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ARTICLE

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Identifying invasive species threats, pathways, and impacts to improve biosecurity

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Abstract

Managing invasive species with prevention and early-detection strategies can avert severe ecological and economic impacts. Horizon scanning, an evidence-based process combining risk screening and consensus building to identify threats, has become a valuable tool for prioritizing invasive species management and prevention. We assembled a working group of experts from academic, government, and nonprofit agencies and organizations, and conducted a multi-taxa horizon scan for Florida, USA, the first of its kind in North America. Our primary objectives were to identify high-risk species and their introduction pathways, to detail the magnitude and mechanism of potential impacts, and, more broadly, to demonstrate the utility of horizon scanning. As a means to facilitate future horizon scans, we document the process used to generate the list of taxa for screening. We evaluated 460 taxa for their potential to arrive, establish, and cause negative ecological and socioeconomic impacts, and identified 40 potential invaders, including alewife, zebra mussel, crab-eating macaque, and red swamp crayfish. Vertebrates and aquatic invertebrates posed the greatest invasion threat, over half of the high-risk taxa were

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omnivores, and there was high confidence in the scoring of high-risk taxa. Common arrival pathways were ballast water, biofouling of vessels, and escape from the pet/aquarium/horticulture trade. Competition, predation, and damage to agriculture/forestry/aquaculture were common impact mechanisms. We recommend full risk analysis for the high-risk taxa; increased surveillance at Florida's ports, state borders, and high-risk pathways; and periodic review and revision of the list. Few horizon scans detail the comprehensive methodology (including list-building), certainty estimates for all scoring categories and the final score, detailed pathways, and the magnitude and mechanism of impact. Providing this information can further inform prevention efforts and can be efficiently replicated in other regions. Moreover, harmonizing methodology can facilitate data sharing and enhance interpretation of results for stakeholders and the general public.

KEYWORDS
biosecurity, Florida, horizon scanning, impact mechanisms, pathways, prevention, rapid risk assessment

INTRODUCTION

Over the past 50 years, introductions of non-native species have doubled, potentially driving biodiversity loss and raising concerns about new invaders (Díaz et al., 2019). Biological invasions have cost the North American economy US $1.26 trillion over roughly the same period of time (Crystal-Ornelas et al., 2021). Managing invasive species with prevention and early-detection strategies can avert severe ecological and socioeconomic impacts, resulting in billions of dollars in economic savings (Cuthbert et al., 2022; Lodge et al., 2016).

Horizon scanning is a process for identifying unknown risks, emerging issues, and opportunities to inform policy, decision-making, and research prioritization (Sutherland & Woodroof, 2009). In the past decade, this method has been applied to invasive species prevention by convening scientists, practitioners, biosecurity staff, and other stakeholders to identify potential invaders and their introduction pathways. For example, 29 non-native taxa were ranked as a high-invasion threat to Great Britain, with quagga mussel (*Dreissena rostriformis bugensis*) posing the greatest predicted risk (Roy et al., 2014). Horizon scanning has also been used in the European Union to prioritize emerging invaders for full risk assessment, which resulted in bans on transporting, possessing, breeding, or releasing some high-risk species into the environment (Genovesi et al., 2015; Roy et al., 2015) and to identify 10 areas of research and action to prevent spread of invasive pathogens (Roy et al., 2017). Results from horizon scans can guide efficient allocation of resources to invasive species research (e.g., identifying data gaps), prevention (e.g., risk analysis and biosecurity surveillance), and eradication (e.g., prioritize targets), which is especially important when dealing with finite biosecurity resources (Gallardo et al., 2016; Kenis et al., 2022).

At a minimum, horizon scanning provides the ranked list and results of rapid risk assessments, but additional types of data can also be included to further inform policy and management action: predominant arrival pathway(s), type of impact (e.g., ecological, socioeconomic—including human health), and the mechanism whereby impacts may occur (hereafter impact mechanism). For example, knowing the arrival pathway can pinpoint surveillance and effectively direct early warning systems toward high-risk pathways (Hulme, 2015; Rainford et al., 2020) and understanding the type and magnitude of impacts can support policy recommendations, provide a sense of urgency to biosecurity action, and increase support from the public for management, especially serious threats to human health (Bacher et al., 2018; Kumschick et al., 2020). Additionally, including confidence estimates for the overall risk determination can identify that there are gaps in the data, but adding confidence estimates to the individual scoring categories in a risk assessment can identify specific areas where uncertainty arises and direct research to fill those gaps (Roy et al., 2018).

Our primary objectives were to identify invasive species threats and demonstrate the utility of a horizon scan that includes these comprehensive details as a holistic process for threat forecasting. We began with the horizon-scanning method outlined by Roy et al. (2014), coupling risk assessment and consensus building among experts, and added detailed pathway and impact analyses, including comprehensive information on arrival pathways, ecological and socioeconomic impacts, and magnitude and mechanism of impact. We provide certainty estimates for individual scoring categories in rapid risk assessments and the final score. We also describe our list-building process in full detail, including how taxa were added and removed. Final rankings were determined through consensus building, a collaborative step where inter-assessor variability (differences in scoring among individuals) is minimized and expertise is maximized in the decision-making process (Sutherland & Woodroof, 2009; Verbrugge et al., 2019). We focused on Florida because it is one of the main "hotspots" for invasion in the United States (Iannone et al., 2016; Stohlgren et al., 2006) and globally (Dawson et al., 2017), and because no horizon scans had been conducted for Florida or any other US state.

METHODS

Study system

Florida's 35 international ports receive substantial imports of biota through economic trade and tourism (Sinclair et al., 2021) receiving approximately $80B of cargo (US Census Bureau, 2021) and an average 130 million tourist visits annually over years 2019, 2021, and 2022 (2020 excluded because of COVID anomaly, https://www.visitflorida.org/resources/research/). The peninsular geography, broad climate range (tropical, subtropical, and temperate), and diverse ecosystems contribute to Florida's vulnerability to invasion. Currently, over half of Florida's land area is in development or used for agriculture, and the quality of the remaining natural areas is deteriorating, creating disturbances that can further facilitate invasion (Volk et al., 2017). Furthermore, invasive species in Florida have a profound economic impact. For example, in 2018, approximately $13.4M in crop production was lost to invasive feral hogs (McKee et al., 2020), weeds in Florida's agricultural lands cost farmers at least $110M annually (Gianessi & Reigner, 2007), and expenditures for invasive plant management in Florida's conservation areas are approximately $45M per year (Hiatt et al., 2019).

The framework

We used a modified version of the horizon-scanning methodology described by Roy et al. (2014) including five steps: (1) assemble a panel of experts, (2) develop a candidate list of taxa for assessment, (3) complete rapid risk assessments and peer review, (4) build consensus among experts on final rankings, and (5) collect additional data after consensus to further detail the threat posed by ranked species. Modifications from the original framework included how the lists were built and filtered (e.g., use of the CAB International [CABI] Horizon Scanning Tool, list processing for global occurrences and synonym corrections), the inclusion and reporting of certainty estimates for each scoring category, and use of the Environmental Impact Classification for Alien Taxa (EICAT) and Socioeconomic Impact Classification for Alien Taxa (SEICAT) frameworks to evaluate potential impacts.

Assembling an expert panel

We convened a workshop with 28 experts from academic, government, and nonprofit agencies and organizations. Participants were selected for their varied expertise in invasion science, taxonomy, policy, and data analysis. Participants were organized into five taxonomic teams: freshwater invertebrates, terrestrial invertebrates, vascular plants (aquatic and terrestrial), vertebrates (aquatic and terrestrial), and marine (algae, plants, invertebrates, and vertebrates). Seven additional experts were added during risk assessment and consensus building to fill emerging knowledge gaps (e.g., expert in impacts to marine systems and replacements for members of teams who could not complete the project).

Develop a candidate list of taxa for assessment

We used the horizon scan tool developed by the Centre for Agriculture and Biosciences International (CABI) to generate a preliminary list of 9629 potentially invasive taxa from the Invasive Species Compendium and Crop Protection Compendium datasheets (downloaded on 15 November 2019, https://www.cabi.org/HorizonScanningTool/). The initial list was narrowed to 7177 taxa before separation by taxonomic group (Table 1). In this step, bacteria, fungi, protozoa, viruses, diseases, taxa with no classification, and taxa already present in Florida were removed. Microorganisms were not included in this scan due to limited expertise and time constraints. Within taxonomic groups, teams removed roughly 6800 taxa based on the following criteria: harmonizing taxonomy, taxa already present in Florida (e.g., new arrivals, taxa with records in regional databases), climate mismatch, lacking invasion or naturalization history, or other criteria specific to each group (e.g., present on noxious weed list-plants and lack of information-freshwater invertebrates). The freshwater invertebrate team and vertebrate

TABLE 1 Steps taken to select and evaluate potentially invasive taxa for the all-taxa horizon scan (excluding microorganisms) for Florida, USA.

Taxa	Start	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Total taxa
Preliminary filtering									
Full CABI list	9629	Bacteria: 275	Fungi: 1318	Protozoa: 45	Viruses: 577	Disease of unknown origin: 11	No classification: 47	Currently present in FL: 179	7177
Taxonomic filtering									
Freshwater invertebrates	27	Add LEMIS: **18**	Add NAS/USFWS risk screening: **96**	Currently present in FL: 3	No data: 6	Synonym correction: 2	Taxa misclassified: 1		129
Marine	91	Native taxa: 4	Currently present in FL: 17	Climate mismatch: 6	Parasites: 2	Taxa misclassified: 2			60
Plants	2128	Synonym correction: 57	Climate mismatch: 568	Not in target location: 198	Present on noxious weed list: 50	No invasion or naturalization history: 423	Expert opinion: 2	Global frequency of occurrence: 730	100
Terrestrial invertebrates	4664	Global frequency of occurrence: 4536	Only genus provided: 5	Currently present in FL: 14	Add taxa invasive elsewhere: **16**	Time constraint[a]: 21			72
Vertebrates	267	Lack of invasion history: 168	Currently present in FL: 25	Add currently in trade (est.): **10**	Add currently in trade (not est.): **8**	Add established (not in trade): **6**	Add limited introduction close to FL: **1**		100
Final total assessed									461

Note: Taxa native elsewhere in the United States (including Hawaii), but not native to Florida, were retained in the list. Information in columns indicates the number and justification of taxa removed or added (in boldface) at each step. "Preliminary filtering" shows initial list processing before distributing to taxonomic groups. "Taxonomic filtering" shows list processing for each taxonomic group. One hundred and fourteen taxa were added to the freshwater invertebrates list from USFWS LEMIS, USGS NAS, and USFWS Ecological Risk Screening Summaries. Twenty-five taxa were added to the vertebrates list from USFWS LEMIS, Global Avian Invasions Atlas, and Kraus (2009).

Abbreviations: CABI, Centre for Agriculture and Biosciences International; FL, Florida; LEMIS, Law Enforcement Management Information System; NAS, Nonindigenous Aquatic Species; USFWS, United States Fish and Wildlife Service.

[a]Could not finish assessments in the allotted time.

teams added 115 and 25 taxa respectively using databases such as the US Fish and Wildlife Service's Law Enforcement Management Information System (LEMIS) organisms in trade data and the US Geological Survey Nonindigenous Aquatic Species (NAS) information resource (Table 1). Taxa native elsewhere in the United States (including Hawaii), but not native to Florida, were retained on the list. In total, 461 taxa were identified for further assessment: 129 freshwater invertebrates, 100 vascular plants, 72 terrestrial invertebrates, 100 vertebrates, and 60 marine taxa. One plant taxon (*Solidago canadensis*) was not fully assessed because its naturalization status in Florida was unclear (Kendig et al., 2022).

Rapid risk assessment and peer review

Taxa were evaluated by experts using a rapid risk assessment tool that scores the likelihood of arrival within the next 10 years (A), establishment (E), and negative impacts (I) (Roy et al., 2014). Each category is scored on a scale of 1 (unlikely to occur/minimal impacts) to 5 (very likely to occur/massive impacts). The 10-year time frame allowed experts to rank species within current climate conditions and establish a minimum frequency to reevaluate the list to incorporate new data, adjust rankings, and add or subtract taxa. The overall score for each taxon was calculated by multiplying category scores ($A \times E \times I = \text{SCORE}$), making 125 the highest possible outcome. To standardize scoring, participants were provided guidelines and an assessment template. Arrival was scored based on invasion history in other regions, presence of a plausible introduction pathway, and qualitative consideration of the frequency of trade and travel between its existing range and Florida. Establishment scores were based on the probability a species would establish a self-sustaining population in Florida. Establishment success depends on the biology of the species (e.g., fecundity and environmental tolerance) and suitability of potential habitats (e.g., climate and resource availability). Impact scores were based on the extent and severity of documented negative impacts to biodiversity, ecosystems, economies, and human health following EICAT and SEICAT criteria (Bacher et al., 2018; Hawkins et al., 2015). Unlike other horizon scans, ecological and socioeconomic impacts were scored based on the severity of impact regardless of the type of impact (e.g., impact type scored separately, Gallardo et al., 2016; human health impacts documented but not scored, Peyton et al., 2019). While we did use these schemes in the rapid risk assessments, experts did not conduct full EICAT/SEICAT analysis.

Experts estimated certainty for each likelihood score and the final score (high, medium, low, and very low). High certainty meant evidence supported elimination of all other possible scores. Very low certainty meant there was weak or no supporting evidence (data-deficient), and the assessor determined all scores were equally likely. Certainty estimates were not quantified but were later used to aid consensus building. Finally, experts identified and categorized primary arrival pathways based on Convention on Biological Diversity (CBD) standardized classification and terminology (Harrower et al., 2018). Completed assessments were peer-reviewed by experts from each team and again by team leaders. A final review of ranked taxa was conducted when details on pathway subcategories and impacts were compiled (see *Additional data collection after consensus*). This resulted in the lowering of impact scores for two taxa when new data were included. Assessments were combined and ordered by scores for consensus building.

Building consensus among experts

The combined list was disseminated to participants to allow time to identify taxa requiring further discussion and consideration of the level of certainty in the rapid risk assessments. A meeting was then held to build consensus. Thresholds for very high, high, moderate, and low risk were determined, and experts discussed taxa of concern. There were no changes in the scoring of taxa during consensus building, and risk designations were defined as very high-risk scoring at least a 4 in each likelihood category, high-risk scoring in any combination of $3 \times 5 \times 5$, $5 \times 5 \times 3$, $5 \times 3 \times 5 = 75$, moderate-risk scoring between 27 and 63, and low-risk scoring less than 27. The distinction between very high- and high-risk taxa was based on the score of 75 having one of the categories scoring 3. A score of 27, or $3 \times 3 \times 3$ was determined to be the bottom threshold for taxa having a moderate threat. The assigned thresholds used in this horizon scan were in alignment with Lucy et al. (2020).

Additional data collection after consensus

When scoring arrival, experts considered which arrival pathways were identified for the taxa evaluated together with other considerations (e.g., frequency of trade and travel to Florida and presence of a plausible introduction pathway). This meant that the subcategories were not always explicitly identified in the template. For this reason, we added pathway subcategories where necessary using the 44 described in Harrower et al. (2018) including pet/aquarium/terrarium release, ship/boat fouling, and interconnected waterways. Next, occurrence records in the United States, Southeastern United States (Alabama, Arkansas, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Tennessee), and the Caribbean were compared with the very high- and high-risk taxa to further characterize the likelihood of arrival from source regions within the United States and islands in close proximity to Florida. The following websites were accessed to collect this information; EDDmapS (http://www.eddmaps.org), Global Biodiversity Information Facility (https://www.gbif.org), and the NAS information resource (http://nas.er.usgs.gov) (all databases accessed February 2022 and April 2023). Finally, to fully inform precautionary actions, information on the impact category (ecological and socioeconomic) and impact mechanism was compiled for the very high- and high-risk taxa. We used the 12 impact mechanisms (e.g., predation, competition, and transmission of disease) outlined in the EICAT protocol (Hawkins et al., 2015; Volery et al., 2020). The SEICAT protocol does not define impact mechanisms, and as a result, we assigned the following socioeconomic impact mechanisms based on Allmert et al. (2022): human health, damage to agriculture/forestry/aquaculture, damage to public facilities, economic cost of management, impact to recreational activities, public nuisance, safety, and social/spiritual/cultural.

RESULTS

From the 460 taxa evaluated, we identified 33 very high-risk and 7 high-risk non-native taxa with high potential to arrive, establish, and cause negative impacts to the environment, economy, or human health within the next decade (Figure 1). We ranked 123 and 297 taxa as moderate- and low-risk, respectively. Four taxa had the maximum score of 125: alewife (*Alosa pseudoharengus*), zebra mussel (*Dreissena polymorpha*), crab-eating macaque (*Macaca fascicularis*), and red swamp crayfish (*Procambarus clarkia*; Figure 2). Overall, vertebrates were the most represented group of the 40 very high- and high-risk taxa (35%, $n = 14$), followed by freshwater invertebrates (25%, $n = 10$) and marine taxa (18%, $n = 7$; Figure 1). When taxa were divided by functional group, 52.5% of very high- and high-risk taxa were omnivores ($n = 21$), 22.5% were primary producers ($n = 9$), 17.5% were predators ($n = 7$), and 7.5% were herbivores ($n = 3$). Assessment information including scores, justifications, and certainty estimates for all 460 taxa is provided at osf.io/x9n52 (Lieurance et al., 2022).

Of the 460 taxa assessed, 22% had a high, 53% had medium, 19% had low, and 2% had very low (data-deficient) degrees of certainty for the total score. The very high- or high-risk taxa had high or medium overall certainty estimates and only the village weaver bird (*Ploceus cucullatus*) had low overall certainty based on a lack of recent distribution data (very low certainty for arrival [*A*]). Moderate-risk taxa had 19% high and 69% medium degrees of certainty for the final score. Only 10% of low-risk taxa had a high degree of certainty for the final score. When focusing on certainty estimates for category scores, very high- and high-risk taxa had high certainty for over 50% of category scores and medium certainty for 44% of category scores (*A*, *E*, *I*; Figure 1).

Most of the taxa evaluated ($n = 460$) had more than one primary arrival pathway (1.54 ± 0.05 mean $\pm$ SE). The most common pathways were "escape from confinement" (26%), "transport-stowaway" (20%), and "transport-contaminant" (17%; Figure 3). Overall, 6% of the pathways were listed as "unknown" across taxa. However, 51% of the pathways for terrestrial invertebrates were listed as "unknown." "Transport-stowaway" and "escape from confinement" were the most common arrival pathways for freshwater invertebrates, "transport-contaminant" for terrestrial invertebrates, and "transport-stowaway" for marine taxa. Vascular plants and vertebrates shared "escape from confinement" as the most common pathway for arrival.

Of the very high- and high-risk taxa, 45% ($n = 18$) were associated with pet/aquarium trade or horticulture escapes, 20% ($n = 8$) were associated with releases from live food/bait, 20% ($n = 8$) were stowaways in ballast water or biofouling vessels, and 28% ($n = 12$) were associated with secondary pathways (e.g., natural dispersal after introduction) (Figure 4; Appendix S1: Table S1). Based on occurrence records, 66% of taxa ranked as very high and high risk are currently present in the United States, 40% of those present are in the Southeastern United States, and 23% are present in the Caribbean with a close proximity to Florida (e.g., Puerto Rico and Dominican Republic).

Overall, 95% ($n = 38$) of very high- and high-risk taxa had evidence of ecological impacts and 53% ($n = 22$) had evidence of socioeconomic impacts with two terrestrial invertebrates (cotton bollworm [*Helicoverpa armigera*] and cabbage moth [*Mamestra brassicae*]), having only socioeconomic impacts to agriculture (Figure 5). The prominent ecological impact mechanisms were competition, predation, and chemical impact on ecosystems (Appendix S1: Table S1). Damage to agriculture/forestry/aquaculture was the most common socioeconomic impact mechanism. We found evidence of human health impacts for five taxa related to allergens produced by plants and transmission of disease (some potentially fatal) to humans from two vertebrates, the crab-eating macaque (*M. fascicularis*) and Tanezumi rat (*Rattus tanezumi*).

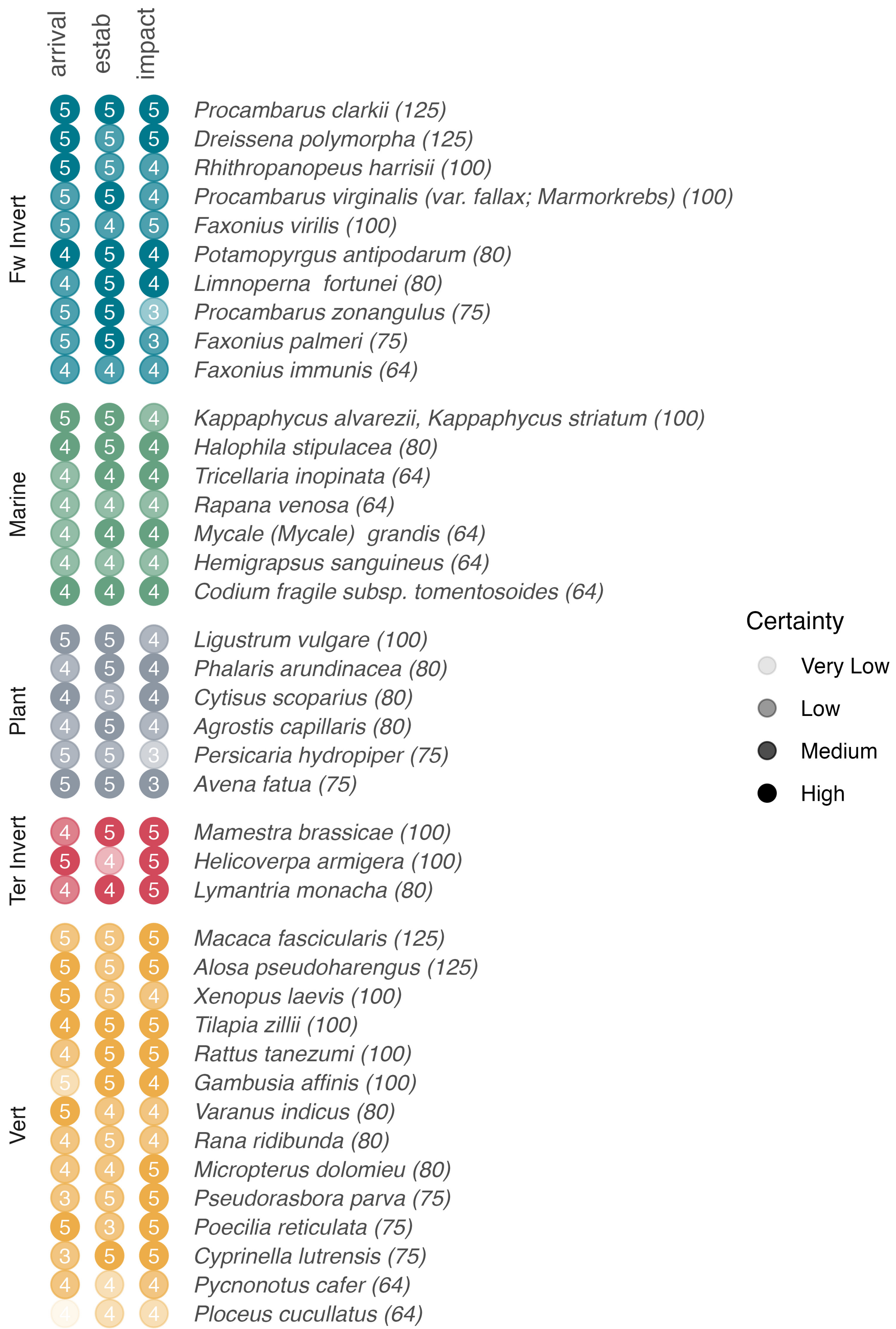

FIGURE 1 Ranked taxa. Taxa that are designated as very high- and high-risk threats to Florida in the next 10 years as determined by their likelihood of arrival, establishment (estab), and negative impacts (impact). Scores (1–5, increasing with greater likelihood) and certainty (increasing with color saturation) are presented in the circles. Ranked taxa are organized by taxonomic grouping (freshwater invertebrate [Fw Invert], blue; marine, green; plant, gray; terrestrial invertebrate [Ter Invert], red; and vertebrate [Vert], yellow), and total scores are included in the parentheses.

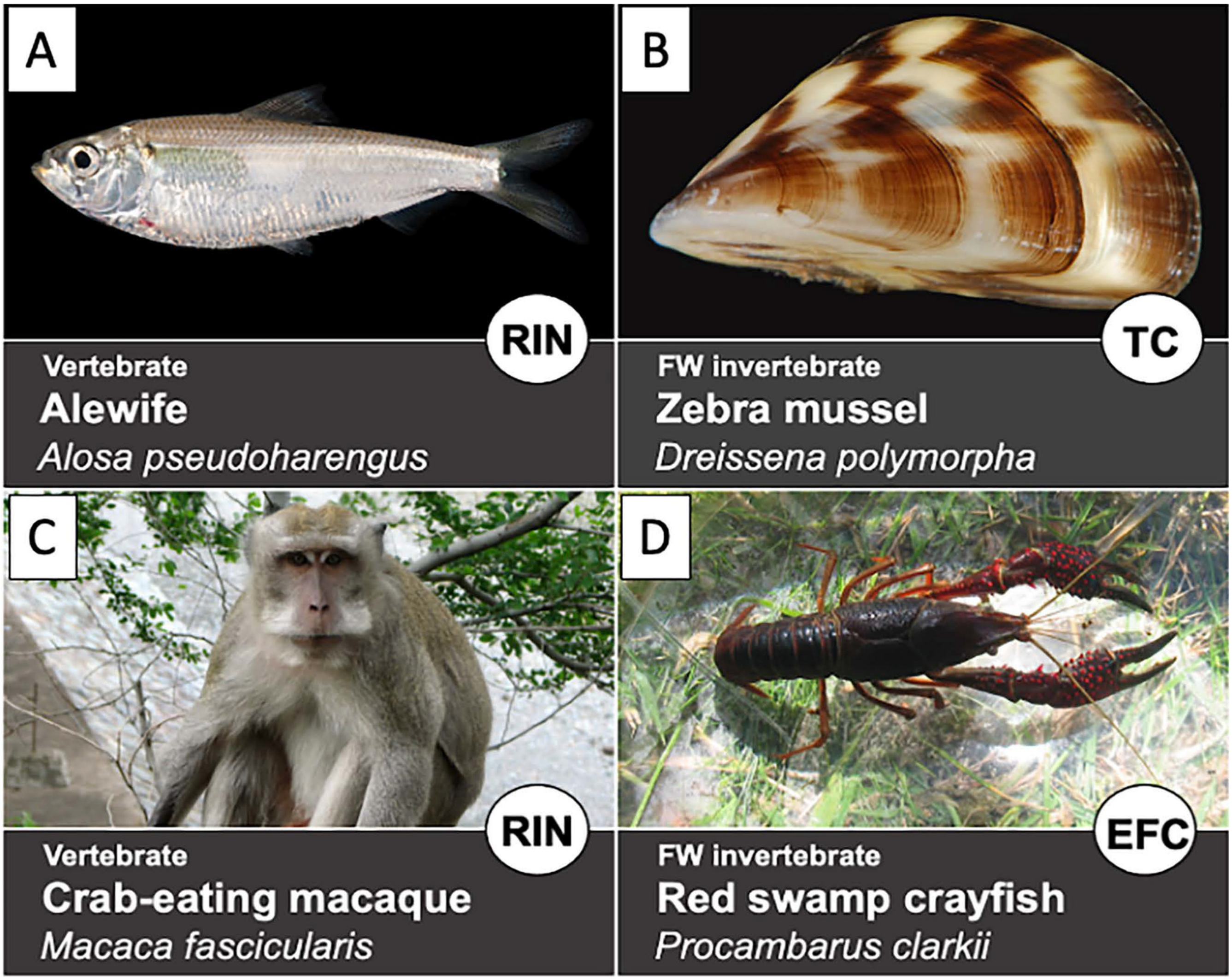

FIGURE 2 Maximum scoring taxa. Taxa that received the maximum score of 125 and were designated as 4 of the 34 very high-risk for invasion in Florida within the next 10 years. The primary pathways are provided in the white circles where (A, C) "RIN" = "release in nature," (B) "TC" = "transport-contaminant," and (D) "EFC" = "escape from confinement." "Fw" = "freshwater." Photo credits: (A) Smithsonian Environmental Research Center, https://www.flickr.com/photos/serc_biodiversity/50734791571/, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=108069833; (B) Smithsonian Environmental Research Center, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=76839795; (C) Eric Bajart, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=5841779; (D) I. Duloup, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=2255402).

DISCUSSION

Horizon scanning is rising in popularity internationally as a method for identifying invasive species threats and their pathways for arrival and is recognized as an important part of invasive species management (e.g., Gallardo et al., 2016; Kenis et al., 2022; Lucy et al., 2020; Oficialdegui et al., 2023; Roy et al., 2015). These efforts produce evidence-based lists of potential invaders to inform development of precautionary measures and management before an invader is introduced (Roy et al., 2014). Here, we present the results of a horizon scan to improve biosecurity and other precautionary measures for Florida, USA, and to serve as a model that showcases a holistic process to predict and communicate invasive species threats. Previous horizon scans have included different combinations of data presented in this scan, such as the primary and subcategories of CBD pathways, ecological and socioeconomic impacts, overall certainty, certainty for impacts, and impact mechanisms. Here, we incorporate all of these components, report certainty estimates for each scoring category to identify threats, provide detailed information to target management, identify research gaps/opportunities, and provide details to invested stakeholders. Furthermore, the most difficult part of starting a process to "identify the unknown" is to

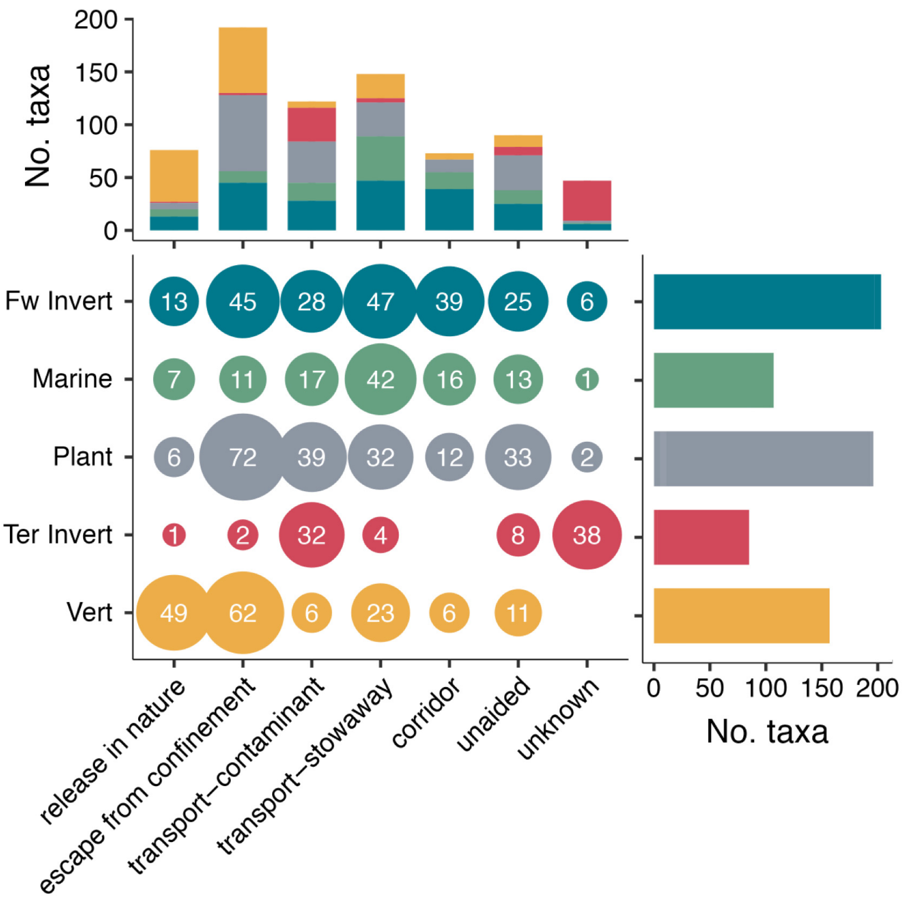

FIGURE 3 Primary pathways of all taxa. Total number of taxa and the number of taxa divided into taxonomic groups that are predicted to arrive through primary pathways (Convention on Biological Diversity level 1) for introduction. Numbers in circles indicate the number of taxa associated with the pathway. Pathway hierarchy is based on categories outlined by the Convention on Biological Diversity (2014) and Harrower et al. (2018). Fw invert, freshwater invertebrate; Ter Invert, terrestrial invertebrates; Vert, vertebrate.

develop a candidate list of potential threats, and here we detail this list-building to provide a starting point for future scans.

Introduction pathways

Identifying and managing pathways is the frontline of invasive species prevention informing targeted biosecurity measures such as pre- and post-border inspections, decontamination, and other early-detection strategies to potentially eliminate many threats at once (Hulme, 2009). We identified two pathway categories associated with global trade, "transport-contaminant" and "transport-stowaway," as prominent pathways for arrival across taxa. Stowaways were commonly reported as taxa fouling vessels and those introduced via ballast water, and contaminants included those coming in on plants, food, bait, and seed stock. Focused biosecurity can identify, contain, and eradicate potential invaders at ports and harbors (Coutts & Forrest, 2007). For example, inspection, fumigation, and/or quarantine of imported plants and nursery materials can prevent introduction of contaminants post entry (Liebhold et al., 2012). Furthermore, focusing management on common pathways can be used to intercept multiple recognized and unknown invasion threats arriving through shared pathways.

Horizon scanning can further assist with pathway-specific management by identifying patterns within taxonomic groups. For example, "escape from confinement," most frequently via the pet/aquarium industry, was common for most vertebrates and many freshwater invertebrates. Taxa released or escaping confinement from the pet/aquarium trade are very concerning as many of the most detrimental invaders impacting Florida's ecosystem health and biodiversity were introduced via this pathway, including Burmese python (*Python bivittatus*) and red lionfish (*Pterois volitans*) (Lockwood et al., 2019; Whitfield et al., 2002).

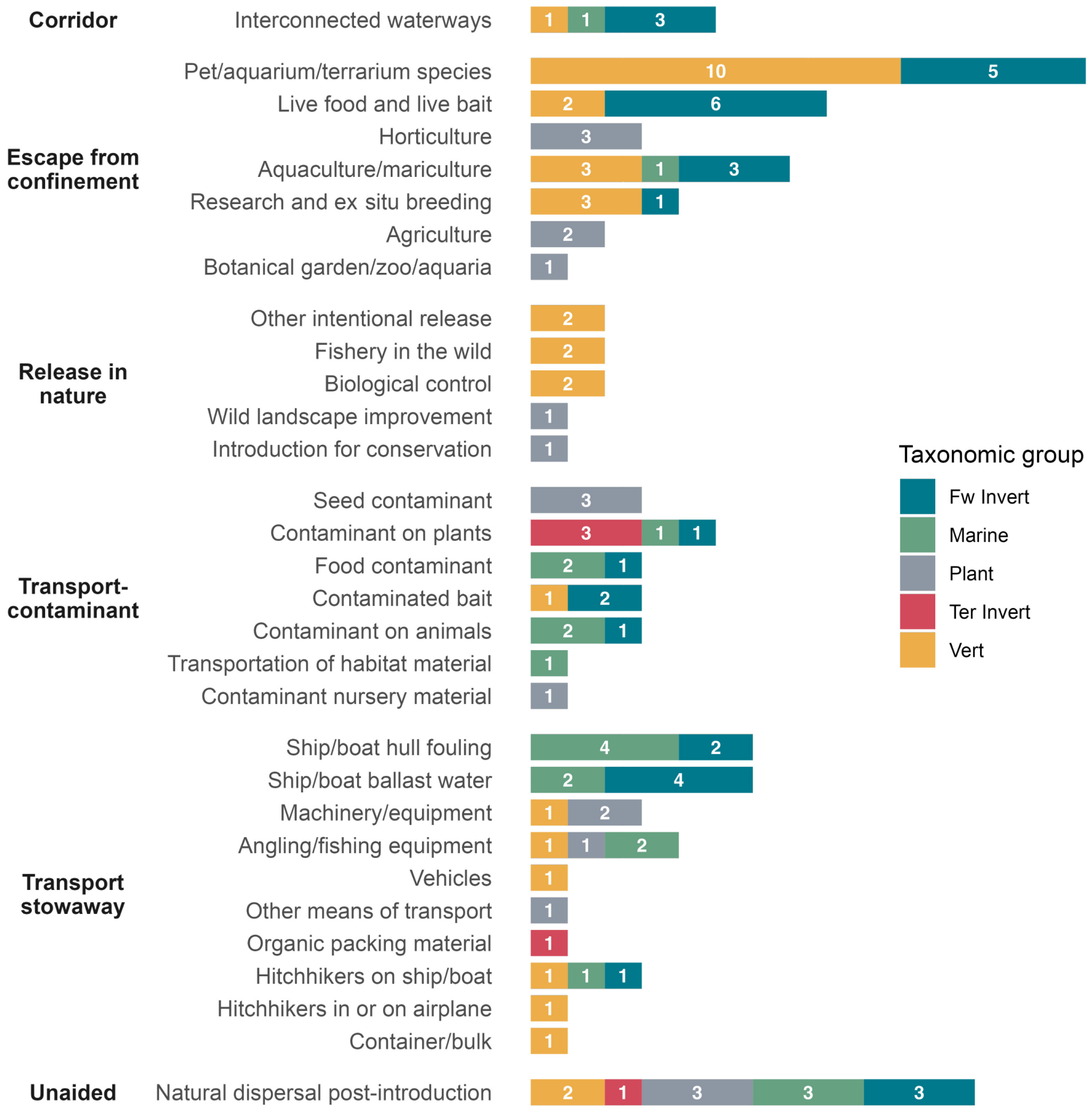

FIGURE 4 Subcategory pathways of the very high and high-risk taxa. The number of taxa classified very high and high risk for arrival through pathway subcategories (Convention on Biological Diversity level 2) for introduction. Numbers in boxes indicate the number of taxa associated with the pathway. Numbers in circles indicate the number of taxa associated with the pathway. Pathway hierarchy is based on categories outlined by the Convention on Biological Diversity (2014) and Harrower et al. (2018). Fw Invert, freshwater invertebrates; Ter Invert, terrestrial invertebrates; Vert, vertebrates.

Overall, there was a low percentage of taxa with "unknown" pathways but, consistent with other horizon scans, the pathways for approximately half of terrestrial invertebrates were listed as "unknown," raising concern that these taxa might be harder to intercept (Kenis et al., 2022; Roy et al., 2014).

Ecological and socioeconomic impacts

Using the information gathered on ecological and socioeconomic impacts (and their impact mechanisms), agencies could prioritize biosecurity measures for high-risk taxa with high impact scores. In this scan, the taxa

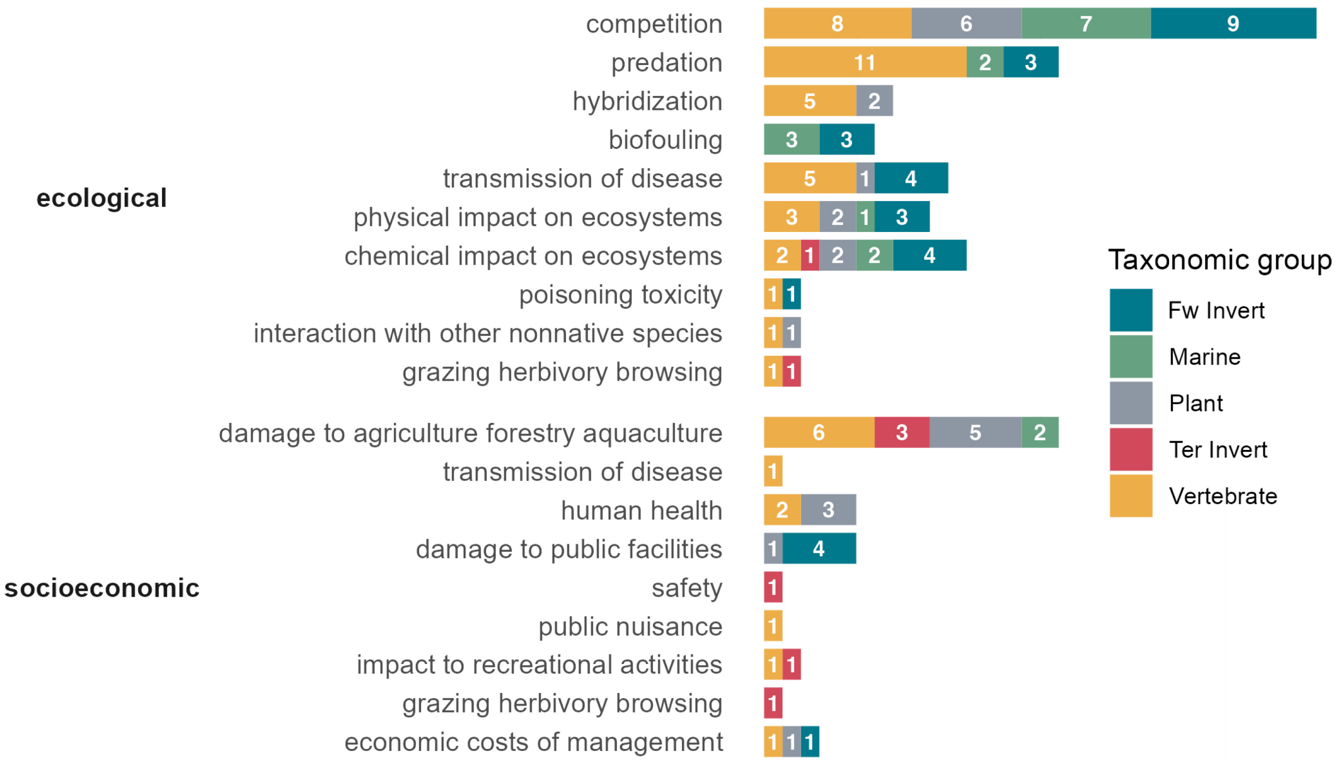

FIGURE 5 Frequency of impact mechanisms for very high and high-risk taxa. Impacts mechanisms were categorized using guidelines for Environmental Impact Classification for Alien Taxa (EICAT) (Hawkins et al., 2015) and Socioeconomic Impact Classification for Alien Taxa (SEICAT) (Bacher et al., 2018). Numbers indicate the number of taxa with evidence of impacts divided by taxonomic groups. Because this illustrates the results of a rapid risk assessment, this is not the equivalent of a full EICAT or SEICAT evaluation. Fw Invert, freshwater invertebrates; Ter Invert, terrestrial invertebrates; Vert, vertebrates.

identified as threats of particular concern include those with a history of causing detrimental impacts to ecosystem function, biodiversity, agroecosystems, and human health. For example, zebra mussel reduces phytoplankton, zooplankton, other benthic invertebrates and alters physical conditions (e.g., reducing phosphorus and increasing water column transparency), resulting in negative impacts to complex food webs (Higgins & Vander Zanden, 2010; Lovejoy et al., 2023; Ward & Ricciardi, 2007). Zebra mussel also inflicts economic damage through biofouling of boats and water-intake pipes. Estimates suggest that an infestation in Lake Okeechobee, Florida's largest freshwater body, would cost $244M over 20 years based on loss of wetland function, maintenance expenditures, and decreased fishing revenue (Lee et al., 2007). Some taxa identified in this scan present serious threats to human health. Tanezumi rats can carry many of the same diseases as black rats (*Rattus rattus*), including Hantavirus, leptospirosis, and bubonic plague (Centers for Disease Control, 2023). Crab-eating macaque is closely related to rhesus macaque (*Macaca mulatta*), a species already established in Florida and known to carry serious human diseases, including a deadly strain of herpes (Wisely et al., 2018).

Currently, Florida has comprehensive rapid-response policies for invasive taxa affecting agriculture, forestry, and human health such as Mediterranean fruit fly (*Ceratitis capitata*), emerald ash borer (*Agrilus planipennis*), and giant African land snail (*Lissachatina fulica*) that include extensive trapping (early detection), quarantines, and targeted management (rapid response) (Florida Department of Agriculture and Consumer Services, 2022). For example, the Florida Department of Agriculture and Consumer Services has eradicated giant African land snail using quarantine and pesticide treatments two separate times and is currently quarantining two counties to contain and eradicate a population that was first detected in 2022 (Florida Department of Agriculture and Consumer Services, 2022). In another example, the new world screwworm (*Cochliomyia hominivorax*), a species that attacks livestock, pets, and wildlife, was successfully eradicated from the Florida Keys after it was observed in a population of the federally endangered Key deer (*Odocoileus virginianus clavium*) (Skoda et al., 2018). Results from this horizon scan could help prioritize future rapid-response actions such as these for state and federal biosecurity action.

Biosecurity and management prioritization

We recommend full risk analysis (including comprehensive risk assessment, pathway analysis, and risk management) for very high- and high-risk taxa, with a specific urgency for the four taxa receiving the maximum score and those with plausible introduction pathways. Taxa ranked as moderate risk with medium to high certainty estimates could be considered for watch lists, and taxa with very low certainty (data-deficient) could be considered for further research. Taxa ranked as low risk should not be considered for "whitelisting" as many of these taxa had low or very low certainty and require more research, pre- and post-border invasion risk assessment, and industry compliance (Hulme et al., 2018). Certainty estimates for individual likelihood scores can further pinpoint data gaps requiring more investigation such as the very low confidence attributed to the arrival score for the village weaver bird.

Horizon scanning could also provide information required to add species to noxious weed, injurious wildlife, and early eradication lists. There is evidence that these lists are highly effective for preventing invasion at the earliest stages (Reaser et al., 2020; Simberloff, 2021). For example, injurious listing under 18 U.S.C. 42 of the Lacey Act prohibits importation and shipment between the continental United States and the other jurisdictions in the shipment clause but does not include any other prohibitions, such as sale, possession, or intrastate transport and to date; 100% of species preemptively listed have not established populations in the United States (Jewell & Fuller, 2021). While the United States has maintained and enforced regulatory lists for decades, horizon scanning has not yet been implemented to add taxa.

Generally, many invaders present in the United States pose a high risk to spread and establish in new states but are less likely to be intercepted by state-level biosecurity (Paini et al., 2010). As illustrated in this process, 44.4% of very high- and high-risk taxa associated with secondary pathways (interconnected waterways and unaided) are already in the Southeastern United States, which suggests biosecurity should not solely focus on international borders. State agencies provide a mechanism to conduct inspections and enforce invasive species regulation throughout the state (Hardin, 2007). Lists, such as the one developed here, can be used to increase prevention efforts at the state level by including species that were previously not a focus for detection.

This ranked list of 40 very high- and high-risk potential invaders is a resource for preventive measures such as comprehensive risk assessment or target analysis for early detection and rapid response (Morisette et al., 2020; Roy et al., 2018). For example, full risk assessments for the six plant species have been completed by the University of Florida/IFAS Assessment of Non-native Plants, a program that provides recommendations for the use of nonnative plants in the state (https://assessment.ifas.ufl.edu). Additionally, high-risk taxa with a climate match to south Florida including halophila seagrass (*Halophila stipulacea*), mangrove monitor (*Varanus indicus*), and golden mussel (*Limnoperna fortunei*) were used to establish a priority prevention list as a part of a multiagency Everglades restoration effort. Further, a small population of red swamp crayfish was identified and eradicated in Clay County, FL, in 2022 (http://nas.er.usgs.gov, accessed April 2023). Clearly, the value of this list is being realized by invasive species research and management practitioners in the state.

Because horizon scanning aims to "identify the unknown," there is no guarantee all threats have been identified. Uncertainty arises through incomplete list compilation, potential bias in data sources, and data limitations for understudied or underreported emerging invaders. For example, 66% of taxa from the CABI Horizon Scanning Tool were classified as pests and only 40% were classified as invasive; 21% of taxa assessed had low or very low certainty indicating a deficiency in available data. Therefore, we recommend this process be repeated at regular intervals to add new threats, fill knowledge gaps for taxa with lower confidence, and consider new information to ensure continued focus on timely and significant threats.

CONCLUSION

This comprehensive horizon-scanning approach provides a framework for future efforts that target international transport and trade hubs, areas with vulnerable habitats and species, and specific high-risk introduction pathways such as organisms in trade and biofouling of vessels. Harmonizing methodologies to complete these horizon scans can facilitate data sharing across horizon scans with comparable results and promote interpretation and communication of results to invested stakeholders and the general public.

Based on these results we recommend (1) comprehensive species-specific and pathway-specific risk analysis of the 40 very high- and high-risk taxa, (2) increased surveillance targeting very high- and high-risk taxa and prominent pathways at Florida's ports of entry and state borders, (3) periodic review (3–5 years) of the scan to revise the list by adding/removing species, filling in knowledge gaps, and determining the effectiveness of taxa rankings, and (4) use of this framework for horizon scans in other parts of the United States, especially border states with international ports and vulnerable habitats and taxa. Moreover, it is well established that investments in prevention yield much higher returns than expenditures on postentry management, prevent economic losses incurred from negative impacts, and provide the greatest long-term net benefits (Cuthbert et al., 2022; Lodge et al., 2016). Therefore, dedicated funding is critical to continue invasive species prevention in Florida and the United States.

AUTHOR CONTRIBUTIONS

All authors conducted risk assessments, peer review, final rankings, and manuscript preparation. Additionally, Donald C. Behringer, Amy E. Kendig, Carey R. Minteer, Lindsey S. Reisinger, and Christina M. Romagosa were taxonomic leads and Julie L. Lockwood co-facilitated the organizational workshop. Deah Lieurance and Susan Canavan conceived the horizon scan and organized the workshop.

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CONFLICT OF INTEREST STATEMENT

All authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data, results from the 460 assessments, detailed pathways and impacts, blank assessment template and guidelines, and the full taxa query from CABI (Lieurance et al., 2022) are available from the Open Science Framework (OSF) Repository: http://doi.org/10.17605/OSF.IO/X9N52.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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