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DATA ARTICLE

The North American Freshwater Migratory Fish Database (NAFMFD): Characterizing the migratory life histories of freshwater fishes of Canada, the United States and Mexico

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Abstract

Aim: Migratory freshwater fishes are those that must access discrete habitats to complete their life cycles. Freshwater fish migrations occur around the world and provide numerous ecosystem services for humans and natural systems; however, many migratory species are in decline globally. A limiting factor to successfully conserve freshwater migratory fishes is that the migratory life histories of many species are unknown or only partially described. To provide researchers with critical and comprehensive information to conserve migratory fishes, we developed the North American Freshwater Migratory Fish Database (NAFMFD).

Location: Canada, Mexico and the United States.

Taxon: Freshwater fish.

Methods: To develop this database, we assigned migratory status, pattern and behaviour to a comprehensive list of freshwater fish species found throughout North America. We assembled the database which included assignments (i.e. migratory status, pattern and behaviour) as well as the sources used to make the assignments. Researchers and managers from across North America reviewed the database for completeness and accuracy on the migratory life histories of fishes.

Results: The database synthesizes current knowledge of migratory status, pattern and behaviour of native and non-native freshwater fishes throughout North America, including 1250 species representing 79 families and 325 genera. Results showcase the diversity of migratory life histories of freshwater fishes on the continent, including that at least 25% of North American freshwater fishes are migratory, 23% are non-migratory and 44% have undetermined migratory status.

Main conclusions: NAFMFD improves the quality of migratory data accessible to researchers, which supports a more holistic understanding of the threats encountered by migratory fishes, including habitat fragmentation. The approach we used in developing NAFMFD can provide guidance for developing similar databases in other regions. Collectively, our work offers new insights into the range of freshwater fish migratory life histories, stimulating a need to better understand this diversity globally.

KEYWORDS
behaviour, conservation assessment, diadromy, migration, pattern, potamodromy

1 | INTRODUCTION

Freshwater fish migrations occur across the globe, with species moving within and between habitats at different life stages and with migration patterns and behaviours varying widely across species and populations (as reviewed by Lucas & Baras, 2001; Morais & Daverat, 2016). The definition of migratory freshwater fish species has changed over time. Early definitions focused on type of waterbodies accessed and direction of movement, and this typically emphasized fishes migrating long distances (Dingle, 1986; McDowall, 1997; Meek, 1916; Myers, 1949). Northcote (1978, 1984) expanded the definition to include movements of large portions of a fish population between multiple habitats, which included diadromous migrations and migrations in wholly freshwaters (i.e. potamodromy). More recently, and especially in conservation and management contexts, distance of movement is not typically the primary factor defining a migratory species; it is instead an emphasis on access to habitats needed for critical life stages, with this emphasis underscoring a species' vulnerability to the loss of habitat access (Lennox et al., 2019). Fish migrations provide numerous ecosystem services for humans and natural systems (Holmlund & Hammer, 1999); however, many migratory fishes are in severe decline globally (Deinet et al., 2020). A recent assessment of migratory fishes in Europe reports that very few large rivers on the continent continue to support viable migratory fish populations (Van Puijenbroek et al., 2019). Additionally, multiple efforts have documented drops in migratory fish abundances from historical levels across North America (Limburg & Waldman, 2009; Musick et al., 2000). Migratory freshwater fishes, like most freshwater fishes, are threatened by stressors such as habitat degradation, invasive species and changing climate. However, habitat fragmentation, defined as the division and isolation of habitats due to anthropogenic barriers such as dams, culverts and road crossings, is a common and especially pervasive threat to migratory fishes globally (Gido et al., 2016).

While habitat fragmentation is challenging for the conservation of many freshwater fish species, the challenge is especially pronounced for migratory species because they require access to multiple, well-connected habitats (Brink et al., 2018; McIntyre et al., 2016). However, compounding this challenge, researchers do not have a full understanding of which fish species are migratory, along with a clear understanding of the types of migratory patterns and behaviours they express (Lennox et al., 2019). Relatively few freshwater migratory fish species have their life histories fully described in the literature, and those that do are typically from socioeconomically important families such as sturgeon (Acipenseridae), freshwater eel (Anguillidae), shad and herring (Clupeidae), and salmon and trout (Salmonidae) (Dingle & Drake, 2007; Lucas & Baras, 2001; Morais & Daverat, 2016). The migratory life history of many small-bodied fishes such as killifishes (Aplocheilidae, Fundulidae), livebearers (Poeciliidae) and several genera of minnows (Cyprinidae) are generally poorly described or unknown (Lucas & Baras, 2001). Improving our understanding of the migratory life histories of lesser-known freshwater fishes is a critical step to conserve and protect migratory species and their habitats.

Currently, electronic databases are available that partially characterize the migratory life histories of freshwater fishes globally. While advantageous for their accessibility, information on the migratory life history for a given fish species can be inconsistent because the databases were developed and reviewed using different approaches. Furthermore, entries in the databases may be incomplete, may lack detail on specific migratory patterns or may have been developed without robust literature and/or expert review. For example, Froese and Pauly (2021) note that users of FishBase (https://www.fishbase.org/) can encounter erroneous entries that are not supported by references because the approach to verify information encoded into the database is not strictly applied. The International Union for Conservation of Nature Red List of Threatened Species (IUCN Red List; IUCN, 2021; https://www.iucnredlist.org/) provides a comprehensive conservation status for many species; however, its characterization of migratory life history for a species can be incomplete because it is not required for the conservation assessment. Additionally, although the Global Register of Migratory Species (GROMS; Riede, 2004; http://www.groms.de/) summarizes knowledge on the migratory life histories of multiple vertebrate species, more than 4000 species included in the database are organisms that migrate at least 100 km. This qualifier for species inclusion in the database leads to an incomplete profile for several major taxa groups, specifically, the many freshwater fishes that migrate distances less than 100 km. Compiling a comprehensive database that specifically details the migratory life histories of freshwater fish species would enhance the ability of researchers to find verified, consistent information and provide a more complete and detailed species profile, aiding in mitigation efforts of declines in migratory fishes globally.

To address this need, we developed the North American Freshwater Migratory Fish Database (NAFMFD) synthesizing current knowledge on native and non-native migratory freshwater fish species in North America. To develop this database, we first assigned migratory status, pattern and behaviour to a comprehensive list of fish species found throughout North America. Next, we assembled the database which included assignments (i.e. status, pattern and behaviour) as well as the sources used to make the assignments. Finally, researchers and managers from across North America reviewed the database for completeness and accuracy on the migratory life histories of fishes. We summarize results along with the conservation status of species provided by the IUCN Red List (IUCN, 2021). We also discuss potential future enhancements to the database and provide recommendations for developing similar databases for other regions.

2 | MATERIALS AND METHODS

2.1 | Geographical scope

Our database includes fishes found across the continent of North America, including Canada, Mexico and the conterminous United States (U.S.) along with the outlying states of Alaska and Hawaii (Figure 1a). Fishes from many countries in Central America are not well represented in the database at this time. Eastern and western Canada and Alaska in the western U.S. contain rivers that drain portions of arctic landscapes and are inhabited by several anadromous salmonid fish species (see Table 1 for life-history strategy definitions; McPhail & Lindsey, 1970; Scott & Crossman, 1973). In large, coastal rivers of the southeastern, western, and northeastern U.S., diadromous fishes access inland and marine habitats, while potamodromous fish species inhabit both coastal and interior portions of watersheds (McDowall, 1988). Potamodromous fishes colonized post-glacial streams and lakes and regularly re-colonize streams subject to intense droughts in the midwestern U.S. (Whitney et al., 2016). In the arid southwestern U.S., potamodromous fishes evolved migration strategies to capitalize on spatiotemporally dynamic habitats at the scale of entire river basins (e.g. Pennock, McKinstry, Cathcart, et al., 2020) and re-colonize streams following wildfires (Gido et al., 2019; Whitney et al., 2017). Streams of Hawaii and of other Pacific Islands experience major, recurring disturbances (e.g. drought, volcanism), and the dominant life-history strategy of fishes on the islands, amphidromy, likely developed in response to those disturbances (McDowall, 2003; McDowall, 2007a). Finer scale variation in environmental and biological conditions within these regions yields additional species-level and population-level differences in migratory life histories across and within basins.

2.2 | Assigning migratory status, pattern and behaviour to fish species

The fish species included in the database were identified from published freshwater fish species lists. For this effort, we broadly define a freshwater fish as a species that uses freshwater habitats at some point in their life cycle. We first included fish species listed in Jelks et al. (2008), which presents a status assessment of many North American fishes; species included in this review are all considered native to North America. Then, we added fish species compiled by Daniel et al. (2015). This step supplemented additional fish species that were not included in Jelks et al. (2008), such as many non-native fish species, which we considered to be species introduced to North America but with historical ranges located exclusively outside of the continent (USGS, 2019). Finally, we supplemented the list with additional native species from Frimpong and Angermeier (2009).

For each fish species, we reviewed published books focused on freshwater migratory fishes and freshwater fish life histories in Canada (e.g. Scott & Crossman, 1973), Mexico (e.g. Miller et al., 2005) and U.S. states (e.g. Jenkins & Burkhead, 1994). The information from published books was supplemented with information from peer-reviewed journal articles and grey literature that were located using the database search engine Google Scholar (https://scholar.google.com/). We defined grey literature as information created by government agencies, academic institutions or non-government organizations that is not controlled by commercial publishers such as reports, proceedings, and dissertations and theses (Paez, 2017). We used Google Scholar at this stage because it provides search results for both peer-reviewed journal articles and grey literature,

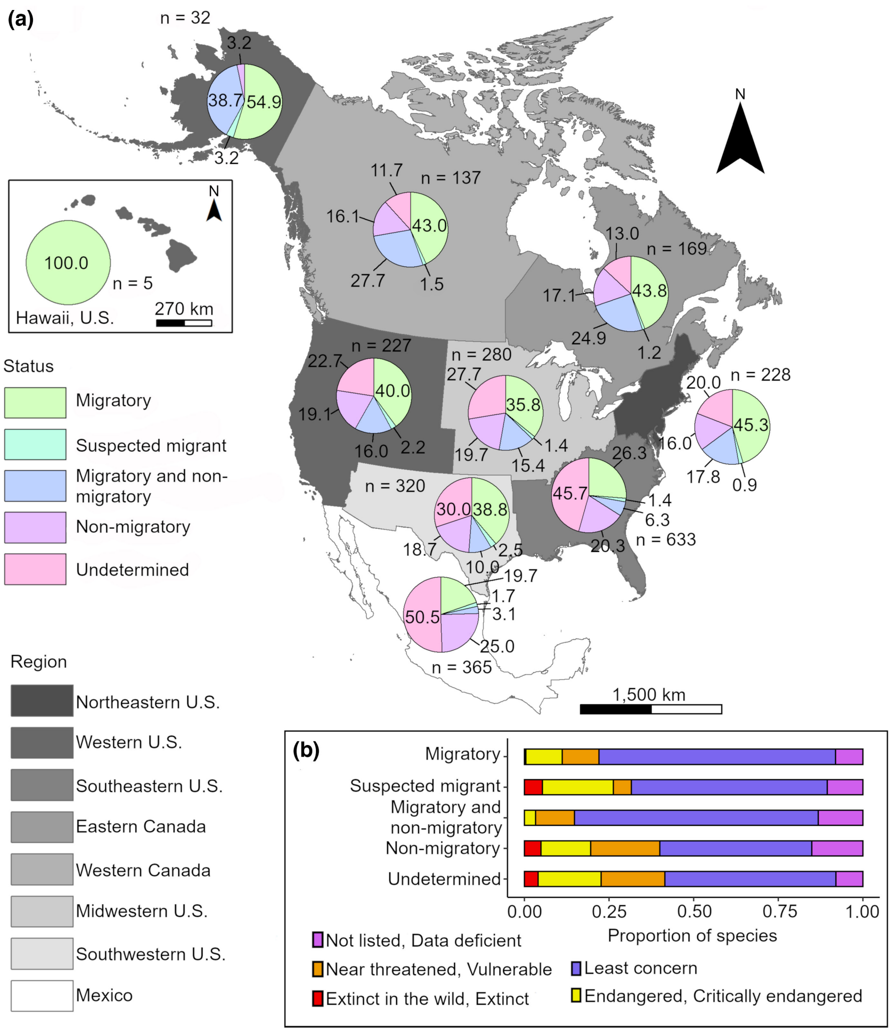

FIGURE 1 (a) Eight geographical regions in North America where fish species were reviewed by experts, along with a distribution of the status of native fish species in the region. While fishes from Hawaii and Alaska were grouped as part of the western U.S. in this figure, we distinguish the status of their native fish species from that of the larger region. Note that because fish species can transcend regional boundaries, a single species could contribute a status to multiple regions. Number of fish species (n) is included for each region. The map projection is Albers, and the projected coordinate system of the map is the USA contiguous Albers equal area conic. (b) IUCN red list (IUCN, 2021) conservation status of native north American freshwater fish species with migratory, suspected migrant, migratory and non-migratory, non-migratory, and undetermined statuses

while other literature database search engines are limited to peer-reviewed journal articles only. Google Scholar literature searches were conducted using scientific and common fish species names and combination of keywords including: "life history," "life cycle," "ecology," "migratory," "migration," "movement," "mobile," "diadromy," "anadromy," "catadromy," "amphidromy," "potamodromy," "non-migratory," "non-mobile" and "sedentary." In addition to information from peer-reviewed journal articles and grey literature, we supplemented information included in GROMS (Riede, 2004). If information on a species' life history was not documented in published books, peer-reviewed literature, grey literature or GROMS, we referred to FishBase (Froese & Pauly, 2021) and the IUCN Red List (IUCN, 2021) as potential sources of information.

Following the literature review, we standardized the information compiled for these fish species using the following data categories and assigned descriptors to each species (Table 1). The term *status* refers to the general migratory life history of the species. This includes whether a species is migratory or non-migratory or if it is suspected to migrate. It also includes whether it displays distinct migratory and non-migratory populations or individuals within a population. Additionally, the term status includes whether the migratory life history could not be determined based on an absence of information (i.e. undetermined). If the species was determined to have a migratory status, we proceeded to assign a pattern. *Pattern* refers to the separate habitats that a migratory fish uses in their life cycle which can include saltwater and freshwater habitats (i.e. diadromous) and/or wholly freshwater habitats (i.e. potamodromous). If the species was diadromous, we assigned one or more of the following *behaviours* to the species, which indicates the timing and direction of a migration of a life stage between separate habitats: anadromous, semi-anadromous, catadromous, semi-catadromous and amphidromous. We did not define behaviours for potamodromous species because specific behaviours are difficult to define or are not well known for most potamodromous fishes (Thurow, 2016). We assigned a fish species a suspected migrant status if we were able to find information on the migratory life history of a species but could not determine the specific pattern for the species. Species with distinct migratory and non-migratory populations or populations comprised of migratory and non-migratory individuals were assigned both a migratory and non-migratory status. If species were found to not migrate from our review (i.e. a source clearly indicated that the species was not migratory), the species was assigned a non-migratory status. If we could not find any statement on the migratory life history of a fish species, we assigned the species an undetermined status.

TABLE 1 Definitions of status, pattern and behaviour assigned to freshwater fish species and the number and percentage of species expressing that status, pattern and behaviour in the database

Status	Pattern	Behaviour	Definition	No. of species (%)
Migratory			Species that must access discrete habitats to complete their life cycles	320 (25%)[a]
	Diadromous		Species that migrate between freshwater and saltwater habitats, and include those species that exhibit anadromous, semi-anadromous, catadromous, semi-catadromous and amphidromous behaviours	82 (25%)[b]
		Amphidromous	Species whose adult stage spawns in freshwater and whose larvae migrate to the sea to feed; juveniles return to freshwater to mature into adults	28 (34%)[c]
		Anadromous	Majority of the species' life is in the sea, and the species migrates to freshwater to spawn	13 (15%)[c]
		Semi-anadromous	Species whose spawning run from the sea extends only as far as the upper estuary rather than into the freshwater environment	20 (24%)[c]
		Catadromous	Majority of the species' life is in freshwater, and the species migrates to the sea to spawn	9 (11%)[c]
		Semi-catadromous	Species whose spawning run extends only as far downstream as estuarine areas rather than into the marine environment	0 (0%)[c]
		Amphidromous + anadromous	Species exhibits both amphidromous and anadromous behaviours	2 (3%)[c]
		Amphidromous + catadromous	Species exhibits both amphidromous and catadromous behaviours	4 (5%)[c]
		Amphidromous + semi-anadromous	Species exhibits both amphidromous and semi-anadromous behaviours	2 (3%)[c]
		Anadromous + semi-anadromous	Species exhibit both anadromous and semi-anadromous behaviours	3 (4%)[c]
		Catadromous + semi-catadromous	Species exhibits both catadromous and semi-catadromous behaviours	1 (1%)[c]
	Potamodromous		Species that migrate entirely within freshwater habitats.	210 (66%)[b]
	Diadromous and potamodromous		Species that exhibit a diadromous pattern (including one or more diadromous behaviours) and a potamodromous pattern	28 (9%)[b]
Suspected migrant			Source indicates a fish species could be migratory but insufficient evidence to assign a specific pattern	20 (2%)[a]
Migratory and non-migratory			Species have distinct migratory and non-migratory populations or populations comprised of migratory and non-migratory individuals	67 (6%)[a]
Non-migratory			Species that do not require migration between two or more habitats to support a life stage	295 (23%)[a]
Undetermined			Absence of information on a fish species' migratory life history	548 (44%)[a]

[a]Percent of migratory, suspected migrant, migratory and non-migratory, non-migratory, and undetermined species.

[b]Percent of migratory species.

[c]Percent of diadromous species.

2.3 | Assembling the database

Our database follows a similar format to Frimpong and Angermeier's (2008) Fish Traits database. We compiled the status, pattern and behaviour assignments for each freshwater fish species into a single database with each row containing information for one species; sources used to assign information were also included (see list of sources in Appendix S1). Species taxonomy was obtained from the Integrated Taxonomic Information System (ITIS; ITIS, 2021; https://www.itis.gov/), with database columns representing family, scientific and common names along with family, genus and species ITIS codes. An additional database column includes species codes from FishBase (Froese & Pauly, 2021). Species codes were obtained using R 4.1.2 (R Core Team, 2021; https://www.R-project.org/) and the rfishbase package (Boettiger et al., 2021; https://github.com/ropensci/rfishbase). Columns representing status, pattern and behaviour are marked as binary (0/1) for each species with 1 indicating that a species exhibits a particular migratory status, pattern and behaviour while 0 represents its absence. The subsequent column in the database identifies the sources for the status, pattern and behaviour assignment for a species, and the following column has cells containing the status, pattern, and behaviour as text (e.g. non-migratory; potamodromous; anadromous) identified from the specific source.

2.4 | Reviewing of the database by north American freshwater fish experts

In all, 16 reviewers, including university researchers and governmental scientists, with expertise in North American freshwater fishes verified the status, pattern and behaviour assigned to each fish species in the database according to their regional knowledge. We divided North America into eight geographical regions (Figure 1a) and recorded a species' presence or absence in a region with species distribution maps and text-based descriptions from FishBase (Froese & Pauly, 2021) and the IUCN Red List (IUCN, 2021) as well as georeferenced record maps from the Global Biodiversity Information Facility (GBIF; GBIF.org, 2021; https://www.gbif.org/). We referred to the Nonindigenous Aquatic Species (NAS) freshwater fish database provided by the United States Geological Survey (USGS) to determine geographical distributions of non-native species in the U.S. (USGS, 2019; http://nas.er.usgs.gov/), we referred to Crossman (1991) to determine distributions of non-native fish species in Canada, and we referred to Espinosa-Pérez and Ramírez (2015) to determine distributions for non-native fish species in Mexico.

3 | RESULTS AND DISCUSSION

Our review resulted in a total of 1250 species (723 native and non-native species from Daniel et al., 2015; 518 native species from Jelks et al., 2008; nine native species from Frimpong & Angermeier, 2009) from 79 families representing 325 genera. This includes 1124 native fish species and 126 non-native fish species. We reviewed 285 sources which included published books, peer-reviewed journal articles and grey literature. Journal articles were the most common sources used to populate the database, with 183 articles used, followed by 52 grey literature documents, and 50 published books. We reviewed information for 140 fish species from GROMS (Riede, 2004) including 93 species that are native and 47 species that are non-native to North America. We referred to FishBase (Froese & Pauly, 2021) and the IUCN Red List (IUCN, 2021) for 88 species that lacked documentation of their migratory life histories in published books, peer-reviewed journal articles, grey literature or GROMS (Riede, 2004).

3.1 | Migratory fishes

Our assessment showed at least 25% of native and non-native species comprising the North American freshwater fish assemblage are migratory (Table 1). Migratory fishes also comprise a substantial proportion of the native freshwater fish assemblages in North America, with the entire native assemblage in Hawaii and greater than one-quarter of all regional assemblages (except that of Mexico) being migratory (Figure 1a). At least 20% of Mexico's fish assemblage is migratory; however, this region also has the highest proportion of species with undetermined status (Figure 1a). Some fish families are entirely migratory, such as sturgeon (Acipenseridae), freshwater eel (Anguillidae), sleeper (Eleotridae) and mojarra (Gerreidae) (Figure 2). The sucker (Catostomide), pike (Esocidae), goby (Gobiidae), lamprey (Petromyzontidae), and the salmon and trout (Salmonidae) families have more than 50% of species considered migratory (Figure 2). Approximately 25% of migratory fish species in our database are listed as near threatened and vulnerable or endangered and critically endangered in North America according to the IUCN Red List (IUCN, 2021; Figure 1b). A recent global assessment of migratory fishes suggests that from 1970 to 2016, abundances of some species in North America have experienced the lowest average decline (−28%) compared to other regions of the world (Deinet et al., 2020); however, this assessment only included population data for 63 freshwater migratory fish species. Our database contains 61 of the species assessed by Deinet et al. (2020) (excluding the Bull Shark, *Carcharhinus leucas*, and the Smalltooth Sawfish, *Pristis pectinata*), plus an additional 259 migratory species. It is unclear how population data for these additional migratory fishes would change the estimate of decline.

Fishes exhibiting a single diadromous pattern comprise 25% of the North American migratory fish assemblage (Table 1). Many amphidromous species are members of the sleeper (Eleotridae) and goby (Gobiidae) families (Figure 2), and although amphidromous fishes comprise the largest percentage (34%) of diadromous fish in North America (Table 1), they have received minimal conservation attention in comparison to fishes with other diadromous behaviours (McDowall, 2007b). Anadromous fishes, like species of sturgeon (Acipenseridae), shad and herring (Clupeidae), smelt (Osmeridae), and salmon and trout (Salmonidae) (Figure 2), comprise only 15% of diadromous fishes and 4% of all migratory fishes (Table 1); however, they are the most well studied of diadromous fishes in general (Acolas & Lambert, 2016; Lucas & Baras, 2001; McDowall, 1988). Approximately 24% of diadromous fishes are semi-anadromous, with this behaviour being well-represented among mojarra (Gerreidae) and drum (Sciaenidae) species. Few migratory fishes (<11%) are catadromous (Table 1), although the pattern is exhibited by the freshwater eel (Anguillidae) family, which includes one native and three non-native fishes (Figure 2).

Potamodromous species comprise the largest percentage (66%) of migratory fishes (Table 1) and are well represented by species in families of sturgeon (Acipenseridae), sucker (Catostomidae), pike (Esocidae), gar (Lepisosteidae) and lamprey (Petromyzontidae) (Figure 2). There are likely more than 210 potamodromous species in North America, considering that 17 out of the 20 suspected

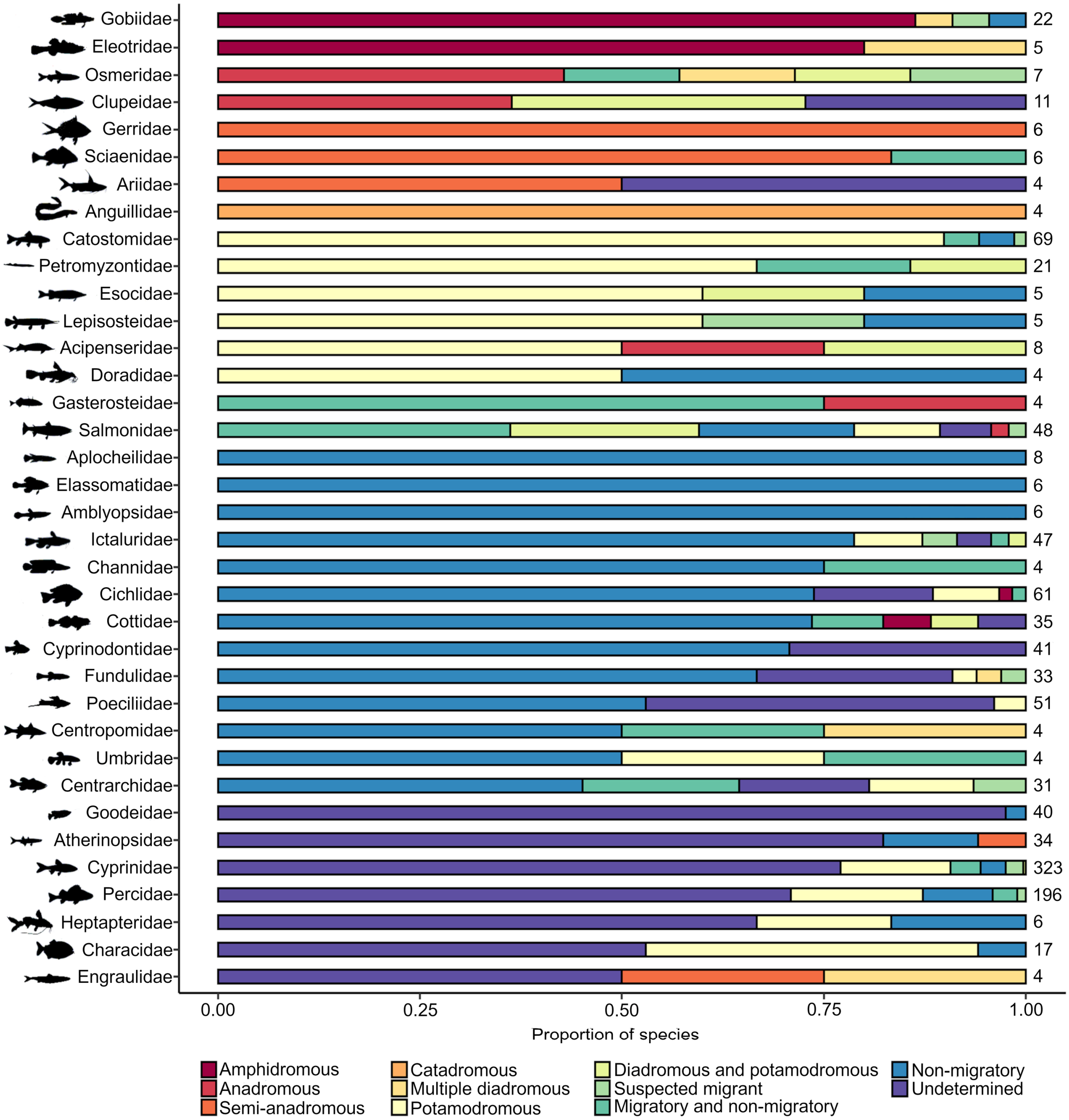

FIGURE 2 Distribution of status, pattern and behaviour of freshwater fish families with four or more species in the database, including native and non-native species. Number of species per family are listed after each stacked bar. The category 'multiple diadromous' refers to fish species that exhibit more than one diadromous behaviour (e.g. anadromous + semi-anadromous; see Table 1). The figure is organized from top to bottom with families with mostly diadromous species (and their behaviours), to those with mostly potamodromous species, then families with mostly migratory and non-migratory species, non-migratory species, and finally undetermined species

migrant species (Table 1) are potamodromous. The total number of known diadromous fish species globally is approximately 250 species (McDowall, 1997) which was estimated by McIntyre et al. (2016) to be comparable to the sum of potamodromous fish species documented in Canada (34 species; Lucas & Baras, 2001), in South American rivers (~67 species; Carolsfeld et al., 2004), and within the Mekong River (165 species; Baran & Myschowoda, 2009). Our estimate reveals that 210 potamodromous fish species occur in North America; this estimate in conjunction with a newer estimate of 172 potamodromous species in the Amazon River basin of South America (Duponchelle et al., 2021) and the 165 potamodromous species from the Mekong River (Baran & Myschowoda, 2009) implies that the number of diadromous fish species globally is under half the sum of potamodromous fish species in these three regions. Although potamodromous species comprise a larger proportion of the global migratory fish assemblage than diadromous species, the life histories of potamodromous fishes have received far less conservation attention in comparison (Thurow, 2016).

3.2 | Multiple migratory statuses, patterns and behaviours

A single species can exhibit considerable diversity in its migratory life history throughout its range in North America. Collectively, approximately 16% of diadromous fish species are known to have population-level variation in their behaviours (Table 1). For example, catadromous and amphidromous behaviours have been observed across populations of the Bigmouth Sleeper (*Gobiomorus dormitor*) within its native range (McBride & Matheson, 2011). Furthermore, about 9% of migratory species are known to have diadromous and potamodromous populations (Table 1). Variation in diadromous and potamodromous patterns (as well as diadromous behaviours) among populations can increase the likelihood of population persistence by spreading the risk of extirpation among life histories. For example, *Oncorhynchus mykiss* is a Pacific salmonid that displays this strategy, exhibiting anadromous (Steelhead Trout) and potamodromous (Rainbow Trout) forms in its native range in the western coastal regions of the continent (Behnke, 2010; Hodge et al., 2016). Different patterns of migration of *O. mykiss* occur seasonally (Behnke, 2010) and may occur simultaneously in cohorts of a single year class among populations and even within a single population of *O. mykiss* (Northcote, 1978); such life-history plasticity is displayed by other salmonid species as well (Behnke, 2010).

Besides exhibiting multiple migratory patterns and behaviours, approximately 6% of the North American freshwater fish assemblage consists of species that exhibit distinct migratory and non-migratory statuses, with variation occurring among populations and individuals (Table 1). These species comprise a larger share of Canadian and Alaskan freshwater fish assemblages than in other regions (Figure 1a). Salmonids are well known to have distinct anadromous, potamodromous and non-migratory populations (Northcote, 1997; Figure 2). For example, Brook Trout (*Salvelinus fontinalis*) can be non-migratory and reside for their entire lives in lakes (e.g. Addison & Wilson, 2010), they can be anadromous if they have access to coastal streams (e.g. Ryther, 1997), or they can be potamodromous if they are land-locked but have access to tributaries (e.g. Huckins et al., 2008). Recent research is finding that populations with migratory and non-migratory individuals are more prevalent than previously thought (Dzul et al., 2021; Pennock, McKinstry, & Gido, 2020). For example, individual Central Stonerollers (*Campostoma anomalum*) can migrate up to 1 km between pools and other riverine habitats while other individual *C. anomalum* remain in pools for their entire life cycles (Pennock et al., 2018). The idea that riverine fishes are mostly 'resident' or non-migratory may be related to sampling biases that failed to detect migrations of different fishes (Gowan et al., 1994; Gowan & Fausch, 1996). Species with both a migratory and non-migratory status have the lowest percentage of species listed as near threatened and vulnerable or endangered and critically endangered (Figure 1b).

3.3 | Non-migratory fishes

Non-migratory fish species comprise at least 23% of the entire North American freshwater fish assemblage (Table 1) and less than 25% of regional freshwater fish assemblages (Figure 1a). The families of cavefish (Amblyopsidae) and pygmy sunfish (Elassomatidae) are entirely non-migratory (Figure 2). Cichlid (Cichlidae), sculpin (Cottidae), pupfish (Cyprinodontidae), killifish (Fundulidae), catfish (Ictaluridae) and livebearer (Poeciliidae) families have greater than 50% of the species as non-migratory (Figure 2). About 30% of non-migratory species are listed as near threatened and vulnerable or endangered and critically endangered in North America (Figure 1b).

3.4 | Fishes with undetermined migratory life histories

Approximately 44% of species in the database were assigned an undetermined status. Fish families with greater than 50% of species assigned an undetermined status include silverside (Atherinopsidae), minnow (Cyprinidae), anchovy (Engraulidae), splitfin (Goodeidae), and perch and darter (Percidae) (Figure 2). Of the regional fish assemblages, Mexico has the most species with undetermined migratory life histories (~50% of 365 total species), followed by the southeastern U.S. (~45% of 633 total species) (Figure 1a). Many splitfin species occupy basins in Mexico (Miller et al., 2005), and many species of minnows, perches and darters are in basins throughout the southeastern U.S. (Page, 1983; Warren et al., 1997) Approximately 32% of species with undetermined migratory status are listed as near threatened and vulnerable or endangered and critically endangered (Figure 1b). Research on the migratory life histories of these species is critical for identifying and understanding the threats driving their declines in North America.

3.5 | Enrichment of the database

The database provides information on the migratory status, pattern and behaviour for 702 out of 1250 freshwater fish species found in North America. In assembling the information for the database, we determined that there are 548 species that require more information to determine their migratory status, pattern and behaviour. Additionally, a comparison of this list with Scharpf (2021) and Tedesco et al. (2017) identifies several species found largely in Central America that could be added to this database. Collectively, these points underscore the importance of developing a better understanding of freshwater fish migrations to effectively conserve this group of fishes. This could include incorporation of distances of migration for individual species which would aid in efforts to understand species' vulnerability to different stressors. To fill these knowledge gaps, researchers are encouraged to submit information to support future versions of the database, including newly described fishes and fishes that are not currently listed in the database.

Submissions will be reviewed by the NAFMFD team, and the database will be periodically updated with verified information (see Data Availability Statement).

4 | CONCLUSION

Our collective effort provides a comprehensive and consistently defined database of freshwater fishes and their migratory status, pattern and behaviour in North America. The database provides information on species' migratory life histories that when coupled with environmental and biological data could help to address causes of migratory fish decline in freshwater systems, including habitat fragmentation. The utility of the database can be enhanced with additional data that can facilitate analyses for users. For example, information detailing body size could inform the user whether small or large barriers would be an issue for a particular migratory species (Januchowski-Hartley et al., 2019). Currently, body sizes for freshwater fishes in the U.S. can be obtained from the database Fish Traits (Frimpong & Angermeier, 2009) and FishBase (Froese & Pauly, 2021). Merging these databases and others with NAFMFD will aid in gaining a better understanding of how fragmentation influences freshwater migratory fishes throughout North America.

The database provides a baseline estimate of the diversity of freshwater migratory fishes on the North American continent stimulating a need to understand this diversity globally. Development of additional continental databases on the migratory life history of freshwater fish assemblages around the world can be accomplished using our approach. If the same approach is applied with the same standardized data categories, this would allow for regional databases to be interconnected. A synthesis of these regional databases would produce a global estimate of the diversity of freshwater fish migratory life histories that would be of great benefit to fisheries researchers worldwide.

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CONFLICT OF INTEREST

We have no conflict of interest to disclose.

DATA AVAILABILITY STATEMENT

The database and associated metadata that support the findings of this study are available as .csv files through the United States Geological Survey's ScienceBase; https://doi.org/10.5066/P9WDLLP0.

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REFERENCES

Acolas, M. L., & Lambert, P. (2016). Life histories of anadromous fishes. In P. Morais & F. Daverat (Eds.), *An introduction to fish migration* (pp. 55–77). CRC Press.

Addison, P. A., & Wilson, C. C. (2010). Matching management to biological scale: Connectivity among lacustrine brook trout populations. *North American Journal of Fisheries Management*, *30*, 1132–1142. https://doi.org/10.1577/M09-146.1

Baran, E., & Myschowoda, C. (2009). Dams and fisheries in the Mekong Basin. *Aquatic Ecosystem Health & Management*, *12*, 227–234. https://doi.org/10.1080/14634980903149902

Behnke, R. J. (2010). *Trout and salmon of North America*. Simon and Schuster.

Boettiger, C., Chamberlain, S., Temple Lang, D., Wainwright, P., & Cazelles, K. (2021). R interface to 'FishBase.' R package version 4.0.0. https://github.com/ropensci/rfishbase

Brink, K., Gough, P., Royte, J., Schollema, P. P., & Wanningen, H. (2018). *From sea to source 2.0.: Protection and restoration of fish migration in rivers worldwide*. World Fish Migration Foundation.

Carolsfeld, J., Harvey, B., Ross, C., & Baer, A. (2004). *Migratory fishes of South America: Biology, fisheries, and conservation status*. The World Bank.

Crossman, E. J. (1991). Introduced freshwater fishes: A review of the north American perspective with emphasis on Canada. *Canadian Journal of Fisheries and Aquatic Sciences*, *48*, 46–57. https://doi.org/10.1139/f91-303

Daniel, W. M., Infante, D. M., Hughes, R. M., Tsang, Y. P., Esselman, P. C., Wieferich, D., Herreman, K., Cooper, A. R., Wang, L., & Taylor, W. W. (2015). Characterizing coal and mineral mines as a regional source of stress to stream fish assemblages. *Ecological Indicators*, *50*, 50–61. https://doi.org/10.1016/j.ecolind.2014.10.018

Deinet, S., Scott-Gatty, K., Rotton, H., Twardek, W. M., Marconi, V., McRae, L., Baumgartner, L. J., Brink, K., Claussen, J. E., Cooke, S. J., Darwall, W., Eriksson, B. K., Garcia de Leaniz, C., Hogan, Z., Royte, J., Silva, L. G. M., Thieme, M. L., Tickner, D., Waldman, J., … Weyl, O. L. F. (2020). *The living planet index (LPI) for migratory freshwater fish*. World Fish Migration Foundation.

Dingle, H. (1986). Ecology and evolution of migration. In S. A. Gauthreaux, Jr. (Ed.), *Animal migration, orientation, and navigation* (pp. 1–101). Academic Press.

Dingle, H., & Drake, V. A. (2007). What is migration? *Bioscience*, *57*, 113–121. https://doi.org/10.1641/B570206

Duponchelle, F., Isaac, V. J., Rodrigues Da Costa Doria, C., Van Damme, P. A., Herrera-R, G. A., Anderson, E. P., Cruz, R. E. A., Hauser, M., Hermann, T. W., Agudelo, E., Bonilla-Castillo, C., Barthem, R., Freitas, C. E. C., Garcia-Davila, C., Garcia-Vasquez, A., Renno, J.-F., & Castello, L. (2021). Conservation of migratory fishes in the Amazon basin. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *31*, 1087–1105. https://doi.org/10.1002/aqc.3550

Dzul, M. C., Kendall, W. L., Yackulic, C. B., Winkelman, D. L., Van Haverbeke, D. R., & Yard, M. D. (2021). Partial migration and spawning movements of humpback chub in the little Colorado River are better understood using data from autonomous PIT tag antennas. *Canadian Journal of Fisheries and Aquatic Sciences*, *78*, 1057–1073. https://doi.org/10.1139/cjfas-2020-0291

Espinosa-Pérez, H., & Ramírez, M. (2015). Exotic and invasive fishes in Mexico. *Check List*, *11*, 1. https://doi.org/10.15560/11.3.1627

Frimpong, E. A., & Angermeier, P. L. (2008). Fish traits database: USGS. https://www.sciencebase.gov/catalog/item/5a7c6e8ce4b00f54eb2318c0

Frimpong, E. A., & Angermeier, P. L. (2009). Fish traits: A database of ecological and life-history traits of freshwater fishes of the United States. *Fisheries*, *34*, 487–495. https://doi.org/10.1577/1548-8446-34.10.487

Froese, R., & Pauly, D. (2021). FishBase. https://www.fishbase.org/.

GBIF. (2021). GBIF Home Page. https://www.gbif.org.

Gido, K. B., Whitney, J. E., Perkin, J. S., & Turner, T. F. (2016). Fragmentation, connectivity, and fish species persistence in freshwater ecosystems. In G. P. Closs, M. Krkosek, & J. D. Olden (Eds.), *Conservation of freshwater fishes* (pp. 292–323). Cambridge University Press.

Gido, K. B., Propst, D. L., Whitney, J. E., Hedden, S. C., Pilger, T. J., & Turner, T. F. (2019). Pockets of resistance: Response of arid-land fish communities to climate, hydrology, and wildfire. *Freshwater Biology*, *64*, 761–777. https://doi.org/10.1111/fwb.13260

Gowan, C., Young, M. K., Fausch, K. D., & Riley, S. C. (1994). Restricted movement in resident stream salmonids: A paradigm lost? *Canadian Journal of Fisheries and Aquatic Sciences*, *51*, 2626–2637.

Gowan, C., & Fausch, K. D. (1996). Mobile brook trout in two high-elevation Colorado streams: Reevaluating the concept of restricted movement. *Canadian Journal of Fisheries and Aquatic Sciences*, *53*, 1370–1381.

Holmlund, C. M., & Hammer, M. (1999). Ecosystem services generated by fish populations. *Ecological Economics*, *29*, 253–268. https://doi.org/10.1016/S0921-8009(99)00015-4

Hodge, B. W., Wilzbach, M. A., Duffy, W. G., Quiñones, R. M., & Hobbs, J. A. (2016). Life history diversity in Klamath River steelhead. *Transactions of the American Fisheries Society*, *145*, 227–238. https://doi.org/10.1080/00028487.2015.1111257

Huckins, C. J., Baker, E. A., Fausch, K. D., & Leonard, J. B. (2008). Ecology and life history of coaster brook trout and potential bottlenecks in their rehabilitation. *North American Journal of Fisheries Management*, *28*, 1321–1342. https://doi.org/10.1577/M05-191.1

ITIS. (2021). The integrated taxonomic information system. https://www.itis.gov/. https://doi.org/10.5066/F7KH0KBK

IUCN. (2021). The IUCN red list of threatened species. Version 2021-1. https://www.iucnredlist.org/.

Januchowski-Hartley, S. R., Jézéquel, C., & Tedesco, P. A. (2019). Modelling built infrastructure heights to evaluate common assumptions in aquatic conservation. *Journal of Environmental Management*, *232*, 131–137. https://doi.org/10.1016/j.jenvman.2018.11.040

Jelks, H. L., Walsh, S. J., Burkhead, N. M., Contreras-Balderas, S., Diaz-Pardo, E., Hendrickson, D. A., Lyons, J., Mandrak, N. E., McCormick, F., Nelson, J. S., Plantania, S. P., Porter, B. A., Renaud, C. B., Schmitter-Soto, J. J., Taylor, E. B., & Warren Jr, M. L. (2008). Conservation status of imperiled north American freshwater and diadromous fishes. *Fisheries*, *33*, 372–407. https://doi.org/10.1577/1548-8446-33.8.372

Jenkins, R. E., & Burkhead, N. M. (1994). *Freshwater fishes of Virginia*. American Fisheries Society.

Lennox, R. J., Paukert, C. P., Aarestrup, K., Auger-Méthé, M., Baumgartner, L., Birnie-Gauvin, K., Boe, K., Brink, K., Brownscombe, J. W., Chen, Y., Davidsen, J. G., Eliason, E. J., Filous, A., Gillanders, B. M., Palm Helland, I., Horodysky, A. Z., Januchowski-Hartley, S. R., Lowerre-Barbieri, S. K., Lucas, M. C., ... Cooke, S. J. (2019). One hundred pressing questions on the future of global fish migration science, conservation, and policy. *Frontiers in Ecology and Evolution*, *7*, 1–16. https://doi.org/10.3389/fevo.2019.00286

Limburg, K. E., & Waldman, J. R. (2009). Dramatic declines in North Atlantic diadromous fishes. *Bioscience*, *59*, 955–965. https://doi.org/10.1525/bio.2009.59.11.7

Lucas, M. C., & Baras, E. (2001). *Migration of freshwater fishes*. Wiley-Blackwell.

McBride, R. S., & Matheson, R. E. (2011). Florida's diadromous fishes: Biology, ecology, conservation, and management. *Florida Scientist*, *74*, 187–213. www.jstor.org/stable/24321795

McDowall, R. M. (1988). *Diadromy in fishes: Migrations between freshwater and marine environments*. Croom Helm.

McDowall, R. M. (1997). The evolution of diadromy in fishes (revisited) and its place in phylogenetic analysis. *Reviews in Fish Biology and Fisheries*, *7*, 443–462. https://doi.org/10.1023/A:1018404331601

McDowall, R. M. (2003). Hawaiian biogeography and the islands' freshwater fish fauna. *Journal of Biogeography*, *30*, 703–710. https://doi.org/10.1046/j.1365-2699.2003.00851.x

McDowall, R. M. (2007a). Hawaiian stream fishes: The role of amphidromy in history, ecology, and conservation biology. *Bishop Museum Bulletin in Cultural and Environmental Studies*, *3*, 3–9.

McDowall, R. M. (2007b). On amphidromy, a distinct form of diadromy in aquatic organisms. *Fish and Fisheries*, *8*, 1–13. https://doi.org/10.1111/j.1467-2979.2007.00232.x

McIntyre, P. B., Liermann, C. R., Childress, E., Hamann, E. J., Hogan, J. D., Januchowski-Hartley, S. R., Koning, A. A., Neeson, T. M., Oele, D. L., & Pracheil, B. M. (2016). Conservation of migratory fishes in freshwater ecosystems. In G. P. Closs, M. Krkosek, & J. D. Olden (Eds.), *Conservation of freshwater fishes* (pp. 324–360). Cambridge University Press.

McPhail, J. F., & Lindsey, C. C. (1970). *Freshwater fishes of northwestern Canada and Alaska*. Fisheries Research Board of Canada.

Meek, A. (1916). *The migration of fish*. Edward Arnold.

Miller, R. R., Minckley, W. L., & Mark, S. M. (2005). *Freshwater fishes of Mexico*. The University of Chicago Press.

Morais, P., & Daverat, F. (2016). *An introduction to fish migration*. CRC Press.

Musick, J. A., Harbin, M. M., Berkeley, S. A., Burgess, G. H., Eklund, A. M., Findley, L., Gilmore, R. G., Golden, J. T., Ha, D. S., Huntsman, G. R., McGovern, J. C., Parker, S. J., Poss, S. G., Schmidt, T. W., Sedberry, G. R., Weeks, H., & Wright, S. G. (2000). Marine, estuarine, and diadromous fish stocks at risk of extinction in North America (exclusive of Pacific salmonids). *Fisheries*, *25*, 6–30.

Myers, G. S. (1949). Usage of anadromous, catadromous and allied terms for migratory fishes. *Copeia*, *1949*, 89–97.

Northcote, T. G. (1978). Migratory strategies and production in freshwater fishes. In S. D. Gerking (Ed.), *Ecology of freshwater fish production* (pp. 326–359). Blackwell Scientific Publications.

Northcote, T. G. (1984). Mechanisms of fish migrations in rivers. In J. D. McCleave, G. P. Arnold, J. J. Dodson, & W. H. Neill (Eds.), *Mechanisms of migration in fishes* (pp. 317–355). Springer.

Northcote, T. G. (1997). Potamodromy in Salmonidae—Living and moving in the fast lane. *North American Journal of Fisheries Management*, *17*, 1029–1045. https://doi.org/10.1577/1548-8675(1997)017<1029:PISAMI>2.3.CO;2

Paez, A. (2017). Gray literature: An important resource in systematic reviews. *Journal of Evidence-Based Medicine*, *10*, 233–240. https://doi.org/10.1111/jebm.12266

Page, L. M. (1983). *Handbook of Darters*. TFH Publications.

Pennock, C. A., Cathcart, C. N., Hedden, S. C., Weber, R. E., & Gido, K. B. (2018). Fine-scale movement and habitat use of a prairie stream fish assemblage. *Oecologia*, *186*, 831–842. https://doi.org/10.1007/s00442-018-4073-y

Pennock, C. A., McKinstry, M. C., & Gido, K. B. (2020). Razorback sucker movement strategies across a river-reservoir habitat complex. *Transactions of the American Fisheries Society*, *149*, 620–634. https://doi.org/10.1002/tafs.10262

Pennock, C. A., McKinstry, M. C., Cathcart, C. N., Gido, K. B., Francis, T. A., Hines, B. A., MacKinnon, P. D., Hedden, S. C., Gilbert, E. I.,

Cheek, C. A., Speas, D. W., Creighton, K., Elverud, D. S., & Schleicher, B. J. (2020). Movement ecology of imperiled fish in a novel ecosystem: River-reservoir movements by razorback sucker and translocations to aid conservations. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *30*, 1540–1551. https://doi.org/10.1002/aqc.3399
R Core Team. (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/
Riede, K. (2004). Global register of migratory species (GROMS): From global to regional scales: Final report of the R&D-Projekt 808 05 081. Federal Agency for Nature Conservation. http://www.groms.de/
Ryther, J. H. (1997). *Anadromous brook trout: Biology, status, and enhancement*. Trout Unlimited.
Scharpf, C. (2021). Checklist of freshwater fishes of North America, including subspecies and undescribed forms. http://www.nanfa.org/checklist.shtml
Scott, W. B., & Crossman, E. J. (1973). *Freshwater fishes of Canada*. Galt House Publications.
Tedesco, P. A., Beauchard, O., Bigorne, R., Blanchet, S., Buisson, L., Conti, L., Cornu, J. F., Dias, M. S., Grenouillet, G., Hugueny, B., Jézéquel, C., Leprieur, F., Brosse, S., & Oberdorff, T. (2017). A global database on freshwater fish species occurrence in drainage basins. *Scientific Data*, *4*, 1–6. https://doi.org/10.1038/sdata.2017.141
Thurow, R. F. (2016). Life histories of potadromous fishes. In P. Morais & F. Daverat (Eds.), *An introduction to fish migration* (pp. 29–54). CRC Press.
USGS. (2019). Nonindigenous Aquatic Species Database. http://nas.er.usgs.gov/.
Van Puijenbroek, P. J., Buijse, A. D., Kraak, M. H., & Verdonschot, P. F. (2019). Species and river specific effects of river fragmentation on European anadromous fish species. *River Research and Applications*, *35*, 68–77. https://doi.org/10.1002/rra.3386
Warren, M. L., Angermeier, P. L., Burr, B. M., & Haag, W. R. (1997). Decline of a diverse fish fauna: Patterns of imperilment and protection in the southeastern United States. In G. W. Benze & D. E. Collins (Eds.), *Aquatic fauna in peril: The southeastern perspective* (pp. 105–164). Lenz Design & Communications.
Whitney, J. E., Gido, K. B., Martin, E. C., & Hase, K. J. (2016). The first to arrive and the last to leave: Colonization and extinction dynamics of common and rare fishes in intermittent prairie streams. *Freshwater Biology*, *61*, 1321–1334. https://doi.org/10.1111/fwb.12668
Whitney, J. E., Gido, K. B., Hedden, S. C., Macpherson, G. L., Pilger, T. J., Propst, D. L., & Turner, T. F. (2017). Identifying the source population of fish re-colonizing an arid-land stream following wildfire-induced extirpation using otolith microchemistry. *Hydrobiologia*, *797*, 29–45. https://doi.org/10.1007/s10750-017-3143-1

BIOSKETCH

The authors represent a diverse group of researchers and managers who collectively work on conservation and management of freshwater fishes. The focus of the group was to develop a comprehensive database that detailed the migratory life histories of freshwater migratory fishes in North America.

Author Contributions: Emily M. Dean developed the database approach and compiled the data; Arthur R. Cooper, Lizhu Wang, Wesley Daniel, Solomon David, Clayton Ernzen, Keith B. Gido, Edward Hale, Tim J. Haxton, William Kelso, Nancy Leonard, Chris Lido, Joseph Margraf, Michael Porter, Casey Pennock, David Propst, Jared Ross, Michelle D. Staudinger, and Gary Whelan reviewed the database for accuracy and completeness; Emily M. Dean summarized the data; and Emily M. Dean led the writing with assistance from Dana M. Infante and Arthur R. Cooper.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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