Effects of Eurasian watermilfoil (*Myriophyllum spicatum*) on North American fishes

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ABSTRACT

Macrophytes serve as habitat to many fish species. The establishment of Eurasian watermilfoil (EWM; *Myriophyllum spicatum*) can change the macrophyte community of a waterbody, leading to a cascade of abiotic and biotic alterations that ultimately change fish communities and demographics. Given the potential negative effects of EWM, we reviewed the literature to describe the effects of EWM on fishes in North America and sought to provide fisheries managers with a summary of these effects. Overall, EWM may have a positive effect on black crappie (*Pomoxis nigromaculatus*), pumpkinseed sunfish (*Lepomis gibbosus*), and yellow perch (*Perca flavescens*), whereas it appears to have a negative effect on largemouth bass (*Micropterus nigricans*), bluegill (*Lepomis macrochirus*), and white crappie (*Pomoxis annularis*). Although largemouth bass and bluegill are relatively well represented in the literature, there is a general lack of information on the effects of EWM on other fish species. In addition, studies are typically limited to the upper midwestern portion of the United States and in lakes or reservoirs. The table presented in this paper provides fisheries managers with a quick way to understand the potential effects of EWM on species of concern as well as an understanding of the current state of the literature. Addressing existing gaps in the literature would be helpful to fisheries managers concerned about an EWM invasion or dealing with established EWM.

Key words: fish demographics, invasive, macrophyte, management

INTRODUCTION

Macrophytes are an important habitat component to a variety of fishes (Killgore et al. 1989, Diehl and Kornijów 1998, Radomski and Goemen 2001). Their structure and richness affect fish assemblage composition and species abundance (Brazner and Beals 1997). In addition to the diverse habitat that macrophytes can provide for fish, they provide food in the form of plant matter and associated periphyton and invertebrates. Areas with macrophytes have greater fish densities and lower predation risk and are used by structure-oriented species (Dibble et al. 1996).

Eurasian watermilfoil (EWM; *Myriophyllum spicatum*) is an invasive macrophyte native to Europe, Asia, and northern Africa (Patten 1954) that represents a threat to aquatic ecosystems in North America and elsewhere. It was documented in North America as early as the 1880s in New York and Virginia (USGS 2023), and in Canada, EWM was first documented in 1961 (Aiken et al. 1979). Since these events, EWM has continued to expand its presence in both countries. Currently EWM is found across the contiguous United States (except Wyoming), in at least three Canadian provinces, and in Mexico, with strong presence in the Columbia River, Mississippi River, and St. Lawrence River watersheds (Figure 1; USGS 2023, GBIF 2024).

EWM can spread by stolons and fragmentation (Madsen et al. 1988) and when not treated can expand from isolated plants (Boylen et al. 1999). The establishment of EWM can lead to changes in water quality like reduced dissolved oxygen (Keast 1984, Frodge et al. 1995, Unmuth et al. 2000) and chlorophyll (Drenner et al. 1998), increased surface water temperature (Unmuth et al. 2000), and mobilization of phosphorus (Barko and Smart 1980, Smith and Adams 1986). In addition to water quality effects, EWM has the potential to replace native macrophytes (Nichols and Mori 1971, Smith and Barko 1990, Madsen et al. 1991, Boylen et al. 1999, Verhoeven et al. 2020) reducing macrophyte species richness (Weaver et al. 1997) and diversity (Newroth 1993). When replacement leads to a reduction in habitat complexity, it tends to be unfavorable to fish species diversity (Smokorowski and Pratt 2007), and the conversion to a new dominant macrophyte could ultimately result in changes to food web dynamics (Wilson and Ricciardi 2009). Although EWM can be treated, eradication is difficult, and treatment against EWM can lead to negative effects on native macrophyte species (Mikulyuk et al. 2020) and fishery-level effects (Bryan and Scarnecchia 1992) such as reduced fish abundance (Whitfield 1984, Bettoli et al. 1993). For these reasons, fisheries managers are concerned when EWM is discovered in a waterbody.

Given the fisheries management challenges EWM presents, being ubiquitous in much of the United States, and its presence spreading throughout North America, we see a need for consolidated information regarding the effects of EWM on fishes. This paper is not a comprehensive EWM literature review (see Grace and Wetzel 1978, Aiken et al. 1979, Barko et al. 1986, Nichols and Shaw 1986, Smith and Barko 1990 for previous reviews of EWM literature and Hussner et al. 2017 for a review of aquatic macrophyte treatment techniques). Rather, we review and summarize the salient literature describing the effects of EWM on fishes in North America, provide a look-up table that lists EWM

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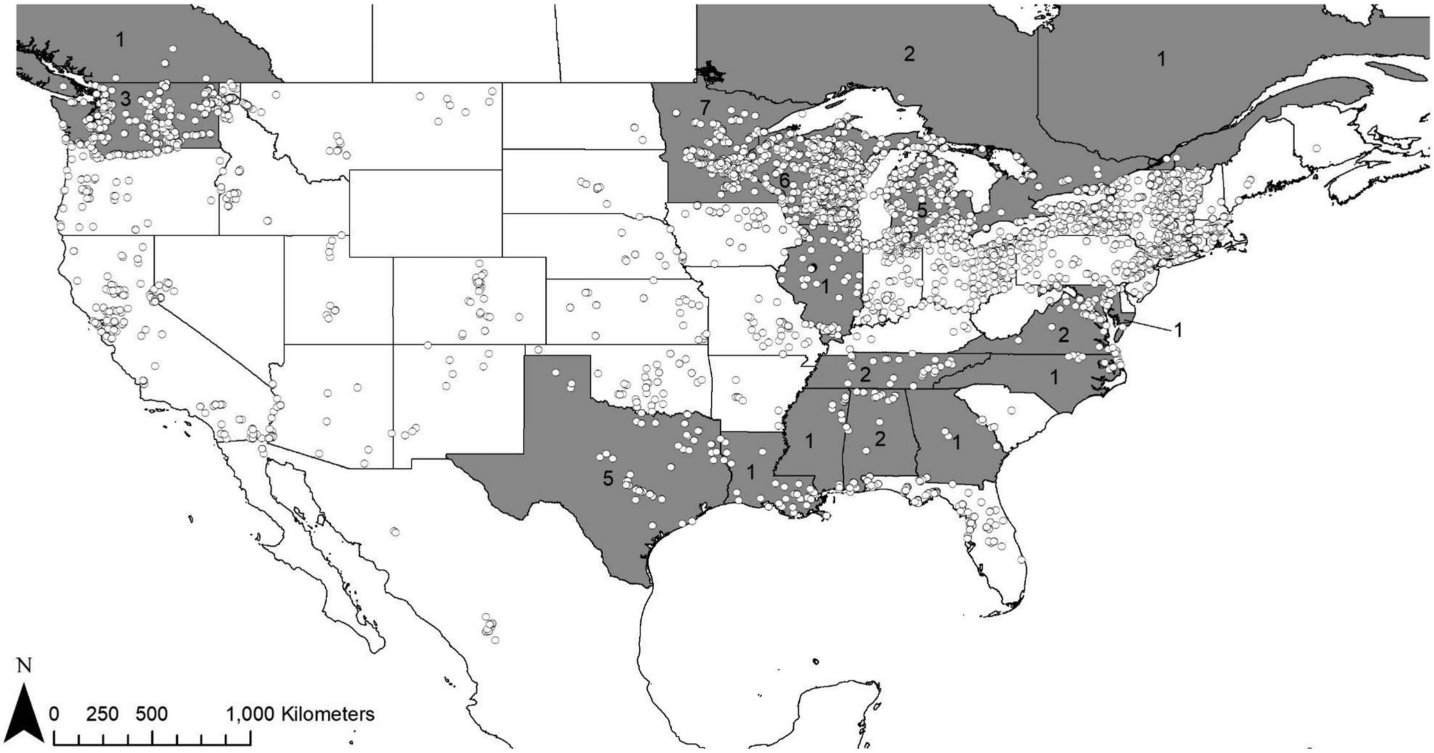

Figure 1. States and provinces with studies (shaded in gray) used to develop Table 1. Bold numbers indicate the number of studies that occurred within that jurisdiction. The black and white points represent EWM observations (United States and Canada [USGS 2023], Mexico; GBIF 2024).

effects on demographics by species, and identify areas where EWM effects on fishes is lacking in the literature.

MATERIALS AND METHODS

To develop this paper, we performed a Google Scholar search for "fish Eurasian watermilfoil" and examined the first 100 citations for relevance and potential review. Relevant citations encountered during this process were also reviewed. We stopped checking search results for relevance and review at 100 because at that point we were no longer finding additional relevant citations.

The demographic categories examined in this paper were based on shared descriptions within the individual studies reviewed (e.g., abundance, size structure, habitat use) and are important to understand when managing fisheries. Each category was assigned an effect as to how the authors stated or *P*-value indicated it was affected by EWM in each study. *P*-values used to indicate significance were study specific and stated as either 0.05 or 0.10. Effects could be negative (−; e.g., reduced abundance), positive (+; e.g., increased growth), no effect (0; e.g., no change in survival), or effect observed but not assigned as negative or positive (ENA; e.g., there was a shift in diet, but the effect of this shift was not evaluated). In addition, a category could be given multiple effects because of multiple life stages, seasons, or methods having different results (e.g., electrofishing demonstrated a higher abundance whereas seines resulted in a lower abundance).

The overall effect of EWM on largemouth bass (*Micropterus nigricans*), bluegill (*Lepomis macrochirus*), yellow perch (*Perca flavescens*), pumpkinseed (*Lepomis gibbosus*), black crappie (*Pomoxis nigromaculatus*), and white crappie (*Pomoxis annularis*) was evaluated for each of these species individually. These popular North American sportfish species had at least three studies that encompassed multiple waterbodies and demographic categories. To evaluate the overall effect of EWM, we compared the percentage of negative and positive effects across the evaluated demographic categories for a species. For example, an increase in catch per unit effort as EWM increased would be considered one positive effect for fish abundance, and a decrease in mean length at a given age would be considered one negative effect for size structure. Overall effect of EWM was considered slight (positive or negative) if the absolute difference between negative and positive effects was 1–10%, moderate if 11–20%, and strong if $> 20\%$. Finally, results are organized in Table 1 alphabetically by species in descending order of the number of studies pertaining to each.

RESULTS AND DISCUSSION

We reviewed more than 300 papers through our literature search and found 40 field studies involving the effects of EWM on 70 species, six groups of fishes, and two hybrids suitable to develop Table 1. The most common fish species evaluated were largemouth bass (19 studies), bluegill (18 studies), yellow perch (eight studies), black crappie (six studies), and pumpkinseed sunfish (six studies). Forty-nine fish groups were evaluated in a single study and 13 were evaluated in two studies. Twelve demographic categories were observed in the literature with the most common being

TABLE 1. OBSERVED EFFECTS OF EWM ON THE DEMOGRAPHICS OF FISHES IN NORTH AMERICA. FISHES ARE LISTED ALPHABETICALLY IN DESCENDING ORDER BASED ON THE NUMBER OF STUDIES EVALUATING EFFECTS. − = NEGATIVE EFFECT, + = POSITIVE EFFECT, 0 = NO EFFECT, ENA = EFFECT OBSERVED BUT NOT ASSIGNED AS NEGATIVE OR POSITIVE.

Species or group	Categories	Effect	Location	Citation
Largemouth bass, *Micropterus nigricans*	Feeding, growth	−/0[a], −	Lake Conroe (reservoir), Texas	Bettoli et al. 1992[b,c,d]
	Abundance, biomass, density, size structure	+/0[a], 0, +, ENA	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
	Feeding, growth	0, −/0[a]	Big Crooked, Big Seven, Camp, Clear, Heron, and Lobdell lakes, Michigan	Bremigan et al. 2005[b,c]
	Growth, reproduction, size structure, survival	−, −, −, +	Lake Seminole (reservoir), Georgia	Brown and Maceina 2002[b,d,e]
	Biomass, density	0, 0	Currituck Sound (estuary), North Carolina	Borawa et al. 1979[b,f]
	Feeding	ENA	Experimental pond, Texas	Dibble and Harrel 1997
	Feeding, growth	0, −/0[a]	Bass, Big Crooked, Big Seven, Camp, Clear, Heron, Lobdell, and Wolverine lakes, Michigan	Hanson 2001[c]
	Abundance, habitat use	0, 0	Lake Opicon, Ontario	Keast 1984[b,f]
	Abundance	−/+/0[a]	Potomac River (estuary), Virginia and Maryland	Killgore et al. 1989[b,d]
	Feeding	0	Auburn, Bush, Pierson, and Zumbra lakes, Minnesota	Kovalenko and Dibble 2011[b]
	Feeding	0	Auburn, Bush, Pierson, and Zumbra lakes, Minnesota	Kovalenko and Dibble 2014
	Habitat use	+	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
	Abundance, growth	+/0[a], −	Loomis Lake, Washington	Parsons et al. 2009[b,c]
	Abundance, size structure	−, −	Matoon Lake, Washington	Parsons et al. 2011[b,c]
	Abundance, growth, feeding	0, −, −/0/ENA[a]	Auburn, Bush, Cedar, Parkers and Zumbra lakes, Minnesota	Pothoven et al. 1999[b,c]
	Growth	0	13 lakes, Wisconsin	Olson et al. 1998[b,c]
	Abundance, growth, size structure, survival	0, −/+/0[a], −, −/0[a]	Fish Lake, Wisconsin	Unmuth et al. 1999[b,c]
	Abundance	+	Chickamauga Reservoir, Tennessee	Scott 1993[b,f], cited by Dibble et al. 1996
	Growth	0	Bass, Big Crooked, Big Seven, Camp, Heron, and Lobdell lakes, Michigan	Valley and Bremigan 2002[c]
Bluegill, *Lepomis macrochirus*	Abundance, biomass, density	0, +, 0	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
	Size structure	−	Cedar Lake (reservoir), Illinois	Collingsworth and Kohler 2010[b]
	Feeding, growth	−/+[a], −/+[a]	Experimental ponds, Michigan	Crowder and Cooper 1982[b]
	Density	+/0[a]	Lake Pontchartrain (estuary), Louisiana	Duffy and Baltz 1998
	Abundance, habitat use	− /+/0[a], −	Lake Opicon, Ontario	Keast 1984[b,f]
	Abundance, density	+/0[a], 0	Potomac River (estuary), Virginia and Maryland	Killgore et al. 1989[b,d]
	Feeding	0	Auburn, Bush, Pierson, and Zumbra lakes, Minnesota	Kovalenko and Dibble 2011[b]
	Feeding	0	Auburn, Bush, Pierson, and Zumbra lakes, Minnesota	Kovalenko and Dibble 2014
	Feeding	0	Auburn, Bush, Pierson, and Zumbra lakes, Minnesota	Kovalenko et al. 2009[b,c]
	Habitat use	+	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
	Abundance, growth	−/+/0[a], −	Auburn, Bush, Cedar, Parkers and Zumbra lakes, Minnesota	Pothoven et al. 1999[b,c]
	Growth	−/0[a]	13 lakes, Wisconsin	Olson et al. 1998[b,c]
	Abundance	0	Auburn, Bush, Pierson, and Zumbra lakes, Minnesota	Slade et al. 2005[b]
	Abundance, growth, size structure, survival	0, +/0[a], −, −	Fish Lake, Wisconsin	Unmuth et al. 1999[b,c]
	Angler harvest or catch, size structure, survival	−/+/0[a], −, −/+[a]	Fish Lake, Wisconsin	Unmuth et al. 2001[b,c]
	Abundance	0	Bass, Big Crooked, Big Seven, Camp, Heron, and Lobdell lakes, Michigan	Valley and Bremigan 2002[c]
	Abundance	+	Lake Mendota, Wisconsin	Weaver et al. 1997[b]
	Feeding	0/ENA[a]	Auburn, Bush, Pierson, and Zumbra lakes, Minnesota	Webb et al. 2016[b,c]

Table 1. Continued.

Species or group	Categories	Effect	Location	Citation
Mixed spp.	Composition	ENA	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
	Biomass, density	+/0[a], +/0[a]	Currituck Sound (estuary), North Carolina	Borawa et al. 1979[b,f]
	Biomass, composition, density	−/+/0[a], −/+/0[a], 0	Lake Drouin, Quebec, Canada	Brind'Amour et al. 2005[b]
	Composition, density	−/+0/ENA[a], +/0[a]	Lake Pontchartrain (estuary), Louisiana	Duffy and Baltz 1998
	Abundance, composition, density, size structure	−/+/0[a], −/+/0[a], −/+[a], −/+/0[a]	Potomac River (estuary), Virginia and Maryland	Killgore et al. 1989[b,d]
	Feeding	0	Auburn, Bush, Pierson, and Zumbra lakes, Minnesota	Kovalenko et al. 2009[b,c]
	Abundance, biomass, composition	0, 0, 0	Auburn, Bush, Pierson, and Zumbra lakes, Minnesota	Kovalenko et al. 2010[b,c]
	Feeding	ENA	Auburn, Bush, Pierson, and Zumbra lakes, Minnesota	Kovalenko and Dibble 2011[b]
	Abundance, biomass, composition, size structure	+/0[a], −/+[a], 0, 0	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
	Abundance, composition	−/+[a], −	Lake Mendota, Wisconsin	Lyons 1989[b,f]
	Abundance, composition	0, 0	Auburn, Bush, Pierson, and Zumbra lakes, Minnesota	Slade et al. 2005[b]
	Abundance, composition	+/ENA[a]	Lake Mendota, Wisconsin	Weaver et al. 1997[b]
Yellow perch, *Perca flavescens*	Biomass, density	0, +	Currituck Sound (estuary), North Carolina	Borawa et al. 1979[b,f]
	Abundance, habitat use	−/+/0[a], −/0[a]	Lake Opicon, Ontario	Keast 1984[b,f]
	Abundance, density	+/0[a], 0	Potomac River (estuary), Virginia and Maryland	Killgore et al. 1989[b,d]
	Habitat use	0	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
	Abundance, growth	+/0[a], −	Loomis Lake, Washington	Parsons et al. 2009[b,c]
	Abundance, size structure	+, −	Matoon Lake, Washington	Parsons et al. 2011[b,c]
	Abundance	+	Chickamauga Reservoir, Tennessee	Scott 1993[b,f], cited by Dibble et al. 1996
	Abundance	+	Lake Mendota, Wisconsin	Weaver et al. 1997[b]
Black crappie, *Pomoxis nigromaculatus*	Abundance, biomass, density	0, +, +	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
	Abundance, habitat use	+/0[a], 0	Lake Opicon, Ontario	Keast 1984[b,f]
	Habitat use	+	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
	Abundance, density, growth, size structure	0, 0, −/0[a], −	Lake Conroe (reservoir), Texas	Maceina et al. 1991[b,c,d]
	Abundance, angler harvest or catch	+, +/0[a]	Chickamauga Reservoir, Tennessee	McDonough and Buchanan 1991[b,f]
	Abundance	−	Lake Mendota, Wisconsin	Weaver et al. 1997[b]
Pumpkinseed sunfish, *Lepomis gibbosus*	Abundance	+	25 lakes, Ontario	Hinch and Collins 1993[b]
	Abundance, habitat use	+/0[a], −/0[a]	Lake Opicon, Ontario	Keast 1984[b,f]
	Abundance, density	+/0[a], 0	Potomac River (estuary), Virginia and Maryland	Killgore et al. 1989[b,d]
	Habitat use	+	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
	Abundance, growth	−/0[a], −	Loomis Lake, Washington	Parsons et al. 2009[b,c]
	Abundance, size structure	+, −	Matoon Lake, Washington	Parsons et al. 2011[b,c]
Golden shiner, *Notemigonus crysoleucas*	Biomass, density	0, 0	Currituck Sound (estuary), North Carolina	Borawa et al. 1979[b,f]
	Abundance, habitat use	+/0[a], 0	Lake Opicon, Ontario	Keast 1984[b,f]
	Abundance	+/0[a]	Potomac River (estuary), Virginia and Maryland	Killgore et al. 1989[b,d]
	Habitat use	+	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
	Abundance	+	Chickamauga Reservoir, Tennessee	Scott 1993[b,f], cited by Dibble et al. 1996
Sunfishes, *Lepomis* spp.	Density	+/0[a]	Cedar Lake (reservoir), Illinois	Collingsworth and Kohler 2010[b]
	Abundance	+	25 lakes, Ontario	Hinch and Collins 1993[b]
	Habitat use	+	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
	Density	−/+[a]	Aliceville Lake (reservoir), Alabama-Mississippi border	Miranda and Hodges 2000[b]
	Abundance	+	Chickamauga Reservoir, Tennessee	Scott 1993[b,f], cited by Dibble et al. 1996
Alewife, *Alosa pseudoharengus*	Abundance, habitat use	+/0[a], 0	Lake Opicon, Ontario	Keast 1984[b,f]
	Abundance density	+/0[a], 0		Killgore et al. 1989[b,d]

Table 1. Continued.

Species or group	Categories	Effect	Location	Citation
			Potomac River (estuary), Virginia and Maryland	
	Habitat use	0	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
Banded killifish, *Fundulus diaphanus*	Abundance	–	Lake Monona, Lake Wingra, and Pewaukee Lake, Wisconsin	Couch and Nelson 1985[b,f] cited by Lyons 1989
	Abundance density	+/0[a], +/0[a]	Potomac River (estuary), Virginia and Maryland	Killgore et al. 1989[b,d]
	Abundance	–	Lake Mendota, Wisconsin	Lyons 1989[b,f]
Brook silverside, *Labidesthes sicculus*	Abundance	+	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
	Abundance	0	Lake Mendota, Wisconsin	Lyons 1989[b,f]
	Abundance	+	Chickamauga Reservoir, Tennessee	Scott 1993[b,f], cited by Dibble et al. 1996
Bullheads, *Ameiurus* spp.	Biomass, density	0, 0	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
	Habitat use	+	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
	Abundance	–/+[a]	Lake Mendota, Wisconsin	Weaver et al. 1997[b]
Inland silverside, *Menidia beryllina*	Abundance	–	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
	Density	0	Lake Pontchartrain (estuary), Louisiana	Duffy and Baltz 1998
	Abundance, density	0, –/0[a]	Potomac River (estuary), Virginia and Maryland	Killgore et al. 1989[b,d]
Rock bass, *Ambloplites rupestris*	Abundance, habitat use	0,0	Lake Opicon, Ontario	Keast 1984[b,f]
	Habitat use	–	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
	Abundance	–	Lake Mendota, Wisconsin	Weaver et al. 1997[b]
Threadfin shad, *Dorosoma petenense*	Abundance, biomass, density, size structure	–, 0, 0, –	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
	Biomass, density	0, 0	Lake Conroe (reservoir), Texas	Maceina et al. 1991[b,c,d]
	Biomass, density	–, –	Lake Conroe (reservoir), Texas	Klussmann et al. 1988[b,c,d], cited by Maceina et al. 1991
White crappie, *Pomoxis annularis*	Abundance, biomass, density	+, +, +	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
	Abundance, density, growth, size structure	+, 0, –/0[a], –	Lake Conroe (reservoir), Texas	Maceina et al. 1991[b,c,d]
	Abundance, angler harvest or catch, survival	–/0[a], –/0[a], –/0[a]	Chickamauga Reservoir, Tennessee	McDonough and Buchanan 1991[b,f]
Bay anchovy, *Anchoa mitchilli*	Abundance	–/+/0[a]	Potomac River (estuary), Virginia and Maryland	Killgore et al. 1989[b,d]
	Density	+/0[a]	Lake Pontchartrain (estuary), Louisiana	Duffy and Baltz 1998
Blackchin shiner, *Notropis heterodon*	Abundance	–	Lake Monona, Lake Wingra, and Pewaukee Lake, Wisconsin	Couch and Nelson 1985[b,f] cited by Lyons 1989
	Abundance	–	Lake Mendota, Wisconsin	Lyons 1989[b,f]
Brown bullhead, *Ameiurus nebulosus*	Abundance, habitat use	0, –/0[a]	Lake Opicon, Ontario	Keast 1984[b,f]
	Abundance	+/0[a]	Potomac River (estuary), Virginia and Maryland	Killgore et al. 1989[b,d]
Channel catfish, *Ictalurus punctatus*	Abundance, biomass, density, size structure	–, –, –, ENA	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
	Abundance	–	Chickamauga Reservoir, Tennessee	Scott 1993[b,f], cited by Dibble et al. 1996
Common carp, *Cyprinus carpio*	Biomass, density	0, 0	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
	Biomass	0	Currituck Sound (estuary), North Carolina	Borawa et al. 1979[b,f]
Freshwater drum, *Aplodinotus grunniens*	Abundance	–	Lake Mendota, Wisconsin	Weaver et al. 1997[b]
	Abundance	–	Chickamauga Reservoir, Tennessee	Scott 1993[b,f], cited by Dibble et al. 1996
Gizzard shad, *Dorosoma cepedianum*	Abundance, biomass, density	–, 0, 0	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
	Abundance	0	Potomac River (estuary), Virginia and Maryland	Killgore et al. 1989[b,d]
Northern pike, *Esox lucius*	Abundance, habitat use	0, – /+/0[a]	Lake Opicon, Ontario	Keast 1984[b,f]
	Habitat use	0	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
Rainwater killifish, *Lucania parva*	Habitat use	+/0[a]	Mobile-Tensaw Delta (estuary), Alabama	Martin and Valentine 2011
	Density	+/0[a]	Lake Pontchartrain (estuary), Louisiana	Duffy and Baltz 1998
Smallmouth bass, *Micropterus dolomieu*	Habitat use	–	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
	Abundance	–	Lake Mendota, Wisconsin	Weaver et al. 1997[b]

TABLE 1. CONTINUED.

Species or group	Categories	Effect	Location	Citation
Spottail shiner, *Notropis hudsonius*	Abundance, density	0, 0	Potomac River (estuary), Virginia and Maryland	Killgore et al. 1989[b,d]
	Habitat use	–	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
White bass, *Morone chrysops*	Abundance	–	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
	Abundance	+	Lake Mendota, Wisconsin	Weaver et al. 1997[b]
White perch, *Morone americana*	Density	0	Currituck Sound (estuary), North Carolina	Borawa et al. 1979[b,f]
	Abundance, density	–/+/0[a], –/0[a]	Potomac River (estuary), Virginia and Maryland	Killgore et al. 1989[b,d]
American eel, *Anguilla rostrata*	Density	0	Potomac River (estuary), Virginia and Maryland	Killgore et al. 1989[b,d]
Atlantic menhaden, *Brevoortia tyrannus*	Abundance	–/0[a]	Potomac River (estuary), Virginia and Maryland	Killgore et al. 1989[b,d]
Blacknose shiner, *Notropis heterolepis*	Habitat use	–	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
Blacktail shiner, *Cyprinella venusta*	Abundance, biomass, density	–, –, –	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
Blueback herring, *Alosa aestivalis*	Density	–/0[a]	Potomac River (estuary), Virginia and Maryland	Killgore et al. 1989[b,d]
Bullhead minnow, *Pimephales vigilax*	Abundance, biomass, density	–, –, –	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
Centrarchids excluding large-mouth bass	Biomass, density	0, 0	Currituck Sound (estuary), North Carolina	Borawa et al. 1979[b,f]
Chinook salmon, *Oncorhynchus tshawytscha*	Feeding	0	Shuswap Lake, British Columbia, Canada	Hatfield 1996
Clown goby, *Microgobius gulosus*	Density	+/0[a]	Lake Pontchartrain (estuary), Louisiana	Duffy and Baltz 1998
Dollar sunfish, *Lepomis marginatus*	Abundance, biomass, density	0, +, +	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
Eurasian ruffe, *Gymnocephalus cernua*	Habitat use	–	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
Freshwater goby, *Gobionellus shufeldti*	Density	0	Lake Pontchartrain (estuary), Louisiana	Duffy and Baltz 1998
Golden topminnow, *Fundulus chrysotus*	Abundance	+	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
Goldfish, *Carassius auratus*	Abundance	0	Potomac River (estuary), Virginia and Maryland	Killgore et al. 1989[b,d]
Gulf pipefish, *Syngnathus scovelli*	Density	+/0[a]	Lake Pontchartrain (estuary), Louisiana	Duffy and Baltz 1998
Hogchoker, *Trinectes maculatus*	Density	0	Lake Pontchartrain (estuary), Louisiana	Duffy and Baltz 1998
Ictalurid spp.	Biomass, density	0, 0	Currituck Sound (estuary), North Carolina	Borawa et al. 1979[b,f]
Iowa darter, *Etheostoma exile*	Abundance	0	Lake Mendota, Wisconsin	Lyons 1989[b,f]
Johnny darter, *Boleosoma nigrum*	Habitat use	–	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
Longear sunfish, *Lepomis megalotis*	Biomass, density, size structure	0, +, –	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
Mosquitofish, *Gambusia affinis*	Density	+/0[a]	Potomac River (estuary), Virginia and Maryland	Killgore et al. 1989[b,d]
Mummichog, *Fundulus heteroclitus*	Density	0	Potomac River (estuary), Virginia and Maryland	Killgore et al. 1989[b,d]
Naked goby, *Gobiosoma bosc*	Density	+/0[a]	Lake Pontchartrain (estuary), Louisiana	Duffy and Baltz 1998
Northern pearl dace, *Margariscus nachtriebi*	Habitat use	0	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
Northern snakehead, *Channa argus*	Habitat use	+	Potomac River (estuary), Virginia	Lapointe et al. 2010[b]
Pinfish, *Lagodon rhomboides*	Density	0	Lake Pontchartrain (estuary), Louisiana	Duffy and Baltz 1998
Pumpkinseed sunfish × bluegill	Habitat use	0	Keweenaw Waterway, Michigan	Leguizamon 2017[b]

Table 1. Continued.

Species or group	Categories	Effect	Location	Citation
Redear sunfish, *Lepomis microlophus*	Abundance, biomass, density	+, 0, +	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
Sculpin, *Cottus* spp.	Habitat use	–	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
Silver redhorse, *Moxostoma anisurum*	Habitat use	0	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
Skilletfish, *Gobiesox strumosus*	Density	+/0[a]	Lake Pontchartrain (estuary), Louisiana	Duffy and Baltz 1998
Smallmouth buffalo, *Ictiobus bubalus*	Abundance	–	Chickamauga Reservoir, Tennessee	Scott 1993[b,f], cited by Dibble et al. 1996
Sockeye salmon, *Oncorhynchus nerka*	Juvenile rearing, reproduction	0, 0	Shuswap Lake, British Columbia, Canada	Hatfield 1996
Speckled worm eel, *Myrophis punctatus*	Density	+/0[a]	Lake Pontchartrain (estuary), Louisiana	Duffy and Baltz 1998
Spot, *Leiostomus xanthurus*	Density		Lake Pontchartrain (estuary), Louisiana	Duffy and Baltz 1998
Spotted gar, *Lepisosteus oculatus*	Abundance, biomass, density	0, +, +	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
Spotted seatrout, *Cynoscion nebulosus*	Density	0	Lake Pontchartrain (estuary), Louisiana	Duffy and Baltz 1998
Spotted sucker, *Minytrema melanops*	Abundance	–	Chickamauga Reservoir, Tennessee	Scott 1993[b,f], cited by Dibble et al. 1996
Spotted sunfish, *Lepomis punctatus*	Biomass, density	+, +	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
Steelhead, *Oncorhynchus mykiss*	survival	–/0[a]	Lake Washington, Washington	Frodge et al. 1995
Striped bass, *Morone saxatilis*	Density	0	Potomac River (estuary), Virginia and Maryland	Killgore et al. 1989[b,d]
Tessellated darter, *Etheostoma olmstedi*	Density	0	Potomac River (estuary), Virginia and Maryland	Killgore et al. 1989[b,d]
Trout-perch, *Percopsis omiscomaycus*	Habitat use	–	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
Walleye, *Sander vitreus*	Habitat use	0	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
Warmouth, *Lepomis gulosus*	Biomass, density	+, +	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
White bass × striped bass	Abundance	–	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
White sucker, *Catostomus commersonii*	Habitat use	0	Keweenaw Waterway, Michigan	Leguizamon 2017[b]
Yellow bass, *Morone mississippiensis*	Abundance	0	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]
Yellow bullhead, *Ameiurus natalis*	Biomass, density	0, 0	Lake Conroe (reservoir), Texas	Bettoli et al. 1993[b,c,d]

[a]Multiple effects due to multiple life stages, seasons, or methods having different results.
[b]EWM present in mixed stands of macrophytes.
[c]EWM removal/treatment study.
[d]Hydrilla, *Hydrilla verticillate*, was the dominant species.
[e]Study location within the range of Florida bass, *Micropterus salmoides* (Kim et al. 2022).
[f]EWM pre- versus postinvasion or while increasing in abundance.

abundance (i.e., catch per unit effort [e.g., fish per 5-min electrofishing or fish per 30 m of gill net]), density (i.e., number or catch per unit area), habitat use, and biomass (Table 1).

Studies typically took place on lakes or reservoirs ($n =$ 33), with two studies occurring on experimental ponds and five in estuaries. Studies occurred in 14 states and three Canadian provinces and were most common in Minnesota, Wisconsin, Michigan, and Texas (Figure 1). We did not observe any studies that occurred in Mexico. The greatest number of waterbodies were evaluated in Ontario, Canada ($n = 25$), Wisconsin ($n = 16$), Michigan ($n = 10$), and Minnesota ($n = 6$). Sixteen studies evaluated the effects of EWM removal on fishes, whereas six studies evaluated the effects of EWM pre- versus postinvasion or while EWM was increasing in abundance.

EWM appears to have a moderately positive effect on black crappie (38% positive vs. 19% negative) and yellow perch (39% positive vs. 22% negative), and a slightly positive effect on pumpkinseed sunfish (36% positive vs. 29% negative) with abundance and density influencing this effect (Table 1). In contrast, EWM appears to have a moderately negative effect on largemouth bass (17% positive vs. 35% negative), and a slightly negative effect on bluegill (29% positive vs. 31% negative) and white crappie (29% positive vs. 36% negative). Growth and size structure are leading this effect for bluegill and largemouth bass, whereas angler harvest or catch, growth, size structure, and survival are responsible for the effect on white crappie (Table 1). Individual *Lepomis* species (other than bluegill), mixed *Lepomis* communities, golden shiner (*Notemigonus crysoleucas*), and alewife predominantly experienced no effect or positive effects from EWM. In contrast, rock bass (*Ambloplites rupestris*), threadfin shad (*Dorosoma petenense*), channel catfish (*Ictalurus punctatus*), and smallmouth bass (*Micropterus dolomieu*) tended to experience negative effects.

Although we did observe some generalities, our review demonstrated that predicting the result of EWM establishment on a given fish species may be difficult considering the varied responses documented in the literature. For example, each of the six species with effect evaluation had demographic categories with negative, positive, and no effect from EWM. In addition, multiple studies documented a negative, positive, and no effect within the same demographic category (e.g., white perch [*Morone americana*; abundance], northern pike [*Esox lucius*; habitat use]) indicating that how a demographic is measured, and the age class evaluated can affect perceived effects. The lack of studies with similar goals and methods also inhibits interpretation of data in Table 1. For example, Bettoli et al. (1993) provided evidence that the presence of EWM can affect components of a fish assemblage; however, this was the only study to perform such an extensive assemblage evaluation.

Other than largemouth bass and bluegill, EWM effects data are lacking in the literature on most fish species actively managed in North America. We found both smallmouth bass and northern pike were addressed in only two studies; salmonid species were also evaluated in only two studies. EWM effects to non-gamefish species were also rarely studied. An additional gap in the data is a lack of study in rivers and run of river reservoirs, both common waterbody types that support popular fisheries. Although the upper Midwest is well represented in the literature, the remainder of the United States is poorly studied despite having relatively high densities of EWM observations in areas across the country. Both Canada and Mexico are also lacking data. Finally, most of the studies we reviewed assessed the effects of EWM removal; additional studies that evaluate fish demographics before versus after EWM establishment would be beneficial to fisheries managers.

Based on the observed effects of EWM on fishes, management of this macrophyte species is consequently management of the associated fishery (Engel 1995, Olson et al. 1998, Unmuth et al. 2001). However, given the literature available, we believe it is difficult at this time to reliably predict how EWM establishment or treatment will affect a given fishery. Others have identified the need for robust and reproducible monitoring, assessment at multiple spatial scales, and comprehensive modeling approaches to understand better invasive macrophyte establishment and fish habitat use (Dibble et al. 1996, Cross and McInerny 2005, Roley and Newman 2008, Schultz and Dibble 2012, Madsen and Wersal 2017, Radomski et al. 2019). We support these observations specifically regarding EWM and suggest that filling the fish species, waterbody type, and spatial data gaps identified in this review will help fisheries managers more effectively mitigate the challenges EWM introduction and establishment present.

SOURCES OF MATERIALS

All materials used to develop this paper are publicly available.

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