Review

America's Most Wanted Fishes: cataloging risk assessments to prioritize invasive species for management action

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Abstract

Hundreds of fish species enter the United States through human intervention (e.g., importation) and some of these fishes pose a substantial risk to the nation's assets and ecosystems. Prevention, early detection, and rapid response (EDRR) are vital to stop species invasions, but time and resources to manage the large suite of fish species that enter the nation are limited. Evaluating the risk of a species' invasion in a location is one way to prioritize among many species for management action. Species risk assessments are often associated with information systems or are published within grey literature or peer-reviewed journal articles. Improving access to available risk assessments could help in prioritizing management action for the most potentially invasive fish species. We aggregated fish species risk assessments, synthesizing the current knowledge on the risk of fish invasions in the United States. To accomplish this, we searched information systems and conducted a literature review. We then summarized risk assessment results along with the importation statuses of fish species and identified if imported, high-risk species are managed under federal or state policy. Within the scope of the conterminous U.S., we found 98 high-risk fish species. Eighteen of these species are imported to the country, but only three species have been recently prohibited from importation according to the Lacey Act. We observed similar patterns at the scales of the Great Lakes region and Florida. Collectively, our work provides a baseline estimate of the high-risk fish invaders that enter the U.S. through importation, underscoring species to consider for priority management action, as well as a benchmark of species that lack risk assessments. Insights from this work can be enriched when joined with other invasive species information, which could be accomplished through a national EDRR information system, an information sharing hub in development by the U.S. Geological Survey.

Key words: fish, prevention, early detection, rapid response, import, United States

Introduction

Fish species have invaded waterbodies in countries all over the world, threatening biodiversity, economies, recreational opportunities, and human health on a global scale (Havel et al. 2015; Cuthbert et al. 2021). A major vector of invasive fish species into countries is through importation (Hulme 2009; Chapman et al. 2017; Turbelin et al. 2017; Bernery et al. 2022). Hundreds of fish species are imported for aquaculture, aquarium, stocking, and bait purposes in the United States (U.S.) (Eskew et al. 2020) with many of these species reported in novel waterbodies across the country (USGS 2023). Freshwater fishes are some of the most well-documented and impactful of aquatic invasive species (Bernery et al. 2022). Impacts to ecosystem structure and function through invasive fish species activity decreases an ecosystem's economic value (Lynch et al. 2016) and resiliency to disturbance, including human-driven changes in climate and landscape conditions (Lundberg and Moberg 2003; Mainka and Howard 2010; Kernan 2015). Preventative and early detection and rapid response (EDRR) practices are vital to stop species invasions and protect U.S. natural and human communities (Leung et al. 2002; Lodge et al. 2006, 2016; Reaser et al. 2020a, b; Simberloff et al. 2020). However, time and resources to employ preventative and EDRR strategies across the large suite of potential fish invaders that enter the U.S. are limited. Prioritizing fish species for management action is one step that can be done to save time and resources (McGeoch et al. 2016).

Evaluating the risk of a species' invasion in a location is one way to prioritize among many species for management action (Meyers et al. 2020). Risk can be defined as the probability of a non-native species' introduction, establishment, spread, and impact in a location. While methodologies can vary among risk assessments, risk outcomes for a species are typically described as low-risk, moderate-risk, or high-risk (Andersen et al. 2004; Lodge et al. 2016; Venette et al. 2021). Species evaluated as high-risk warrant priority action for more detailed risk analysis, prevention, detection, eradication, or control (Burgos-Rodríguez and Burgiel 2020; Meyers et al. 2020). Risk assessments for non-native fish species in the U.S. are stored in information systems or are published as grey literature or peer-reviewed journal articles. Improving access to these risk assessment results could allow for prioritization of fish species for management action in the U.S.

Online information systems maintained by federal and state agencies as well as non-governmental organizations house and/or produce risk assessments that can vary in taxonomic focus (e.g., plants, vertebrates, invertebrates) and geographic scope (e.g., states, regions). For example, the Invasive Species Centre (https://www.invasivespeciescentre.ca/) is an information system that stores risk assessments for taxa from locations around the world; while providing access to information that is broad in taxonomic focus and geographic scope, the information system does not produce its own assessments. Meanwhile, the Great Lakes Aquatic Nuisance Species Information System (https://www.glerl.noaa.gov/glansis/) stores Great Lakes state, regional, and provincial risk assessments from the U.S. and Canada in addition to producing risk assessments using its own methodology (e.g., Sturtevant et al. 2014; Davidson et al. 2017). One feature of the information system is its ability to display side-by-side comparisons of risk assessment results for a species which aids in risk interpretations. The Aquatic Invaders Marketplace (https://takeaim.org/) is another Great Lakes information system that focuses on traded aquatic species and includes a resource of risk assessments in North America in addition to Notre Dame's Science-Based Tools for Assessing Invasion Risk (https://takeaim.org/predict/greatlakes/stair/). The U.S. Fish and Wildlife Service's (USFWS) Ecological Risk Screening Summaries is an information system (ERSS; https://www.fws.gov/story/ecological-risk-screening-summaries) that produces risk assessments characterized for the conterminous U.S. using its own methodology (USFWS 2020) and stores this information in a searchable database. Sometimes, risk assessments are not associated with any information system, existing standalone as grey literature (e.g., technical or government reports; Paez 2017) or peer-reviewed journal articles, which are often available online.

Clearly, there is a wealth of risk assessment information available, and many risk assessment efforts are on-going. However, this information is sporadically located online, increasing the difficulty of developing comprehensive lists of species with risk assessments or comparing assessment results across species in locations of interest (Kumschick and Richardson 2013; Venette et al. 2021). Aggregating risk information is needed to improve the comprehensibility of species risk assessments, reduce potential duplication of assessment efforts, and increase the accessibility, utility, and longevity of existing information systems (Ellison 2010; Simpson et al. 2019; Wallace et al. 2020). Moreover, cataloging the impressive number of risk assessments that are available can help to support the prioritization of preventative and EDRR efforts relative to the many potential fish invaders that enter the U.S.

In support of this need, we catalogued available risk assessments synthesizing current knowledge on the risk of potential invasive fish species in the U.S. To accomplish this, we searched existing information systems and conducted an intensive literature review. We synthesized species risk assessment information by recording and comparing risk (i.e., low, moderate, high) of species from the source risk assessments, stratified by spatial scale. We coupled these results along with importation and policy data of fishes, identifying imported, high-risk species that are not managed under federal or state policy. These fishes represent a list of prioritized species to consider for management action, like preventative or EDRR efforts. We discuss future directions, including aggregation of risk assessments for other potentially invasive taxa. We also provide a brief introduction to a unified online interface, a national EDRR information system, that once implemented, could serve as an information sharing hub for invasive species networks, data, and information systems and is in development by the U.S. Geological Survey and Department of the Interior (Reaser 2020).

Materials and methods

Aggregate risk assessments

To aggregate risk assessments, we first searched existing information systems, including. the USFWS ERSS, GLANSIS, AIM, and ISC. In the second stage, we searched for risk assessments online using the search engine Google Scholar because it provides results for both peer-reviewed and grey literature (Paez 2017). We used a combination of keywords including "U.S.", "United States", "invasive species", "risk assessment", "risk screen", "risk evaluation", and "risk status." We also explored the Web of Science (17 February 2023). We used optimal search terms generated from the R package "litsearchr" (Graemes et al. 2019), which included the keywords: ("invas* speci*" OR "invas* alien* speci*" OR "invas* ecolog*" OR "invas* biolog*" OR "biolog* invas*") AND ("U.S." OR "United States") AND ("risk*" OR "risk* assess*" OR "risk* status*"). We practiced forward and backward citation searching in all the literature that was reviewed. Also, in all three stages of our search, we excluded risk assessments that were not conducted within the region of interest, the U.S., or did not include fishes.

Synthesize species risk

We synthesized known risk of species to understand assessment completeness for a given fish family, to facilitate comparison among results for species, and to generate a prioritized list of fishes to consider for management action. We stratified fish species risk assessments by spatial extent to account for geographic variation in risk. To facilitate synthesis, we specified standard definitions of the five typical categories in which risk is assessed (Andersen et al. 2004; Lodge et al. 2016; Venette et al. 2021). *Introduction* is the species' risk of arrival at one or more points into a new environment. *Establishment* is defined as the risk that one or more arriving populations of a species colonizes, reproduces, and survives in an environment despite threats of local extinction. *Spread* refers to the risk of the dispersal of a species from initial locations of establishment and occupying habitat within a new environment. *Impact* is the risk of environmental, economic, social, political, and/or cultural impacts driven by an established invasive species. Finally, *status* is described as the overall risk of the species' invasiveness in a location which is typically based on the risks of introduction, establishment, spread, and impact.

The descriptors of introduction, establishment, spread, impact, and status are low, moderate, or high, referring to the degree of risk, obtained from the original source material. We created two additional descriptors: multiple and undetermined. The descriptor, multiple, refers to a species that was characterized with different descriptors (i.e., low, moderate, high) for a single category from different risk assessments. Differences in risk assessment outcomes at a particular spatial extent for a given species could be a result of differences in risk assessment methodology. Differences in outcomes could also be due to what information was available at the time of assessment, likely contingent on access to invasive species information. The descriptor, undetermined, describes a category in which there was a lack of certainty to assign low, moderate, or high according to the source risk assessment. Finally, if a risk assessment did not address a category or used a descriptor that was not low, moderate, or high, we did not attempt to impute or interpret a descriptor and thus a species could be missing a descriptor for said category; this would often be the case for assessments that used numerical scales with no thresholds given (e.g., Gonzalez 2010) or the assessment used other types of descriptors to characterize species status, like "invasive" or "watchlist" (see Davidson et al. 2017).

Assemble catalog resource

To aid researchers and managers in accessing the source risk assessments, we compiled the risk assessments for each fish species into a single data file with each row containing information for one species (Supplementary material Table S1). Valid species taxonomy was obtained from the Integrated Taxonomic Information System (ITIS 2021; https://www.itis.gov/). The taxonomy of species lacking records in ITIS were checked using Eschmeyer's Catalog of Fishes (https://www.calacademy.org/scientists/projects/eschmeyers-catalog-of-fishes). Database columns include scientific names from these sources, the spatial extent of the risk assessment for species, and the link to the source risk assessment.

Results and discussion

Overview

We found risk assessments for 2,075 fish species representing over 125 families (Table S1) conducted at multiple spatial scales, including states, territories, regions, and the conterminous U.S. (Table S2). We summarized the risk statuses of fishes within three of those extents, the conterminous U.S. (Tables S3, S4), the Great Lakes region (Tables S5, S6), and the state of Florida (Tables S7, S8), because these are the spatial extents at which the most fish species have been evaluated, therefore, providing the best insights from the information we collected. Methodology of risk assessments varied among spatial extents and species (Table S2). Risk statuses also varied across species (Figures 1A, 2A, 3A) and the ratio of species evaluated relative to the total species in a family also varied (Figures 1B, 2B, 3B). A risk status also varied across spatial extents for a given species (Tables S3, S5, S7). Using data from the Law Enforcement Management Information System (LEMIS; Eskew et al. 2020), we identified the risk status of fishes imported into the U.S. between 2000 and 2014 (Tables S4, S6, S8). By comparing high-risk fishes with fishes prohibited in federal policy (e.g. Lacey

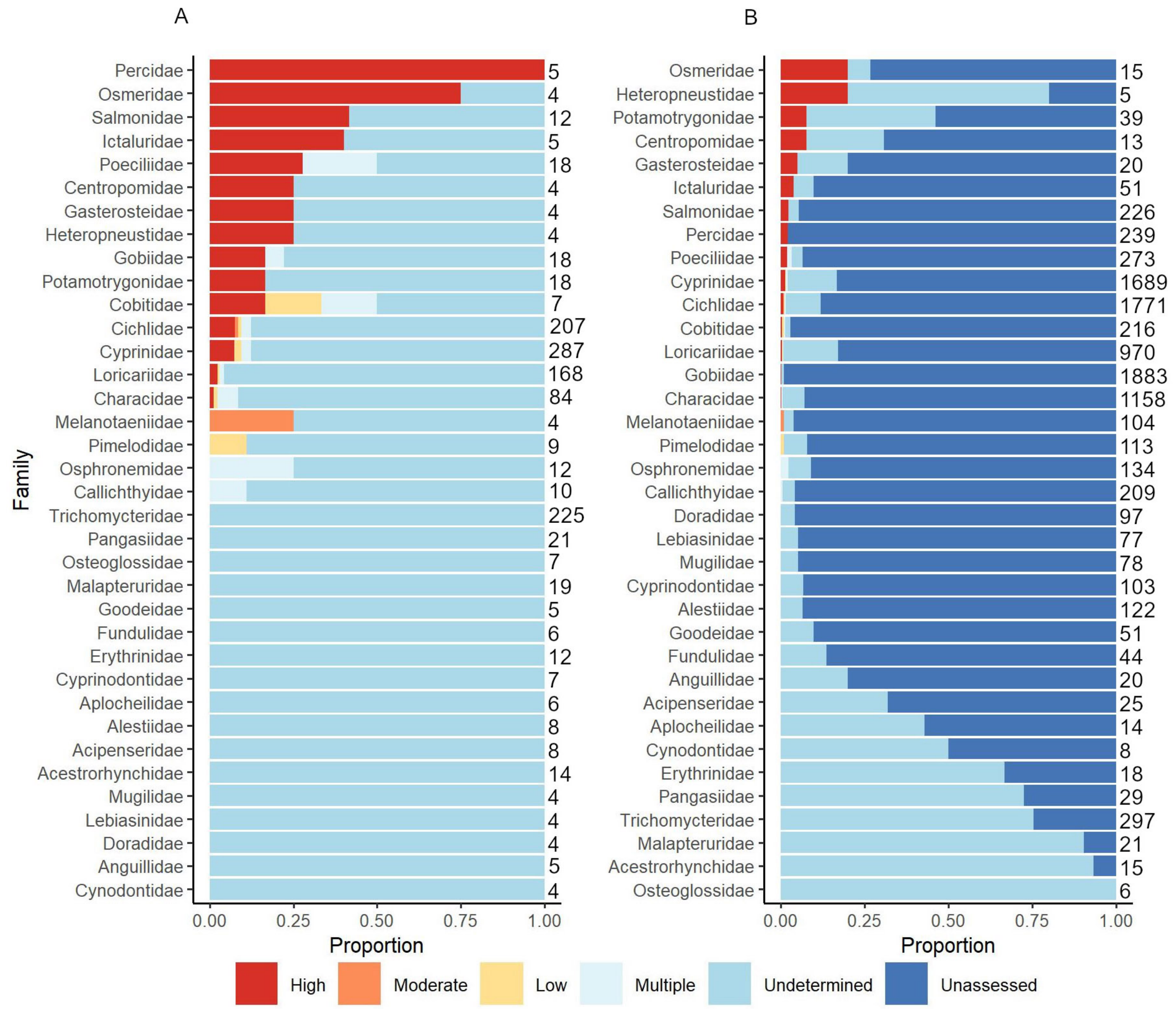

Figure 1. The proportion of risk statuses of fish families with four or more species assessed at the extent of the conterminous U.S. Panel (A) shows the proportion of species with high, moderate, low, multiple, and undetermined risk statuses of assessed species (total number of species evaluated in a family). Panel (B) shows the ratio of assessed to unassessed species in a given family (total species in a family). Total species in a family were obtained from FishBase (Froese and Pauly 2023).

Act; Jewell and Fuller 2021) or in policies of the Great Lakes states and Florida (Table S9), we provide insights into imported fish species to consider for priority management action in the U.S.

Statuses of fishes: Conterminous U.S.

We found risk assessments conducted at the scale of the conterminous U.S. for 1,366 fish species (Table S3). The USFWS evaluated more than 1,300 species using the ERSS procedure (USFWS 2020). Marcot et al. (2019) evaluated 50 species using the ERSS procedure (USFWS 2020) as well as the Freshwater Fish Injurious Species Risk Assessment Model (FISRAM; USFWS 2019). Hill et al. (2015, 2017, 2023) and Vilizzi et al. (2019, 2021) collectively evaluated over 150 species using the freshwater Fish Invasiveness Screening Kit (FISK; Copp et al. 2009; Lawson et al. 2015) and the Aquatic Species Invasiveness Screening Kit (AS-ISK; Copp et al. 2016). Together, Nico

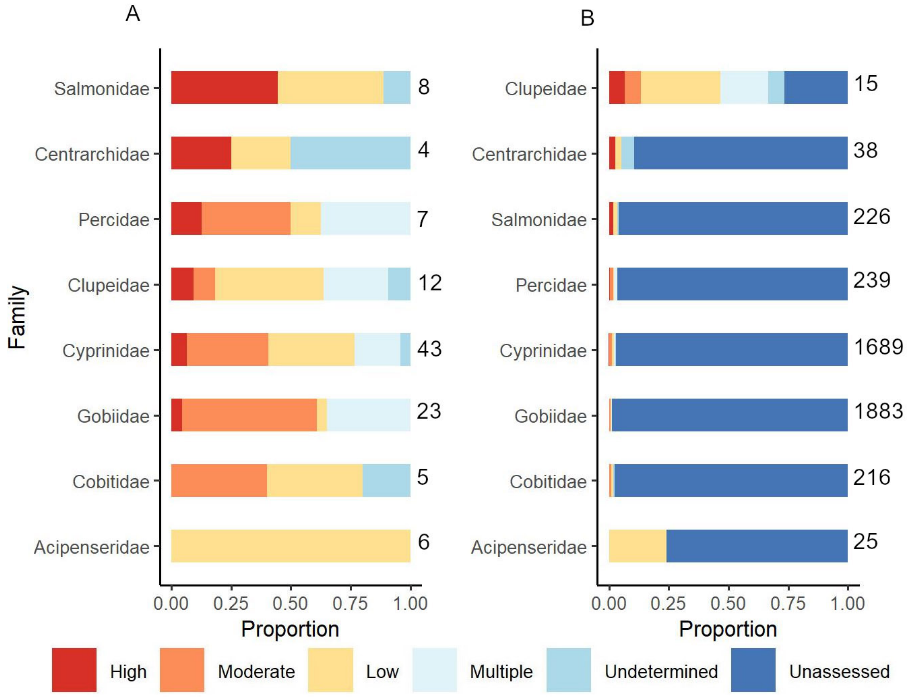

Figure 2. The proportion of risk statuses of fish families with four or more species assessed at the extent of the Great Lakes region. Panel (A) shows the proportion of species with high, moderate, low, multiple, and undetermined risk statuses of assessed species (total number of species evaluated in a family). Panel (B) shows the ratio of assessed to unassessed species in a given family (total species in a family). Total species in a family were obtained from FishBase (Froese and Pauly 2023).

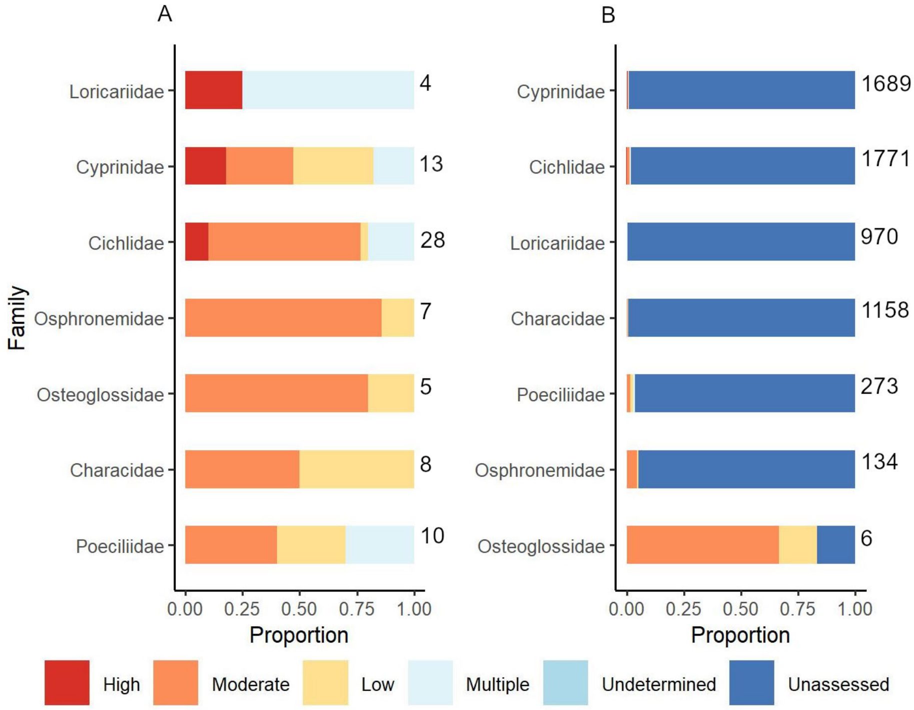

Figure 3. The proportion of risk statuses of fish families with four or more species assessed at the extent of Florida. Panel (A) shows the proportion of species with high, moderate, low, multiple, and undetermined risk statuses of assessed species (total number of species evaluated in a family). Panel (B) shows the ratio of assessed to unassessed species in a given family (total species in a family). Total species in a family were obtained from FishBase (Froese and Pauly 2023).

and Williams (1996) and Courtenay and Williams (2004) evaluated 30 species following the Generic Nonindigenous Aquatic Organism Risk Analysis Review Process (ANSTF 1996, 2010; Orr 2003).

At the extent of the conterminous U.S., we found the largest number of fish species evaluated (Figure 1A) to be species of minnow and carp (Cyprinidae; 287), pencil catfish (Trichomycteridae; 225), cichlid (Cichlidae; 207), and armored catfish (Loricariidae; 168). Species with high-risk statuses (Figure 1B) include approximately less than 5% of species of Cyprinidae, Cichlidae, Loriicaridae, and loach (Cobitidae); between 5% and 10% of species of stickleback (Gasterosteidae), bullhead catfish (Ictaluridae), perch and darter (Percidae), livebearer (Poecilidae), and salmon and trout (Salmonidae); and between 10% and 25% of species of snook and barramundi (Centropomidae), airsac catfish (Heteropneustidae), smelt (Osmeridae), and freshwater stingray (Potamotrygonidae). The statuses of more than 50% of species of shark catfish (Pangasiidae) and trahira (Erythrinidae), 75% of species of Trichomycteridae, small scale pike characin (Acestrorhynchidae), and electric catfish (Malapteruridae), and all arowana and arapaima species (Osteoglossidae) are undetermined.

We were able to synthesize status information for 97% of the species with risk assessments at the conterminous U.S. extent (Table S3). Of those fishes, 98 species have high-risk statuses (Table 1), of which, eighteen of those high-risk species were imported into the U.S. between 2000 and 2014 (Table S4). Although importation of African barramundi *Lates niloticus* Linnaeus, 1758 (Centropomidae), European river perch *Perca fluviatilis* Mitchill, 1814 (Percidae), and Wels catfish *Silurus glanis* Linnaeus, 1758 (Siluridae) became prohibited at the federal level circa 2016 (Tables S4, S9), there are fifteen high-risk species that are known to be imported but are not prohibited from importation at the federal level. Four of these species have well-distributed and robust populations in the U.S. and include largemouth bass *Micropterus salmoides* Lacepède, 1802 (Centrarchidae), common carp *Cyprinus carpio* Linnaeus, 1758 and grass carp *Ctenopharygodon idella* Valenciennes, 1844 (Cyprinidae), and lionfish *Pterois volitans* Linnaeus, 1758 (Scorpaenidae) (Tovey et al. 2009; DeVaney et al. 2009; Hixon et al. 2016; USGS 2023). In contrast, the other high-risk fishes have smaller and more isolated distributions in the country (Agostinho et al. 2021; USGS 2023). These species include oscar *Astronotus ocellatus* Agassiz, 1831, peacock bass *Cichla ocellaris* Bloch & Schneider, 1801, and Nile tilapia *Oreochromis niloticus* Linnaeus, 1758 (Cichlidae); pond loach *Misgurnus anguillidactus* Cantor, 1842 (Cobitidae); and sailfin molly *Poecilia latipinna* Lesueur, 1821, guppy *P. reticulata* Peters, 1859, and green swordtail *Xiphophorus helleri* Heckel, 1848 (Poecilidae). The limited distributions and isolation of these species enhances their vulnerability to eradication which could be exploited in control efforts (e.g., Tobin et al. 2011). Furthermore, the geographic inconspicuousness of the species,

Table 1. List of fish species with high-risk statuses in the conterminous U.S., in the Great Lakes region, and in the state of Florida. Horizontal lines separate families and species for clarity.

Family Name	Fish species name	Conterminous U.S.	Great Lakes	Florida
Atherinidae	*Atherina boyeri* (Risso, 1810)	X	X	
Atherinopsidae	*Menidia beryllina* (Cope, 1867)	X		
	Odontesthes bonariensis (Valenciennes, 1835)	X		
Callichthyidae	*Hoplosternum littorale* (Hancock, 1828)			X
Centrarchidae	*Lepomis microlophus* (Günther, 1859)	X	X	
	Micropterus dolomieu (Lacepède, 1802)	X		
	Micropterus salmoides (Lacepède, 1802)	X		
Centropomidae	*Lates niloticus* (Linnaeus, 1758)	X		
Channidae	*Channa argus* (Cantor, 1842)	X		X
	Channa marulius (Hamilton, 1822)			X
Characidae	*Pygocentrus nattereri* (Kner, 1858)	X		
Cichlidae	*Amatitlania nigrofasciata* (Günther, 1867)	X		X
	Astronotus ocellatus (Agassiz, 1831)	X		
	Cichla kelberi (Kullander & Ferreira, 2006)	X		
	Cichla ocellaris (Bloch & Schneider, 1801)	X		X
	Cichlasoma uropthalma (Günther, 1862)	X		X
	Coptodon rendalli (Boulenger, 1897)	X		
	Coptodon zilli (Gervais, 1848)	X		X
	Hemichromis letourneuxi (Sauvage, 1880)	X		
	Herichthys cyanoguttatus (Baird & Girard, 1854)	X		
	Oreochromis aureus (Steindachner, 1864)	X		X
	Oreochromis mossambicus (Peters, 1852)	X		X
	Oreochromis niloticus (Linnaeus, 1758)	X		X
	Parachromis managuensis (Günther, 1862)	X		X
	Pelmatotilapia mariae (Boulenger, 1899)	X		
	Sarotherodon melanotheron (Rüppell, 1852)	X		
	Serranochromis robustus (Günther, 1864)	X		
Clariidae	*Clarias batrachus* (Linnaeus, 1758)	X		X
	Clarias fuscus (Lacepède, 1803)	X		
	Clarias gariepinus (Burchell, 1822)	X		
Clupeidae	*Alosa aestivalis* (Mitchell, 1814)	X		
	Alosa pseudoharengus (Wilson, 1811)	X	X	
Cobitidae	*Misgurnus anguillicaudatus* (Cantor, 1842)	X		X
Cyprinidae	*Abramis brama* (Linnaeus, 1758)	X		
	Alburnus alburnus (Linnaeus, 1758)	X		
	Barbus barbus (Linnaeus, 1758)	X		
	Carassius auratus (Linnaeus, 1758)			X
	Carassius gibelio (Bloch, 1782)	X		
	Ctenopharyngodon idella (Valenciennes, 1844)	X	X	X
	Culter alburnus (Basilewsky, 1855)	X		
	Cyprinella lutrensis (Baird & Girard, 1853)	X		
	Cyprinus carpio (Linnaeus, 1758)	X	X	X
	Gobio gobio (Linnaeus, 1758)	X		
	Hypophthalmichthys molitrix (Valenciennes, 1844)	X		
	Hypophthalmichthys nobilis (Richardson, 1845)	X		X
	Leuciscus idus (Linnaeus, 1758)	X		
	Mylopharyngodon piceus (Richardson, 1846)	X		
	Opsariichthys uncirostris (Temminck & Schlegel, 1846)	X		
	Pimephales promelas (Rafinsque, 1820)			X
	Phoxinus phoxinus (Linnaeus, 1758)	X		
	Protochondrostoma genei (Bonaparte, 1839)	X		
	Pseudorasbora parva (Temminck & Schlegel, 1846)	X		
	Rhodeus amarus (Bloch, 1782)	X		
	Rutilus aula (Bonparte ,1841)	X		
	Rutilus rutilus (Linnaeus, 1758)	X	X	
	Scardinius erythrophthalmus (Linnaeus, 1758)	X	X	
	Tinca tinca (Linnaeus, 1758)	X	X	

Table 1. (continued).

Family Name	Fish species name	Conterminous U.S.	Great Lakes	Florida
Esocidae	*Esox lucius* (Linnaeus, 1758)	X		
	Esox masquinongy (Mitchill, 1824)	X		
Gasterosteidae	*Gasterosteus aculeatus* (Linnaeus, 1758)	X	X	
Gobiidae	*Neogobius melanostomus* (Pallas, 1814)	X	X	
	Ponticola platyrostris (Pallas, 1814)	X		
	Proterorhinus semilunaris (Heckel, 1837)	X		
Heteropneustidae	*Heteropneustes fossilis* (Bloch, 1794)	X		
Ictaluridae	*Ictalurus furcatus* (Valenciennes, 1840)	X		
	Pylodictis olivaris (Rafinesque, 1818)	X		
Loricariidae	*Hypostomus plecostomus* (Linnaeus, 1758)	X		X
	Pterygoplichthys anisitsi (Eigenmann & Kennedy, 1903)			X
	Pterygoplichthys disjunctivus (Weber, 1991)	X		X
	Pterygoplichthys multiradiatus (Hancock, 1828)	X		X
	Pterygoplichthys pardalis (Castelnau, 1855)	X		
Moronidae	*Morone americana* (Gmelin, 1789)	X	X	
Notopteridae	*Chitala ornata* (Gray, 1831)	X		
Odontobutidae	*Perccottus glenii* (Dybowski, 1877)	X		
Osmeridae	*Hypomesus nipponensis* (McAllister, 1963)	X		
	Osmerus eperlanus (Linnaeus, 1758)	X	X	
	Osmerus mordax (Mitchill, 1814)	X		
Osphronemidae	*Trichogaster lalius* (Hamilton, 1822)	X		
	Trichopodus trichopterus (Pallas, 1770)	X		
Percidae	*Gymnocephalus cernua* (Linnaeus, 1758)	X	X	
	Perca flavescens (Mitchill, 1814)	X		
	Perca fluviatilis (Linnaeus, 1758)	X	X	
	Sander lucioperca (Linnaeus, 1758)	X		
	Sander vitreus (Mitchill, 1818)	X		
Petromyzontidae	*Petromyzon marinus* (Linnaeus, 1758)		X	
Poeciliidae	*Belonesox belizanus* (Kner, 1860)	X		
	Gambusia affinis (Baird & Girard, 1853)	X		X
	Gambusia holbrooki (Girard, 1859)	X		
	Poecilia latipinna (Lesueur, 1821)	X		
	Poecilia reticulata (Peters, 1859)	X		X
	Poecilia sphenops (Valciennes, 1846)	X		X
	Xiphophorus helleri (Heckel, 1848)	X		
	Xiphophorus variatus (Meek, 1904)	X		
Polypteridae	*Polypterus delhezi* (Boulenger, 1899)			X
Pomacentridae	*Neopomacentrus cyanomos* (Bleeker, 1856)	X		
Potamotrygonidae	*Potamotrygon falkneri* (Castex & Maciel, 1963)	X		
	Potamotrygon motoro (Müller & Henle, 1841)	X		
	Potamotrygon schuhmacheri (Castex, 1964)	X		
Salmonidae	*Coregonus albula* (Linnaeus, 1758)	X		
	Coregonus lavaretus (Linnaeus, 1758)	X		
	Coregonus maraena (Bloch, 1779)	X		
	Coregonus peled (Gmelin, 1789)	X		
	Hucho hucho (Linnaeus, 1758)	X		
	Oncorhynchus kisutch (Walbaum, 1792)		X	
	Oncorhynchus mykiss (Walbaum, 1792)		X	
	Oncorhynchus tshawytscha (Walbaum, 1792)		X	
	Salmo trutta (Linnaeus, 1758)		X	
Scorpaenidae	*Pterois miles* (Bennett, 1828)	X		
	Pterois volitans (Linnaeus, 1758)	X		
Siluridae	*Silurus glanis* (Linnaeus, 1758)	X		

and the idiosyncratic nature of invasion processes (Kerns et al. 2021) could warrant investment in novel, sensitive techniques of early detection and monitoring (e.g., Larson et al. 2020; Sepulveda et al. 2020). It is important to note we did not review all state and territory policies, which could be a critical next step to identify the mosaic of regulations that impede high-risk fish invasions in the U.S. (Reed et al. 2023).

Statuses of fishes: Great Lakes

We found risk assessments conducted at the Great Lakes region spatial extent for 942 fish species (Table S5). The Great Lakes region refers to eight Midwest states (Illinois, Indiana, Ohio, Michigan, Minnesota, New York, Pennsylvania, Wisconsin) that have access to the Great Lakes; some risk assessments include the Ontario province of Canada that borders Lake Huron, Lake Erie, and Lake Ontario. Howeth et al. (2016) evaluated over 780 species using a traits-based approach. Ricciardi and Rasmussen (1998) evaluated two species using guidelines developed from marine and terrestrial invasion ecology. Kolar and Lodge (2002) coupled a literature review with modelling techniques to evaluate approximately 60 fishes, and Snyder et al. (2014) followed similar methods to evaluate more than 100 species. MacIsaac et al. (2015) re-evaluated 10 species from Kolar and Lodge (2002) and Snyder et al. (2014) using additional data. By integrating existing frameworks, Fusaro et al. (2017) and Davidson et al. (2017) evaluated 26 fish species. Lower et al. (2019, 2020, 2021) provided new and updated species risk assessments to Fusaro et al. (2017) and Davidson et al. (2017). In 2021, Davidson et al. evaluated 40 fish species using previously established methods (e.g., Davidson et al. 2017). Additional risk assessments in the Great Lakes region included Cudmore et al. (2012, 2017) and Grippo et al. (2017) that followed ANSTF (1996, 2010) and Orr (2003) to evaluate seven species in total, Ivan et al. (2020) that used bioenergetics modelling to evaluate bighead carp *Hypophthalmichthys nobilis* Richardson, 1845 and silver carp *H. molitrix* Valenciennes, 1844, and Avlijaš et al. (2018) that used FISK to evaluate a single species, the tench *Tinca tinca* Linnaeus, 1758 (Cyprinidae).

In the Great Lakes (Figure 2A), fish families with the greatest number of species assessed included Cyprinidae (43), Salmonidae (8), and Percidae (7), as well as herring (Clupeidae, 12) and gobies (Gobiidae, 23). Less than 10% of these families have high-risk statuses, although less than 10% of these families have been evaluated (except Clupeidae; Figure 2B). We were only able to synthesize status information for 15% of the species at the Great Lakes extent because risk assessments mostly focused on certain components like the introduction, establishment, or impact of the species (Table S5). Of fishes with statuses, we found 19 high-risk species (Table 1). High-risk fishes to the Great Lakes that were imported into the U.S. between 2000 and 2014 (Table S6) included *Perca fluviatilis* (Percidae); *Cyprinus carpio, Ctenopharygodon idella*, and rudd *Scardinius erythrophthalmus* Linnaeus, 1758 (Cyprinidae); and three-spine stickleback *Gasterosteus aculeatus* Linnaeus, 1758 (Gasterosteidae). The importation of *Perca fluviatilis* is prohibited at the federal level and the possession of the other high-risk species is regulated, restricted, or prohibited in at least one of the Great Lakes states (Tables S6, S9). Although we did not identify these fish species in U.S. imports, two high-risk fishes, Black Sea sand smelt *Atherina boyeri* Risso, 1810 (Atherinidae) and European smelt *Osmerus eperlanus* Linnaeus, 1758 (Osmeridae) could enter the Great Lakes via other means, such as through ballast water (Snyder et al. 2014). However, tighter ballast regulations on transoceanic ships have decreased the rate of discovery of new species by 85% in the Great Lakes region, the lowest in two centuries (Ricciardi and MacIsaac 2022).

The invasion of *Hypophthalmichthys molitrix* and *H. nobilis*, hereafter referred to as *Hypophthalmichthys* spp. (Kočovský et al. 2018) from established populations in the Mississippi River Basin has been a great concern of Great Lakes natural resource managers and the public (Hansen and Johnson 2010; Rasmussen et al. 2011). Hence, we expected *Hypophthalmichthys* spp. would have high-risk statuses. However, we found *Hypophthalmichthys* spp. have moderate-risk statuses in the Great Lakes region (Table S5). The risk of introduction and establishment of *Hypophthalmichthys* spp. is considered moderate or low although the ecological and economic impact of the species is expected to be high, potentially contributing to a moderate status (Table S5). *Hypophthalmichthys* spp. could substantially impact plankton and planktivorous fishes in the Great Lakes, threatening critical fisheries and the natural and human communities that depend on them (Sass et al. 2014; Ivan et al. 2020). Managing the ecological and economic impacts of *Hypophthalmichthys* spp. in addition to managing the impacts of currently established invasive species in the Great Lakes could be tremendously challenging. Millions of U.S. dollars and an enormous amount of research, labor, and time is spent to collaboratively control the production and spread of the established invasive sea lamprey *Petromyzon marinus* Linnaeus, 1758 (Petromyzontidae), a parasitic fish that collapsed Great Lakes fisheries upon its invasion of the region in the early 1900s (Brant 2019). If *Hypophthalmichthys* spp. were to establish, there will likely need to be trade-offs in control resources jeopardizing the effectiveness of the region's *P. marinus* control program. Great Lakes managers with this perspective may be more interested in prioritizing invasive fish species by ecological and economic impact rather than status, which would make *Hypophthalmichthys* spp. high-risk, warranting investment in prevention or EDRR of the species in the Great Lakes (Chapman et al. 2021). Managers with similar perspectives in other regions, states, or territories may also take this approach to target species for prevention to circumvent additional burdens on eradication and control costs in regional and state management plans.

Statuses of fishes: Florida

We found risk assessments conducted at the spatial extent of the state of Florida (Table S7) for 102 fish species (Table S8). Hardin and Hill (2012) following ANSTF (1996, 2010) and Orr (2003) evaluated the risk of a single species, the barramundi *Lates calcarifer*. Lawson et al. (2013, 2015) and Hill and Lawson (2015) used FISK to evaluate over 95 species. Lastly, Vilizzi et al. (2019) used FISK and Vilizzi et al. (2021) used AS-ISK to collectively evaluate approximately 100 species.

In Florida, fish families with the greatest number of species assessed (Figure 3A) included Cichlidae (28), Cyprinidae (13), and Poeciliidae (10). Less than 1% of Cichlidae, Cyprinidae, Heteropneustidae, and walking catfish (Clariidae) species have been evaluated in the state of Florida (Figure 3B). We were able to synthesize status information for 99% of the species at the Florida extent (Table S7), with twenty-six species having a high-risk status (Table 1). High-risk species imported into the U.S. between 2000 and 2014 included *Cichla ocellaris* (Cichlidae); *Misgurnus anguillicaudatus* (Cobitidae); *Poecilia reticulata* (Poeciliidae); *Cyprinus carpio, Ctenopharygodon idella*, goldfish *Carassius auratus* Linnaeus, 1758, and fathead minnow *Pimephales promelas* Rafinsque, 1820 (Cyprinidae); brown hoplo *Hoplosternum littorale* Hancock, 1828 (Callichthyidae); blue tilapia *Oreochromis aureus* Steindachner, 1864, Mozambique tilapia *O. mossambicus* Peters, 1852, and Nile tilapia *O. niloticus* Linnaeus, 1758 (Cichlidae). Interestingly, the importation of these fish species is not prohibited federally, and possession is not regulated by the state for several of the species: *Ctenopharygodon idella* and *Oreochromis* spp. were recently designated as species that require special permits (see Rule 68-5.001, F.A.C.).

Florida's climate, peninsular nature, and multiple points of entry (Simberloff et al. 1997) provide high-risk fishes with opportunities to establish and expand their ranges in the state. High-risk, established fishes could spread to other parts of the southeastern U.S. especially with changes in climate. Climate change is warming water temperatures and modifying hydrologic regimes that benefit the establishment and spread of invasive fish species in aquatic habitats (Rahel and Olden 2008; Finch et al. 2021). Hence, research (e.g., Schofield 2020), monitoring and tracking (e.g., Wallace et al. 2016), and control and removal (e.g., Hill and Sowards 2015; Schofield et al. 2019) in Florida can help to inform efforts to curtail fish species invasions in the U.S. more broadly.

Future directions

Aggregating online information makes literature and data more readily accessible and available, revealing knowledge and data gaps that support advancements in invasive species science and management (Simpson et al. 2019; Wallace et al. 2020; Venette et al. 2021). In recognition of this, we aggregated invasive species risk assessments which took hundreds of person-hours to manually curate. We were able to use the aggregated information to identify fish species for consideration for priority management action at multiple spatial scales. We were also able to underscore species that lack risk assessments or require more research to be effectively evaluated. A future step to aid in invasive species science and management could be the inclusion of additional invasive taxa risk assessments. For example, thousands of risk assessments for plants are available in an information system maintained by the U.S. Department of Agriculture's Animal and Plant Health Inspection Service (USDA APHIS; https://www.aphis.usda.gov/aphis/ourfocus/planthealth/plant-pest-and-disease-programs/pests-and-diseases/sa_weeds/sa_noxious_weeds_program/ct_riskassessments) and an information system maintained by the University of Florida's Institute of Food and Agricultural Sciences (UF/IFAS; https://assessment.ifas.ufl.edu/). Through our approach established in this paper, risk assessments for plants, invertebrates, and other vertebrate taxa could be aggregated. Experts could use this information to prioritize other taxa for management action like was demonstrated for fishes, and risk assessments could be coupled across taxa to identify the community of high-risk invaders that threaten the U.S. The value of the information aggregated here can be further enriched when joined with other types of invasive species information; for example, an expert could couple risk assessment results with detection samples to target habitats for intensive monitoring of high-risk species.

Into the future, global connectivity is expected to continue to increase, and along with it, the transport and movement of species (Hulme 2021). Because of this, new species will need to be assessed for risk, and previously assessed species will need to be re-evaluated as new information becomes available. Hence, the aggregation of risk assessments and other information to support invasive species science and management is an ongoing, iterative process. An objective of the national EDRR framework is to make existing and emerging risk assessments and other invasive species information accessible and available in a unified system (Reaser 2020; DOI 2021; NISC 2023). The risk assessments aggregated in this work fall within the first steps of meeting that objective. Continuing to increase the access and availability of invasive species information to scientists and managers can help to inform EDRR practices to protect U.S. assets and ecosystems from species invasions.

Conclusion

Collectively, our effort provides a comprehensive catalog of fishes and their risk assessments in the U.S. We were able to use this information to understand non-native fish species that are high-risk at national, regional, and state scales. When we coupled risk assessment data with import data and policy information for fishes, we were able to prioritize fish species to consider for priority management action. Potential future directions include aggregating risk assessments for other vertebrates, invertebrates, and plants, and moving towards a unifying information system. By making risk assessment data readily accessible and available, researchers, managers, and policy-makers can couple risk assessments with other invasive species information to plan preventative and EDRR efforts in support of invasive species management programs at multiple geographic scales for the benefit of U.S. human communities and natural ecosystems.

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Authors' contribution

WM Daniel conceived the presented idea and supervised the project. EM Dean and A Jordon developed the data, and EM Dean prepared and wrote the manuscript. A Jordon, AC Agnew, ND Hernandez, CR Morningstar, M Neilson, SE Piccolomini, B Reichert, AK Wray, and WM Daniel provided ideas in the early development of the project and edited the final draft of the manuscript.

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Supplementary material

The following supplementary material is available for this article:

Table S1. List of fish species with risk assessments conducted within the U.S.
Table S2. List of risk assessments organized by spatial extent.
Table S3. List of fish species and synthesized risk assessment data at the extent of the conterminous U.S.
Table S4. List of high-risk fish species at the extent of the conterminous U.S., if they have been imported according to LEMIS (Eskew et al. 2020), and if the importation of the species is managed at the federal level.
Table S5. List of fish species and synthesized risk assessment data at the extent of the Great Lakes.
Table S6. List of high-risk fish species at the extent of the Great Lakes, if they have been imported to the nation according to LEMIS (Eskew et al. 2020), and if the importation/possession of the species is managed at the federal level or in individual Great Lakes states.
Table S7. List of fish species and synthesized risk assessment data at the extent of the state of Florida.
Table S8. List of high-risk fish species at the extent of the state of Florida, if they have been imported into the nation according to LEMIS (Eskew et al. 2020), and if the importation/possession of the species is managed at the federal level or in the state of Florida.
Table S9. Names of and links to federal policy and state policies examined in the study.

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