weights ($w_i$) were determined by expert opinion and apply to every terrestrial invasive species that is evaluated by the Minnesota Invasive Terrestrial Plants and Pests Center. Reviews of the literature and simple modeling exercises then inform criteria ratings assigned to a given species. A detailed rationale for each rating for Japanese beetle occurs in Supplement 2. By using standard reference scales that are unique to each criterion, we convert the qualitative criteria ratings to standardized numerical rating scores ($r_i$) (see Supplement 1 for complete lists of criteria ratings and rating scores). The overall priority score, 0.566, is then compared to the maximum score for any terrestrial invasive species evaluated with this system to assign its relative rank. At the time of this publication, the priority score for Japanese beetle was 75.56% of the maximum score.

| Criteria ($w_i$) | Criteria Rating ($r_i$) | $w_i$*$r_i$ |
|---|---|---|
| <u>Potential for Invasion</u> | | |
| Arrival | | |
| *Proximity to MN* (0.005) | Very high (1.00) | 0.005 |
| *Existence of pathways to MN* (0.005) | High (1.00) | 0.005 |
| *Innate dispersal capacity* (0.005) | Moderately Low (0.40) | 0.002 |
| Establishment | | |
| *Suitable climate* (0.026) | High (1.00) | 0.026 |
| *Presence of hosts or habitat* (0.026) | High (1.00) | 0.026 |
| Hybridization (0.029) | Low (0.33) | 0.010 |
| Spread | | |
| *Existence of pathways within MN* (0.009) | High (1.00) | 0.009 |
| *Reproductive potential* (0.022) | Low (0.33) | 0.007 |
| *Extent of invasion* (0.020) | Very high (1.00) | 0.020 |
| *Existence of non-human vectors* (0.020) | Negligible (0.25) | 0.005 |
| <u>Severity of Impact</u> | | |
| Problem Elsewhere (0.055) | High (1.00) | 0.055 |
| Economic Impacts | | |
| *Lost yield/marketability* (0.149) | High (1.00) | 0.149 |
| *Costs of quarantine/mitigation* (0.057) | High (1.00) | 0.057 |
| *Lost recreation/real-estate value* (0.065) | Low (0.33) | 0.021 |
| Environmental Impacts | | |
| *Negative impacts to native species* (0.128) | 2 of 5 (0.50) | 0.064 |
| *Negative impacts to ecosystem services* (0.256) | 1 of 7 (0.25) | 0.064 |
| Facilitate Other Invasions (0.124) | Low (0.33) | 0.041 |
| **Overall Priority** ($\Sigma w_i r_i$) | | **0.566** |

weighted by the negative consequences of invasion. Within each of these two broad parent criteria, panelists proposed sub-criteria and refined definitions for each to eliminate redundancies and organize potential parent-child(-grandchild) relationships (Box 1). Importantly, the panel was told that criteria could not be unique to a particular taxonomic group. Care was taken to avoid using different terms to indicate the same fundamental concept or to use the same term to indicate different concepts (Kaplan, 1997).

Following the panel discussion and identification of decision criteria, panelists worked individually to assign the relative importance of each criteria, irrespective of species. Criteria were presented in pairs to 12 panelists (three panelists were unable to contribute to this exercise). Each panelist indicated which criterion was more important using a scale of 1–9 (i.e., $v$, the fundamental scale of absolute numbers). The responses were converted to the appropriate, $a_{i,j}$, to indicate the magnitude and directionality for the comparison of criterion $i$ with criterion $j$ (Fig. 1). To aggregate pairwise comparisons among the 12 panelists, each opinion was assumed of equal importance and the (unweighted) geometric mean of responses for a given comparison was calculated (Forman and Peniwati, 1998). The aggregated scores were rounded to the nearest whole integer and used to populate the summary comparison matrix ($A$) for a given criteria. The summary results from all panelists' pairwise comparisons were entered into the software Comparion® (ver. 6, Expert Choice, Inc., Arlington, VA) to create the complete comparison matrix. The software calculated final weightings for each criterion (using the dominant eigenvector) and consistency ratios (termed "inconsistency ratio" by the software) for each matrix.

### 2.4. Establishment of consistent measurement standards for each criterion

We used the ratings method of AHP (Saaty, 2008) to characterize the decision criteria so they could be consistently evaluated for each species. In this method, qualitative ratings (e.g., high, medium, low) were defined within each criterion and each rating assigned a rating score ($r_i$). The ratings and scores were defined by MITPPC staff. For a given criterion, we relied on our previous experience with pest risk assessment to consider the type and quality of information that was likely to be available for any given invasive species, which then informed the nature of the ratings. For criteria which previous experience suggested data might be sparse, the rating descriptions were purely qualitative, and reflected the strength of support for a possible outcome, not the extent or intensity of an outcome. For example, records of occurrence for species are often spatially biased and incomplete relative to their true geographic distribution (Syfert et al., 2013). These issues can arise for a number of reasons, but can be particularly common for species new to an area, such as invasive species. Therefore, for a criterion related to the spatial proximity of a species to Minnesota, the intensity of risk would be based on descriptive distances that, while relatively coarse (e.g., state-level), are more likely to be accurately characterized in the literature. A species occurring within Minnesota, even with a limited

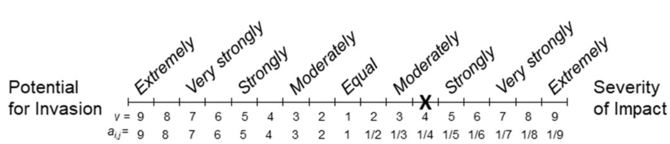


**Fig. 1.** Example numberline provided to expert panelists for identifying the relative importance of decision criterion using the Analytic Hierarchy Process. A value of $v = 1$ indicates equal importance, whereas $v = 9$ indicates that one criterion is "extremely" more important than the other. In this example, a panelist indicated they viewed Severity of Impact to be four times more important than the Potential for Invasion for ranking the unmanaged threat an invasive species may pose in Minnesota. For further analysis, each panelist's response was converted to the positive reciprocal scale, $a_{i,j}$, which indicates the magnitude and directionality for the comparison of criterion $i$ (here, Potential for Invasion) to criterion $j$ (here, Severity of Impact).

distribution, is likely at greater risk of spreading to other parts of the state than a species that has not yet arrived. Similarly, species occurring in states (or Canadian provinces) immediately adjacent to Minnesota are likely to have greater opportunities of arrival than those at more distant geopolitical regions. For quantitative criteria, rating descriptions were roughly log-based (e.g., $\log_2$ or $\log_{10}$) in scale. For example, the differences among rating categories for a criterion related to climate suitability could be based on a doubling ($\log_2$) of the area of Minnesota estimated as climatically suitable. Quantitative estimates of area (as a percentage of total state land) would be considered reasonable for this criterion due to available information from sources such as the USDA Plant Hardiness Zones and spatially-explicit pest risk maps constructed using climate variables.

Rating scores are values less than or equal to 1. For a criterion with $x$ rating categories, the lowest rating score was calculated as $1/x$ and the highest score was 1, with a $1/x$ interval between levels. For example, a criterion with three rating categories would have corresponding rating scores of 1.0, 0.66, and 0.33. For all criteria, the lowest rating score is always non-zero. This scaling allowed us to acknowledge some degree of threat, even for poorly studied species. Detailed rating descriptions and corresponding scores for each criterion are provided in Supplement 1. Rating scales for each criterion and their associated scores were also entered into Comparion® (Expert Choice®).

### 2.5. Review literature to rate each species

Once rating definitions were established, each species was evaluated by MITPPC staff. Evaluations were based on reviews of multiple information sources (e.g., peer-reviewed journal articles, books, published reports, university publications, government documents, etc.) and simple modeling exercises. Brief guidance for an evaluator regarding the kind of information to be considered when justifying a given rating for a species is included in Supplement 1. An example evaluation for one of the MITPPC prioritized species, Japanese beetle (*Popillia japonica* Newman), is also included as Supplement 2. Draft evaluations are shared with subject matter experts. If disagreements with the initial ratings occur (which has happened in <10% of all assessments thus far), the expert(s)'s proposed rating is adopted if empirical justification is provided.

Ratings assigned to each species are malleable. Reconsideration of ratings can be initiated when new information becomes available that could affect how criteria were previously characterized for a species. For example, Palmer amaranth (*Amaranthus palmeri* S. Watson) was reevaluated following its first detection in Minnesota in 2016, which resulted in significant changes to its ratings for the arrival and spread criteria.

### 2.6. Analysis to determine the relative rank of each species

Criteria ratings ($r_i$) for each species were entered into Comparion® to generate an overall priority score for each species. The priority score is calculated by multiplying each rating score by the weight for an associated criterion, summing over all criteria (i.e., $\Sigma w_i r_i$). An example illustrating this calculation can be seen in Box 1. All final priority scores are ultimately expressed as a percentage of the score for the most threatening species (across all taxonomic groups). This relative ranking de-emphasized labelling species as strictly risky or not risky based on an absolute score.

We then investigated whether our process prioritized agricultural species over non-agricultural species. Species were categorized as either primarily "agricultural" (i.e., food and forage crops, not including silviculture), "non-agricultural" (e.g., forests, prairies, wetlands, ornamental/turf), or "multiple" (i.e., significantly affecting both agricultural and non-agricultural areas) based on the primary habitat(s) they negatively affect. We compared affected habitats across all species, within taxonomic groups (i.e., plants, plant pathogens, and invertebrates), and among the highest 15 ranked species within and across taxa.

## 3. Outcomes of the MITPPC prioritization

### 3.1. Decision criteria and their relative importance

The expert panel initially identified 18 decision criteria for assessing the threat a species may pose to Minnesota, of which ten were associated with the potential for invasion and eight were associated with the severity of impact from invasion (i.e., consequence of invasion). One criterion related to impacts on human health was removed after initial analysis, leaving 17 total decision criteria. Each criterion and its position in the final decision hierarchy are depicted in Box 1, and a brief explanation of each criterion is provided in Supplement 1.

The degree of expert agreement about the relative importance between two criteria varied depending on the comparison. In the extreme example, when asked to compare the importance of establishment to hybridization/host-shifting potential, at least one panelist identified establishment as being extremely more important than hybridization/host-shifting potential (i.e., selected a 9, the maximum difference offered) and at least one panelist selected the converse (Fig. 2). Nonetheless, all consistency ratios of the comparison matrices based on the aggregated (geometric mean) score were within acceptable range: those with four child criteria had values ≤ 0.08 and those with three had values ≤ 0.05 (Table 1).

Experts viewed the potential negative impact(s) a species may have with nearly four times greater importance than the potential the species would invade (Fig. 2). Within the impacts criterion, negative environmental impacts were perceived as ~1.5 times more important than

**Table 1**
Consistency ratios of comparison matrices used by the Minnesota Invasive Terrestrial Plants and Pests Center to prioritize terrestrial invasive species for research support through the Analytic Hierarchy Process. Ratios were calculated using Comparion® (ver. 6, Expert Choice, Inc., Arlington, VA) following the method of Saaty (Saaty, 1977, 2000). Values ≤ 0.10, ≤0.08, and ≤0.05 are considered acceptable for matrices with 5 or above, 4, and 3 criteria, respectively (Saaty and Sodenkamp, 2008).

| Decision Criteria | Number of child criteria | Consistency ratio |
|---|---|---|
| Potential for Invasion | 4 | 0.03 |
| Arrival | 3 | 0.00 |
| Establishment | 2 | 0.00 |
| Spread | 4 | 0.01 |
| Severity of Impact | 4 | 0.04 |
| Economic Impact | 3 | 0.02 |
| Environmental Impact | 2 | 0.00 |

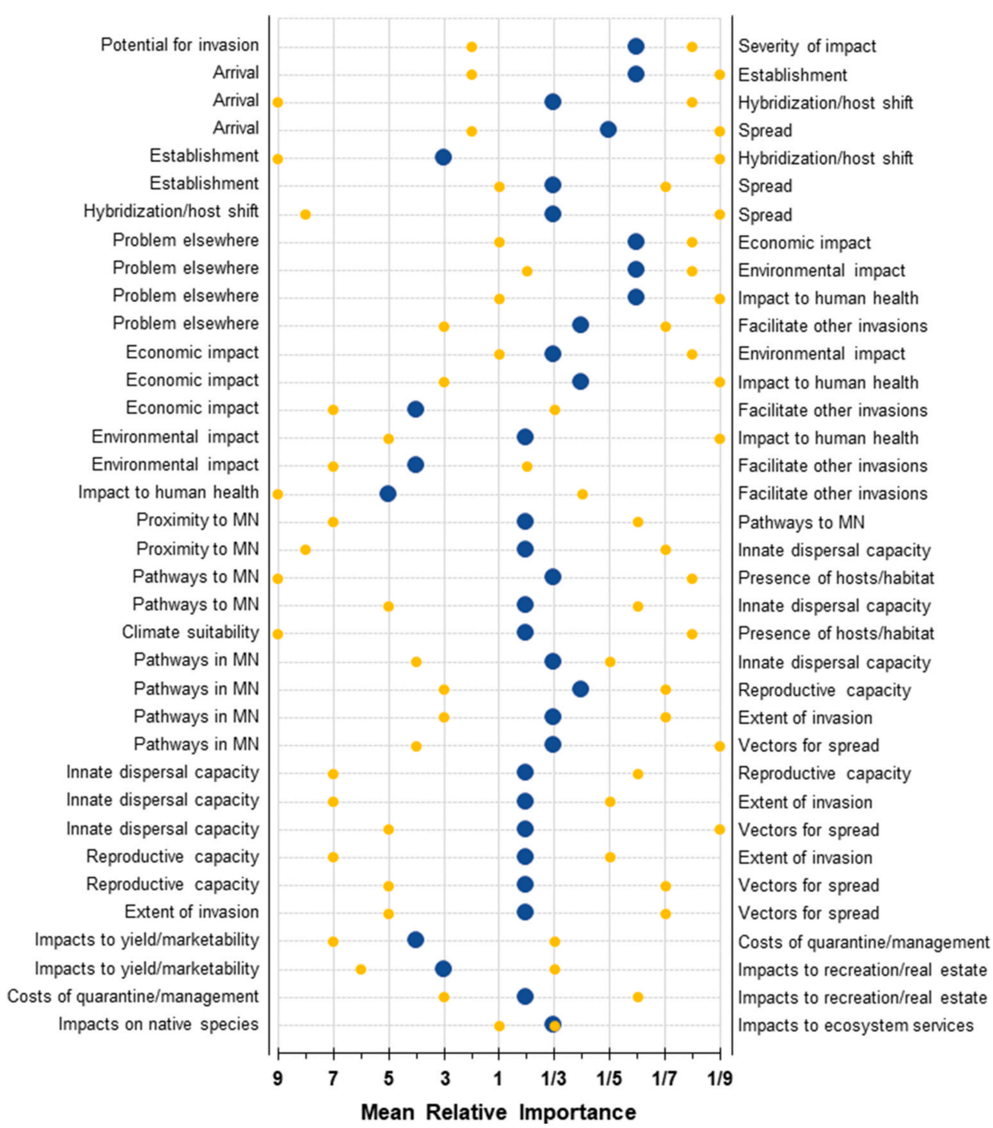


**Fig. 2.** Summary of all pairwise comparisons of decision criteria for ranking the threat posed by a terrestrial invasive species in Minnesota. Twelve expert panelists individually indicated which criterion was more important than another, where 1 is equal importance and 9 "extremely" more important (see also Fig. 1). Responses were aggregated among panelists for a given comparison using the geometric mean, rounded to the nearest whole number, and converted to the positive reciprocal scale, $a_{i,j}$ (see also Fig. 1). Yellow dots represent the maximum and minimum value where at least one panelist responded. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

negative economic impacts, and whether a species posed a problem in other geographic areas was consistently viewed with relatively little importance to the other three impact criteria (Fig. 2). The final contributions of the decision criteria to the overall threat level are shown in Fig. 3. The importance of impacts was influenced most by the child criteria of consequences to ecosystems services and economic impacts to yield and marketability, which each contributed ~26 and 15%, respectively, to the overall weight of impact (Fig. 3). Of the ~17% that criteria associated with the potential for invasion contributed to the final priority scores, the child criteria associated with spread contributed the most (~7%) (Fig. 3).

### 3.2. Relative rankings of species

The highest ranked species across all taxa at the time of this publication (n = 167) is the wetland plant, *Typha angustifolia* L. (narrowleaf cattail) (Fig. 4). The insect *Dendroctonus ponderosae* Hopkins (mountain pine beetle) ranked second highest, with a relative score of ~98% of that for *T. angustifolia* (Fig. 5). Across all taxa, plants and invertebrates were generally rated higher than plant pathogens. The highest ranked pathogen, the causative agent of Dutch elm disease (*Ophiostoma novo-ulmi* Brasier), ranked 21 with a relative score of ~83% of that for *T. angustifolia* (Fig. 6).

As expected from the criteria weightings, the overall ranking of a species (irrespective of taxonomic group) was more sensitive to differences in ratings associated with impact than those associated with the potential for invasion (Figs. 4–6). In general, a species' ranking decreased as scores for its potential impact(s) decreased. Based on impacted habitats (Supplement 3), the species evaluated by MITPPC have thus far been dominated by those that primarily affect non-agricultural systems. Non-agricultural species make up 56% of all species, which increased to 67% among the highest ranked species (i.e., the top 15) (Supplement 4 A and 4 E). This dominance appears driven by plants; 71% of all plants and 60% of the highest ranked plants are considered non-agricultural pests (Supplement 4 B and 4 F). None of the currently evaluated invasive plants (n = 79) were considered predominantly issues of agriculture (Supplement 3). Several species are considered equally problematic in both agricultural and non-agricultural systems, with the latter typically being forests or grasslands (e.g., *Berberis* spp., *Centaurea* spp.). In contrast, 50% of plant pathogens (n = 46) and 45% of invertebrates (n = 42) are predominately issues in agriculture (Supplement 4 C-D). Among the 15 highest ranked species within these two taxa, the pattern shifts slightly such that a greater percentage affect non-agricultural systems (53 and 60% of pathogens and invertebrates, respectively) (Supplement 4G-H). Nearly half (~8) of the top invertebrate and top pathogen species categorized as non-agricultural pests are primarily threats to forests (e.g., *D. ponderosae*, *Scolytus* spp., *O. novo-ulmi*, *Ceratocystis* [now *[now Bretziella]Bretziella*] *fagacearum* (Bretz) Z.W. de Beer, Marincowitz, T.A. Duong & M.J. Wingfield).

## 4. Discussion

The Analytic Hierarchy Process is a beneficial framework for prioritization of invasive species for three primary reasons: First, the nature of the process forces the discussion from which species should be most important (perhaps for unknown or subjective reasons) to which attributes make a species important. We believe this distinction provides greater transparency in the decision-making process. Second, AHP easily allows additional species to be considered at any point without undoing the original work. Such an approach provides flexibility to prioritizations over time while maintaining some amount of consistency. Lastly, AHP enables revision of criteria ratings as new scientific information is acquired and an updating of species rankings to reflect the change in knowledge.

The structured and systematic nature of AHP highlights many details of the decision-making process that may otherwise be difficult to track. An interesting result from the MITPPC prioritization was that the potential impact of a species was viewed with far greater importance by experts than the potential the species would invade (Fig. 2). For many prioritization processes, details of criteria and their influence on a final decision is often opaque, an issue raised previously by others (Randall et al., 2008). Notably, however, the Victorian Weed Risk Assessment developed by the State of Victoria, Australia using AHP found that impact was also weighted about four times greater than criteria associated with "invasiveness", a category that is similar to the potential for invasion criterion used by MITPPC (Devorshak, 2012; Raymond and Pegler, 2004; Weiss and McLaren, 2002). Though aspects of the

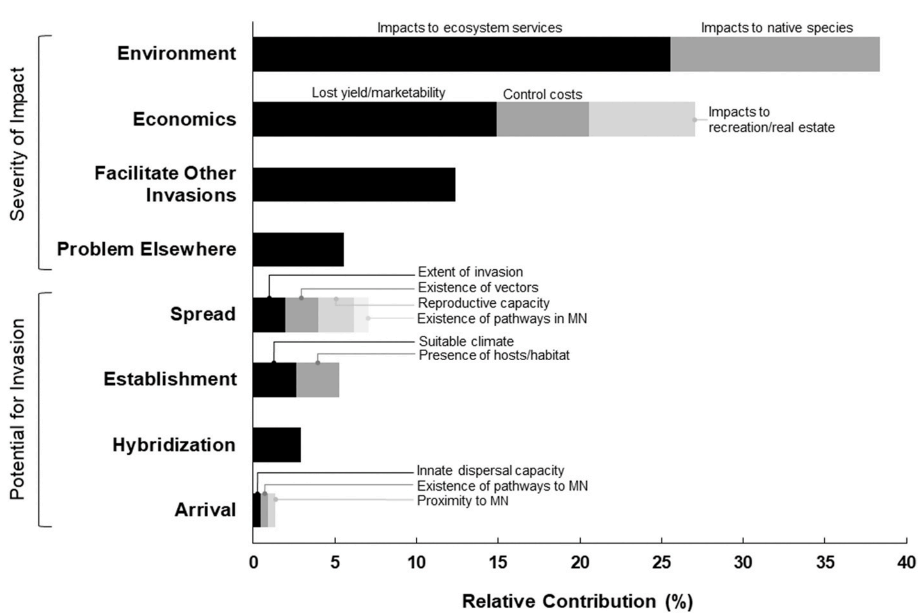


**Fig. 3.** The final decision criteria and associated relative weights (i.e., relative contributions) identified using the Analytic Hierarchy Process that were used to calculate the relative level of threat posed by different terrestrial invasive species to Minnesota. In general, the seven criteria associated with the Severity of Impact contributed 83% to the final species priority scores. The ten criteria associated with the Potential for Invasion contributed 17% to the final species priority scores.

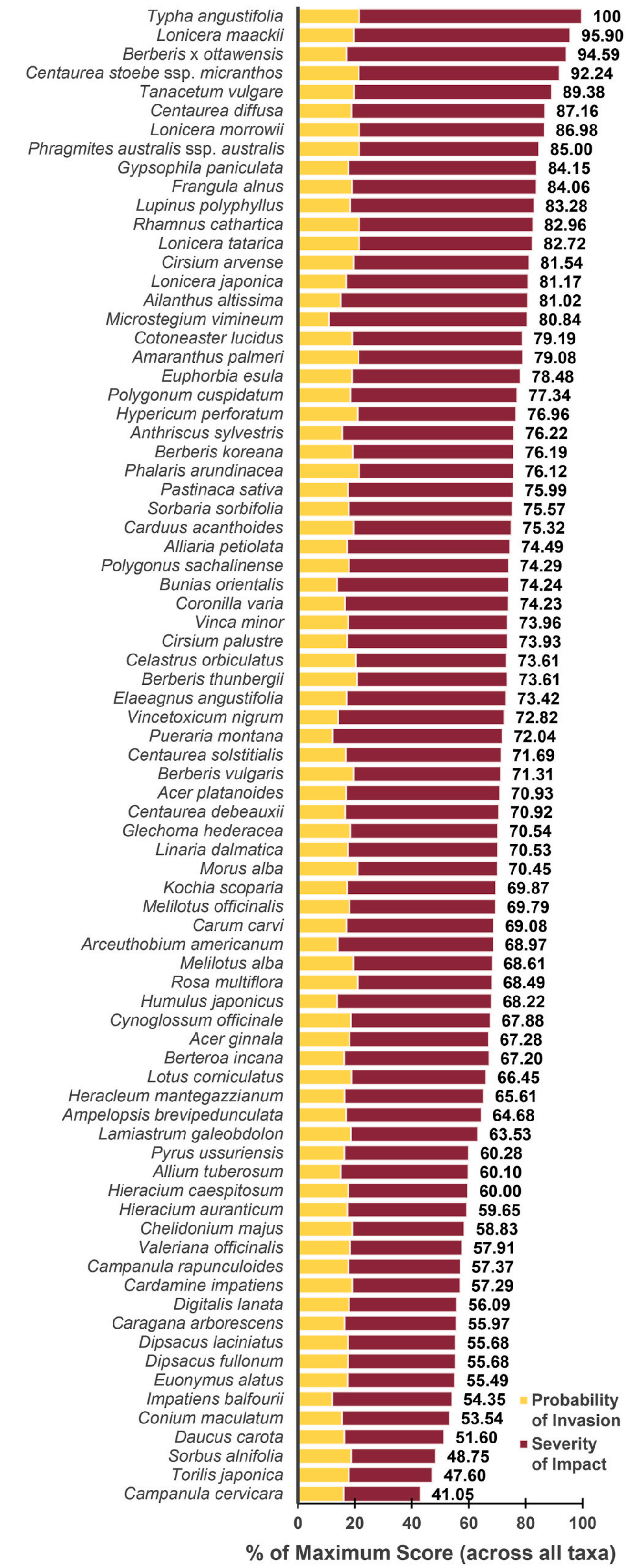


**Fig. 4.** The relative rankings of 79 invasive plant taxa evaluated by the Minnesota Invasive Terrestrial Plants and Pests Center. Rankings are expressed as a relative percentage of the taxon with the highest overall priority score (see Box 1 in main text for further explanation) across all taxa (i.e., *Typha angustifolia* as of 2020). The relative contributions of criteria associated with the potential for invasion versus the severity of impact to final scores are also depicted for each species.

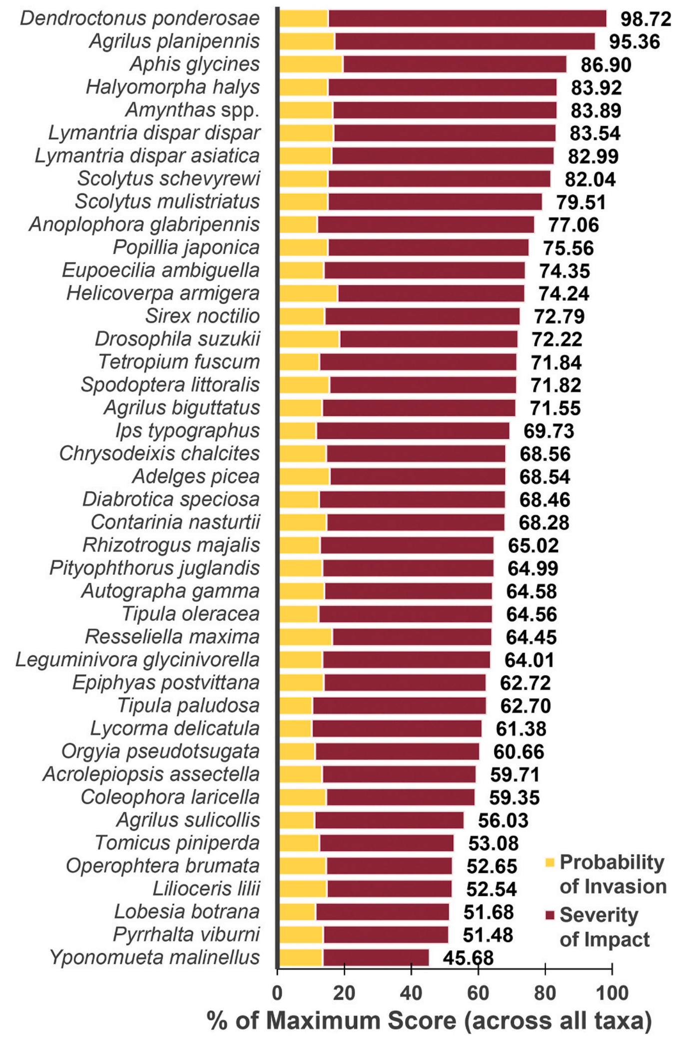


**Fig. 5.** The relative rankings of 42 invasive invertebrate taxa evaluated by the Minnesota Invasive Terrestrial Plants and Pests Center. Rankings are expressed as a relative percentage of the taxon with the highest overall priority score (see Box 1 in main text for further explanation) across all taxa (i.e., *Typha angustifolia* as of 2020). The relative contributions of criteria associated with the potential for invasion versus the severity of impact to final scores are also depicted for each species.

Victorian hierarchy structure differed from ours (e.g., characters related to geographic distribution were considered a separate parent criterion and the impact criterion consisted of 21 sub-criteria), the broad characterizations were similar. Moreover, the Objective Prioritization of Exotic Pests Impact Assessment currently used by USDA-APHIS to rank species for surveillance efforts is based entirely on evaluating impacts of invasion (USDA-APHIS-PPQ, 2019). The consistency of our results with these earlier efforts suggests that our findings, though based on a relatively small subset of experts (12), are representative of broader perceptions of risk of invasive species.

To characterize impact, our expert panel initially included a criterion for negative human health effects, a common factor included in other assessments of risk from invasive species. The AHP analysis showed that human health outweighed all other impact criteria, including a slightly higher importance compared to environmental impacts (Fig. 2). However, the panel could not devise a useful rating scale for potential human health effects that adequately reflected the nature of scientific information available. For example, some moth species have urticating hairs as caterpillars that can be severely irritating to human skin (Smith-Norowitz, 2010). Unfortunately, the severity and frequency of contact

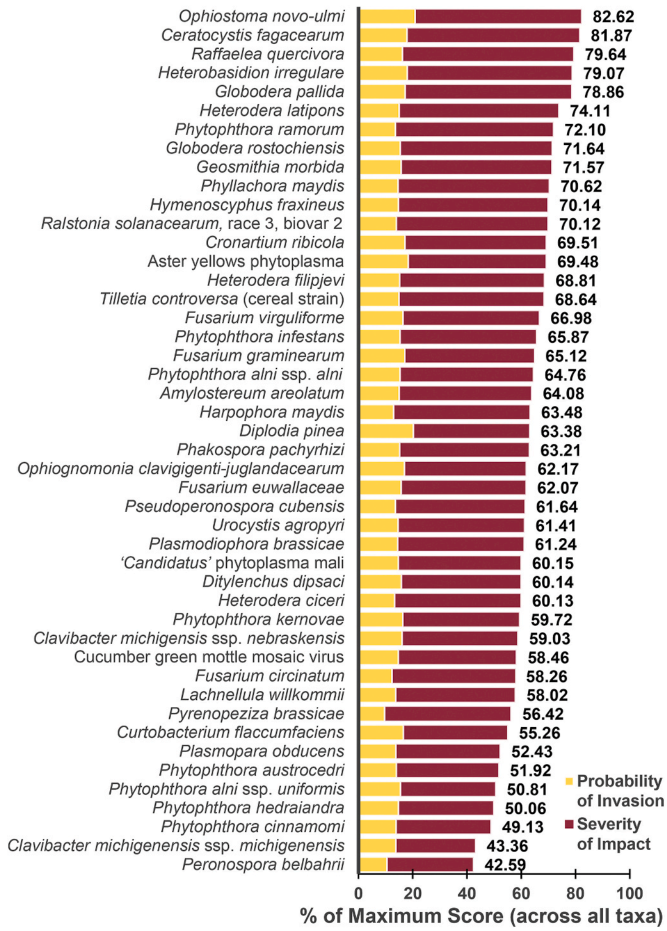


**Fig. 6.** The relative rankings of 46 invasive plant pathogen taxa evaluated by the Minnesota Invasive Terrestrial Plants and Pests Center. Rankings are expressed as a relative percentage of the taxon with the highest overall priority score (see Box 1 in main text for further explanation) across all taxa (i.e., *Typha angustifolia* as of 2020). The relative contributions of criteria associated with the potential for invasion versus the severity of impact to final scores are also depicted for each species.

dermatitis caused by these hairs, generally or for particular species, is nearly absent from the literature. Without an effective way to distinguish between effect levels, species that had any potential for negative human interaction received a high rating for that criterion, and ultimately received a high overall priority score because of the large weight of human health within impacts. Such heavy influence from one criterion led to some species with otherwise minimal risk being very highly ranked, an imbalance the panel felt was not reflective of the quality of available knowledge and consequent threat risk. Therefore, negative human health impact was excluded from the final decision criteria.

The use of AHP by MITPPC also has limitations. The most significant issue is that the process does not work well for poorly studied species. This dilemma is inherent to any prioritization or risk assessment framework (e.g., Brunel et al., 2010; McGeoch et al., 2016; Wainger et al., 2007), though is nonetheless important to acknowledge. For understudied species, the reasons for lack of available information – whether in quantity or quality – can vary. Some species do not yet occur in the U.S. (or Minnesota), or have only recently arrived. Previous research may only be available in inaccessible foreign literature or pertain to dynamics within the species native range, which may not reflect behavior in an adventive range. In other cases, though a non-native species may be present in the U.S., impacts may not be obvious, as for some horticultural species that escaped cultivation and spread into unintended areas. Empirical evidence of the effect(s) such species have on the systems they invade is often lacking, though their mere presence may be perceived as harm. For example, the plant, *Allium tuberosum*, is a popular garden species that has reportedly spread outside of cultivation (USDA-NRCS, 2019). While some anecdotes describe negative behavior from such spread in the U.S. (Chayka and Dziuk, 2017; Hilty, 2017), evidence of negative economic or environmental effects from *A. tuberosum* is nearly absent. Whether this represents a true lack of measurable impact, or of negative impact that has yet to be measured, underscores the dilemma.

The effect of data-limitation becomes most apparent when rating a species for a given decision criterion. The evaluation standards for rating MITPPC's decision criteria do not include a separate assessment of the level of uncertainty in the assessment. Where robust evidence cannot be found, low ratings are often chosen due to lack of support for higher categories, a consequence noted in other invasive species classification schemes (e.g., Blackburn et al., 2014). As became evident when considering human health effects above, establishing meaningful, reliable ratings levels for each decision criteria is a challenge. As more levels within a criterion are included, greater resolution among species becomes possible and nuance related to quality of evidence can be captured. However, if differences among levels are too small, distinctions among species may be unreliable.

In typical pest risk assessment work, three rating levels are routine: high, medium, and low. Some applications go further and adopt more than three levels, but in either case, the factors that distinguish between risk levels are often left to expert discretion and consequently unstandardized. The advantage of such an approach is that it allows an assessor to consider factors that may be idiosyncratic to a particular species when providing a rating. The difficulty is that differences in the interpretation of the question lead to different assessments among experts or groups of experts (Venette and Gould, 2006). The MITPPC criteria ratings are structured to capture the quality of scientific information available, utilizing quantitative thresholds wherever possible to dictate a rating. More consistent measurement standards make the prioritization process scalable (i.e., simplifies the addition of more species) and robust (i.e., provides greater consistency of response across evaluators). This structure may nonetheless come at the cost of misestimating the risk from poorly studied species. Consequently, the MITPPC's application of AHP is most useful for organizing a research program to respond to known threats, not for confidently determining whether any given species might pose a threat. However, AHP establishes a framework that allows for easy incorporation of information when knowledge gaps become filled (e.g., new insights related to the biology of a given species) without undoing the original decision structure.

A broad challenge for MITPPC was to identify research priorities that transcend the goals and values of any individual or institution in Minnesota so that research from MITPPC projects benefits multiple stakeholders and partners. As seen in Fig. 2, simply defining the relative importance of two criteria related to invasion risk can yield divergent views. While there was only one case where expert opinions covered the range of extremes of relative importance (i.e., establishment versus hybridization/host shift potential), multiple comparisons showed high variability among some expert perceptions (Fig. 2). However, other comparisons showed relatively high agreement among experts regarding which criteria was more important (e.g., impact on native species versus impact to ecosystem services; problem elsewhere versus negative environmental impact) (Fig. 2). By calculating the "average" (i.e., geometric mean) of the decision criteria comparisons across the expert panelists, AHP allows for differing perceptions of risk to be objectively included in the final decision.

The selection of taxa to be considered by MITPPC could indirectly emphasize the interests of some stakeholders over others, so tracking the taxonomic and habitat diversity of species helps MITPPC be aware of unintentional emphasis. Taxonomically, nearly half (~47%) of all currently evaluated species have been plants. While the highest prioritized species affect multiple habitats, the majority of plants currently considered by MITPPC are primarily issues in non-agricultural settings (Supplement 4 B and 4 F). However, we consider this dominance to be reasonable; the majority of invasive plant species were originally introduced for cultivation (e.g., food, fiber, landscaping, medicinal use) (Pimentel et al., 2007), so perceptions of harm are perhaps less likely to occur in cultivated settings. In contrast, currently evaluated plant pathogen and invertebrate species, which are more likely to be unintentionally introduced into an area (Pimentel et al., 2007), are relatively split between those impacting primarily agricultural vs. non-agricultural habitats (Supplement 4C-D and 4G-H). Generally, plant pathogens tended to rank lower relative to plants and invertebrates. There is inherent difficulty in comparing risk across taxonomic groups, and most other invasive species prioritization processes focus on a specific taxon (e.g., Buerger et al., 2016; Randall et al., 2008; Weiss and McLaren, 2002). However, it was infeasible for MITPPC to devise separate prioritization schemes for each taxonomic group. Since it is unclear if the lower rankings for pathogens are due to an aspect of the prioritization that might unintentionally favor certain taxa (e.g., biological differences, information availability, etc.), MITPPC initially decided that projects being considered for funding must focus on at least one species that ranked among the top 15 taxa in any of the three taxonomic groups (plants, plant pathogens, or invertebrates). Though 15 is an arbitrary cutoff, limiting research priorities in this way allowed greater organismal diversity to be considered while still focusing research and resources on the most threatening species within broad taxonomic groupings. Importantly, all species maintain their individual overall rankings, so they can still be viewed relative to all other organisms evaluated.

We have found that our application of AHP bolsters credibility with diverse decision makers and communities. Anecdotal feedback from legislative stakeholders has been consistently supportive of the MITPPC process, in part because the process is thorough (i.e., includes numerous, diverse decision criteria) and not beholden to a single entity's opinion. Moreover, having a set of focused priorities (i.e., the top 15 species within each taxonomic group) allows the impacts of individual research projects to be more clearly linked to the combined effort of protecting the state's terrestrial resources. Calls to address invasive species issues in the state have previously been broad, and consequently, research efforts were often perceived as unfocused and results were difficult to connect with timely and meaningful impact. The structure of the MITPPC priorities allows greater potential for cross-project synergy among its funded research, which will further amplify the impact of individual projects. Despite the recentness of MITPPC-funded research (<5 years), project synergies are emerging related to shared research questions (e.g., investigations using species distribution modeling), interacting species (e.g., soybean aphid and buckthorn), and to shared habitats or locations (e.g., specific field sites).

## 5. Conclusion

The Minnesota Invasive Terrestrial Plants and Pests Center used the Analytic Hierarchy Process to establish a scalable and dynamic procedure for identifying its research priorities. The process was founded on the participation of 15 subject matter experts from multiple academic disciplines and state agencies. The panel agreed on 17 decision criteria for ranking the terrestrial invasive species that pose the greatest threat to Minnesota in the absence of management. Panelists also assigned relative weights to each criteria, which in aggregate, identified factors associated with the severity of invasion impact, rather than the potential for invasion, to be the greatest contributors in identifying the most threatening species. Specifically, negative environmental impact was the most influential threat criterion. The use of AHP allowed for differing views on matters associated with invasions risk to be included in the final decision. It also provided a transparent and evidence-based decision structure, which strengthens the credibility of MITPPC activities with many stakeholders.

## Credit author statement

A.C. Morey: Formal analysis, Investigation, Data curation, Writing – original draft & Editing, Visualization, R.C. Venette: Conceptualization; Methodology, Formal analysis, Investigation, Resources, Writing – review & editing, Project administration

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Supplemental materials

All supplemental materials for this article are available through the University of Minnesota Digital Conservancy, and can be freely assessed using the persistent link, https://doi.org/10.13020/t6gc-z164.

Supplementary Materials Legends

**Supplement 1**: Template species evaluation form for the Minnesota Invasive Terrestrial Plants and Pests Center. This form is structured to serve as instruction to an evaluator. For each criterion, a brief description is provided for context, followed by guidance on the information to seek for selecting and justifying a given rating. In addition, the quantitative rating scores (see section 2.4 in main text for explanation) are provided in bold brackets after each rating category.

**Supplement 2:** The completed Minnesota Invasive Terrestrial Plants and Pests Center evaluation form for Japanese beetle (*Popillia japonica* Newman).

**Supplement 3:** Invasive plant, plant pathogen, and invertebrate species evaluated by the Minnesota Invasive Terrestrial Plants and Pests Center. Each species is broadly categorized as primarily affecting agriculture (i.e., food and forage crops, not including silviculture) or non-agricultural (e.g., forests, prairies, wetlands, ornamental/turf) terrestrial habitats. Species that significantly impact both agricultural and non-agricultural habitats are labeled as "multiple". Priority scores are presented as a percentage of the maximum scores across all taxa.

**Supplement 4:** The terrestrial invasive species evaluated by the Minnesota Invasive Terrestrial Plants and Pests Center (MITPPC) categorized by the habitats they primarily harm. Habitats were considered agricultural (i.e., food and forage crops, not including silviculture) or non-agricultural (e.g., forests, prairies, wetlands, ornamental/turf). Species that significantly impact both agricultural and non-agricultural habitats were included in a "multiple" category. The top line of charts shows all taxa (**A**; n=167), only plant (**B**; n=79), only plant pathogen (**C**; n=46), or only invertebrate (**D**; n=42) taxa evaluated by MITPPC as of 2020. The bottom line of charts show the current top 15 ranked species across all taxa **(E)**, among only plants **(F)**, among only plant pathogens **(G)**, and among only invertebrates **(H)**.

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