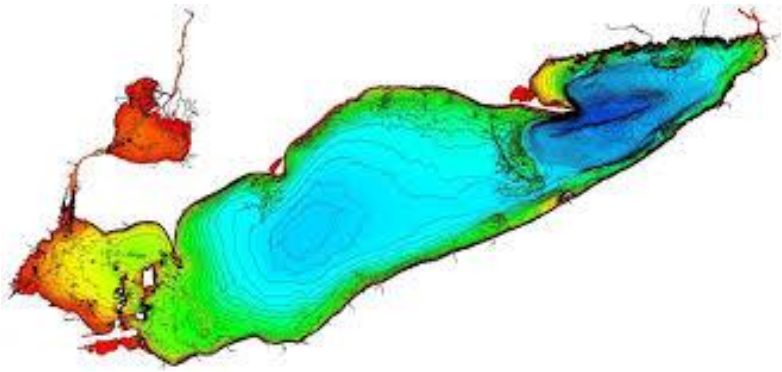
FISH COMMUNITY OBJECTIVES FOR THE LAKE ERIE BASIN



Fishery Management Document 2020-01

The Great Lakes Fishery Commission was established by the Convention on Great Lakes Fisheries between Canada and the United States, which was ratified on October 11, 1955. It was organized in April 1956 and assumed its duties as set forth in the Convention on July 1, 1956. The Commission has two major responsibilities: first, develop coordinated programs of research in the Great Lakes, and, on the basis of the findings, recommend measures that will permit the maximum sustained productivity of stocks of fish of common concern; second, formulate and implement a program to eradicate or minimize sea lamprey populations in the Great Lakes.

The Commission is also required to publish or authorize the publication of scientific or other information obtained in the performance of its duties. In fulfillment of this requirement the Commission publishes two types of documents, those that are reviewed and edited for citation indexing and printing and those intended for hosting on the Commission's website without indexing or printing. Those intended for citation indexing include three series: Technical Reports—suitable for either interdisciplinary review and synthesis papers of general interest to Great Lakes fisheries researchers, managers, and administrators, or more narrowly focused material with special relevance to a single but important aspect of the Commission's program (requires outside peer review); Special Publications—suitable for reports produced by working committees of the Commission; and Miscellaneous Publications—suitable for specialized topics or lengthy reports not necessarily endorsed by a working committee of the Commission. One series, Fishery Management Documents, is not suited for citation indexing. It is intended to provide a web-based outlet for fishery-management agencies to document plans or reviews of plans while forgoing technical review and style editing by Commission staff. Those series intended for citation indexing follow the style of the *Canadian Journal of Fisheries and Aquatic Sciences*. The style for Fishery Management Documents is at the discretion of the authors. Sponsorship of publications does not necessarily imply that the findings or conclusions contained therein are endorsed by the Commission.

Great Lakes Fishery Commission
2200 Commonwealth Blvd., Suite 100
Ann Arbor, MI 48105

FISH COMMUNITY OBJECTIVES FOR LAKE ERIE

James Francis[1], Travis Hartman[2], Kristopher Kuhn[3], Brian Locke[4], and Jason Robinson[5]

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[1]**J. Francis.** Michigan Department of Natural Resources, Waterford Fishery Station, 7806 Gale Road, Waterford, MI 48327, USA.
[2]**T. Hartman.** Ohio Division of Wildlife, 305 East Shoreline Drive, Sandusky, OH 44870, USA.
[3]**K. Kuhn.** Pennsylvania Fish and Boat Commission, 595 East Rolling Ridge Drive, Bellefonte, PA 16823, USA.
[4]**B. Locke.** Ontario Ministry of Natural Resources and Forestry, 320 Milo Road RR 2, Wheatley, ON N0P 2P0, Canada.
[5]**J. Robinson.** New York State Department of Environmental Conservation, 178 Point Drive North, Dunkirk, NY 14048, USA.
*Correspondence (e-mail: info@glfc.org).

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EXECUTIVE SUMMARY

Herein, the Lake Erie Committee (LEC) of the Great Lakes Fishery Commission presents its goal, vision, mission, and objectives for the fish community of the Lake Erie basin (i.e., Lake St. Clair, Lake Erie, and associated connecting waters). This document updates the LEC's original goals and objectives from 2003 informed by periodic assessments of progress toward achievement. The new goal and vision re-affirm the commitments of fishery-management agencies from Michigan, New York, Ohio, Ontario, and Pennsylvania to cooperatively attain shared objectives that support fish communities and desired fisheries of societal benefit and a healthy ecosystem in accordance with A Joint Strategic Plan for Management of Great Lakes Fisheries (Joint Plan) (GLFC 2007). The mission advocates the use of the best available science to make decisions and inform fishery management by these five agencies following tenets of the Joint Plan and eleven guiding principles, including support from key partner and stakeholder groups. Presented are eleven fish community objectives with their associated targets that guide LEC decisions involving intensively managed species (fish populations that support broadly distributed fisheries and the invasive Sea Lamprey) (Table 1), other managed species (fish populations that support localized fisheries), rehabilitation species (important species that lack self-sustaining populations), and prey fish (largely unfished and unmanaged populations of ecological importance to the fish community). Measures to facilitate evaluation of progress for each objective every five years through state-of-the-lake conferences and reports are identified. The fish community objectives in this document explicitly focus on species that contribute to a functional food web for a healthy and resilient Lake Erie ecosystem and that sustain desired fisheries.

Table 1. Common and scientific names of fish and invertebrates referenced in this report.

Common Name	Scientific Name
Alewife	*Alosa pseudoharengus*
Asian carps	*Hypophthalmichthys* spp.
Black Basses	*Micropterus* spp.
Blue Pike	*Sander vitreus glaucus*
Burbot	*Lota lota*
Channel Catfish	*Ictalurus punctatus*
Cisco	*Coregonus artedi*
Common carp	*Cyprinus carpio*
Freshwater Drum	*Aplodinotus grunniens*
Gizzard Shad	*Dorosoma cepedianum*
Lake Sturgeon	*Acipenser fulvescens*
Lake Trout	*Salvelinus namaycush*
Lake Whitefish	*Coregonus clupeaformis*
Muskellunge	*Esox masquinongy*
Northern Pike	*Esox lucius*
Rainbow Smelt	*Osmerus mordax*
Rainbow Trout	*Onchorhynchus mykiss*

Common Name	Scientific Name
Round Goby	*Neogobius melanostomus*
Sauger	*Sander canadense*
Sea Lamprey	*Petromyzon marinus*
Shiners	*Notropis* spp.
Smallmouth Bass	*Micropterus dolomieu*
Steelhead	*Oncorhynchus mykiss*
Walleye	*Sander vitreus*
White Bass	*Morone chrysops*
White Perch	*Morone americana*
Yellow Perch	*Perca flavescens*
Invertebrates	
Burrowing mayfly	*Hexagenia* spp.
Spiny water flea	*Bythotrephes longimanus*
Quagga mussel	*Dreissena bugensis*
Zebra mussel	*Dreissena polymorpha*

INTRODUCTION

For the purposes of this document, the Lake Erie basin includes Lake St. Clair, Lake Erie, and connecting waters, including the St. Clair River, Detroit River, and Upper Niagara River. The fish community of the Lake Erie basin supports valuable recreational and commercial fisheries in Canada and the United States. Fisheries-management responsibility in Lake Erie lies with the Michigan DNR, the New York State Department of Environmental Conservation, the Ohio DNR, the Ontario Ministry of Natural Resources and Forestry, and the Pennsylvania Fish and Boat Commission. These agencies cooperatively manage fisheries through the Lake Erie Committee (LEC) of the Great Lakes Fishery Commission in accordance with A Joint Strategic Plan for Management of Great Lakes Fisheries (Joint Plan) (GLFC 2007).

In the Joint Plan, a common goal statement was developed for all Great Lakes fishery-management agencies

> *To secure fish communities, based on foundations of stable self-sustaining stocks, supplemented by judicious plantings of hatchery-reared fish, and provide from these communities an optimum contribution of fish, fishing opportunities and associated benefits to meet needs identified by society for*
>
> *wholesome food,*
>
> *recreation,*
>
> *cultural heritage,*
>
> *employment and income, and*
>
> *a healthy aquatic ecosystem.*

Using this common goal statement, fisheries agencies of lake committees are committed to developing common fish community objectives (FCOs) with the means to assess progress periodically via state of Lake Erie (SOLE) conferences and reports. The process of setting FCOs and evaluating progress toward their attainment is intended to guide cooperative management decisions of LEC fisheries agencies. The initial Lake Erie FCOs (Ryan et al. 2003) addressed species of high fishery value and necessary habitats to support sustainable production of locally adapted native fish stocks. Evaluations from three SOLE conferences (2004, 2009, and 2014) indicated mixed progress toward the attainment of the original FCOs.

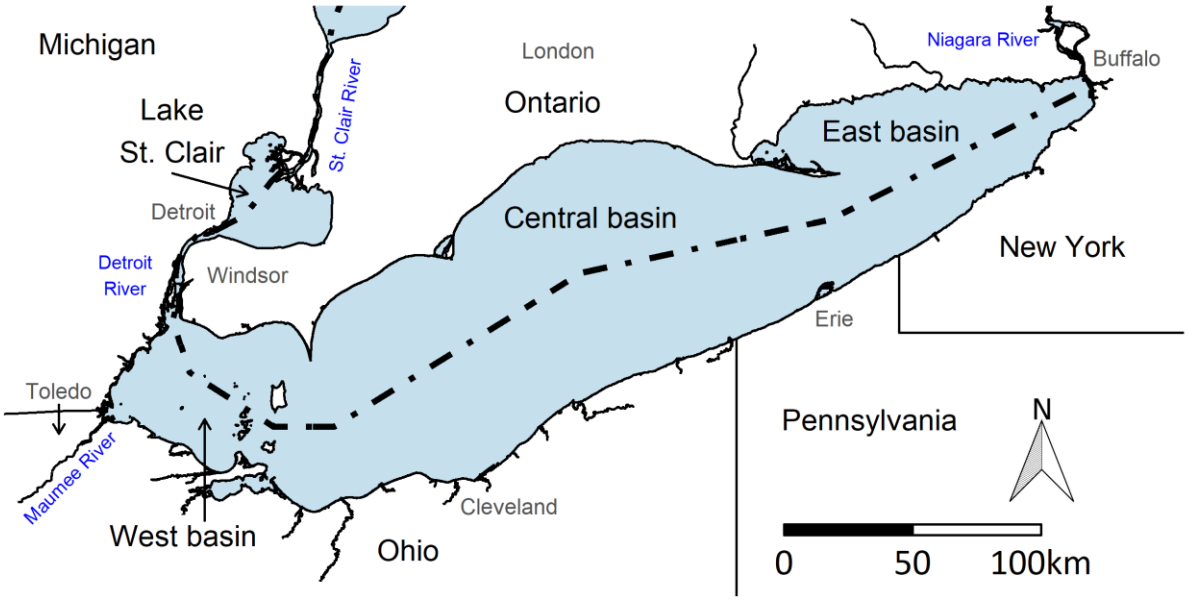
The revised FCOs in this document explicitly focus on species that contribute to a functional food web in a healthy Lake Erie ecosystem to support resilient ecosystems and sustainable desired fisheries with the implicit understanding that the entire ecosystem depends on appropriate environmental conditions and functional habitats. It follows that these new FCOs are informative for environmental managers setting priorities and determining project locations while working in the basin.

DESCRIPTION OF THE LAKE ERIE BASIN

The Lake Erie basin is specifically comprised of the open waters and major tributaries of the western basin, central basin, and eastern basin of Lake Erie; the St. Clair and Detroit River System (SCDRS) that consists of Lake St. Clair and its connecting waters with Lake Erie and Lake Huron; and the Upper Niagara River, the primary outlet from Lake Erie (Fig. 1). These areas lie predominantly within four states (Michigan, New York, Ohio, Pennsylvania) and the Province of Ontario.

Formed 3,500 to 12,000 years ago by glacial activity, Lake Erie is the southernmost, shallowest (19 m, average depth), and smallest by volume (484 km^3) of the five Laurentian Great Lakes (Bolsenga and Herdendorf 1993). Lake Erie's drainage area (77,519 km^2) to surface area (25,700 km^2) ratio of 3.0 is second only to Lake Ontario (3.4) among the Great Lakes (Robertson and Saad 2011). Average water residence time is only 2.6 years, the lowest among the Great Lakes (Quinn 1992). The lake's three basins (western, central, and eastern) differ in bathymetry, substrates, hydrology, and biological productivity, with a general gradient from shallow to deep moving eastward across the lake. Lake St. Clair has a surface area of 1,100 km^2, a volume of 3.4 km^3, an average depth of only 3.4 m, and average water residence time of only 7 days (Bolsenga and Herdendorf 1993).

Fig. 1. Map of the Lake Erie basin.



These features cause Lake St. Clair and Lake Erie to be more affected by short-term (<20 yr) fluctuations in climate and lake levels than most other Great Lakes (Quinn 1992). Lake Erie receives 80-90% of its inflow from the SCDRS, starting with flowage from Lake Huron through the St. Clair River into Lake St. Clair (where it forms the largest delta in the Great Lakes) and ending with flowage from the Detroit River into the western basin (Bolsenga and Herdendorf 1993). Water exits Lake Erie in the eastern basin primarily through the Upper Niagara River, which extends 35 km to Niagara Falls. Below the falls, it becomes the Lower Niagara River and flows 23 km into Lake Ontario.

Many tributaries flow into Lake Erie, most prevalently from U.S. jurisdictions. The 220 km Maumee River has the largest watershed (21,540 km^2) of any Great Lakes tributary (extending from Indiana and Michigan into Ohio) and accounts for about 5% of the lake's inflow. The Lake Erie basin contains 17 metropolitan areas of over 50,000 residents and about 12 million people overall, roughly one third of the total population in the Great Lakes basin (www.epa.gov/greatlakes/lake-erie). Accordingly, Lake Erie supports and can be affected by many societal uses throughout its watershed and open waters.

THE LAKE ERIE BASIN FISH COMMUNITY AND FISHERIES

The Lake Erie basin fish community has supported world-renowned freshwater fisheries for species of societal demand for over two centuries. Prior history of the basin's fish community and fisheries is well chronicled for the 1800s to the 1960s (Regier et al. 1969; Regier and Hartman 1973; others) and from the 1970s to the present (Schneider and Leach 1977; Hatch et al. 1987; Ludsin et al. 2001; Ryan et al. 2003; Vandergoot et al. 2019). Highly vegetated shallow areas, such as Lake St. Clair, support dominant esocid-centrarchid communities (MacLennan et al. 2003). Offshore fish communities are strongly influenced by thermal stratification, dissolved oxygen levels, bottom structure (reefs), and circulation patterns (gyres). Eutrophic conditions found in the western basin and nearshore areas are generally inhabited by warm-water predators, including Black Basses, White Perch, White Bass, Channel Catfish, Freshwater Drum, and a prey base dominated by Gizzard Shad and age-0 spiny-rayed fish, along with seasonal use by cool-water fish, such as Walleye and Yellow Perch. Mesotrophic areas of Lake Erie support cool-water fish communities of Walleye, Yellow Perch, Smallmouth Bass, Northern Pike, and Muskellunge, with a Shiner forage base. Oligotrophic offshore areas support cold-water salmonids (Lake Trout, Lake Whitefish, Steelhead) and Burbot, with a prey-fish assemblage dominated by Rainbow Smelt, Shiners, Alewife, and, historically, Cisco. Rainbow Smelt uniquely serves as an important prey fish and a species of fishery value (primarily commercial).

Walleye, Yellow Perch, Lake Whitefish, White Bass, and Rainbow Smelt have persisted as primary targets of commercial fisheries in the basin. In all jurisdictions, significant recreational fisheries focus on Walleye and Yellow Perch, with additional strong interest in White Bass, Black Basses, Muskellunge, Northern Pike, Rainbow Trout, Lake Trout, Channel Catfish, Lake Sturgeon, and other species. The commercial and recreational fisheries of the Lake Erie basin are among the most-valuable freshwater fisheries in the world, providing billions of dollars and thousands of jobs annually, a renewable source of protein, and diverse angling opportunities, collectively enhancing the overall quality of life to societies in the basin.

Although much of the fish community in the Lake Erie basin consists of healthy, reproducing, native species, some fish are not reproducing sufficiently and are supported through hatchery plantings. Native Lake Trout was extirpated from Lake Erie by the mid-1900s, and a population has been sustained since the 1980s only by plantings of non-Lake Erie strains coupled with Sea Lamprey control (Markham et al. 2008). Native Lake Sturgeon of the St. Clair River, Lake St. Clair, and Detroit River System (SCDRS) is one of the healthiest stocks of this species in the Great Lakes, but other historically important stocks in Lake Erie are absent or of low abundance. Restoration of a Maumee River stock of Lake Sturgeon was initiated with plantings in 2018. Non-native Steelhead and other salmonids provide localized recreational-fishing opportunities, primarily during seasonal spawning runs into tributaries but cannot reproduce sufficiently and require plantings to satisfy societal demand in the Lake Erie basin.

Habitats in the Lake Erie basin support self-sustaining resident and migratory fish stocks of fishery and ecological importance, along with a variety of prey fish and other species that contribute to a functional ecosystem. Nearshore fish communities organize around dynamic coastal habitats, such as wetlands, bays, rivers, and estuaries (Davies et al. 2005; Markham and Knight 2017).

MANAGEMENT OF THE LAKE ERIE BASIN FISH COMMUNITY

Sustaining a productive fish community with desired fishery benefits is complex and challenging for fishery managers in the Lake Erie basin (Roseman et al. 2008; Roseman et al. 2013). The basin's responsiveness to climatic events and impacts from anthropogenic disturbances affects fish-population dynamics and fishery performance. The permanent loss of native fish stocks and establishment of invasive species have resulted in an evolving food web that influences fish community structure. Societal activities in the basin affect environmental conditions and fish habitats through inputs of nutrients, sediments, chemicals, and unwanted organisms into the lake and through physical modifications of shorelands and watersheds. Governmental structures and processes differ among the five jurisdictions of the two countries in the basin and affect timely harmonization of cooperative management and enforcement actions to achieve common goals and objectives. Moreover, statutory management authority is diffuse and spread among environmental (land, water, invasive species) and fishery managers in the basin. Therefore, fishery managers focus primarily on managing fishing mortality and augmentation through fish stocking to achieve and maintain desired fish community structure.

Since its formation in 1965, the Lake Erie Committee (LEC) has developed and implemented various approaches to cooperatively manage fishing mortality on shared stocks in concert with major changes in environmental conditions over the decades. Formalized interagency quota management has been used for some species (Walleye, Yellow Perch) while less-formal approaches have been applied to fisheries on other shared stocks (Lake Whitefish, White Bass, Rainbow Smelt). Stocking has been used to boost restoration of naturally reproducing fish populations (Lake Trout, Lake Sturgeon) and to provide put-grow-take fisheries (Steelhead). Interagency task groups provide scientific information that is critical for the LEC decision-making process.

A formal interagency Lake Erie Percid Management Advisory Group and other approaches have been used to provide stakeholder input for LEC decisions. LEC agencies have worked with various environmental managers to address habitat protection and improvement in the basin, particularly through collaboration in the Lake Erie Partnership, to fulfill the binational Great Lakes Water Quality Agreement.

The LEC and its member agencies have also collaborated with various government groups and universities to prevent or minimize adverse impacts from invasive species on the fish community and fisheries in the basin. Sea Lamprey control has been administered binationally since the 1950s by the Great Lakes Fishery Commission in partnership with several federal agencies of each nation (Fisheries and Oceans Canada, U.S. Fish and Wildlife Service, U.S. Army Corps of Engineers) and remains essential for maintaining a fish community that supports highly valued fisheries. Other invasive organisms, such as Asian carps, Round Goby, and dreissenids, have also drawn LEC management and research attention (see LEC 2012, 2017a, 2018, 2019). To guide the management of Lake Erie fisheries, the LEC relies on the following updated goal and objectives.

GOAL STATEMENT

The Lake Erie Committee embraces the common goal statement in A Joint Strategic Plan for Management of Great Lakes Fisheries (GLFC 2007) and has developed the following vision, mission, guiding principles, and fish community objectives accordingly.

VISION FOR LAKE ERIE

The Lake Erie basin will consist of diverse fish communities that support ongoing societal benefits, including thriving commercial and recreational fisheries, improved fish habitat and desirable ecosystem performance, and reduced adverse impacts from invasive fish.

MISSION FOR MANAGING FISH STOCKS OF COMMON CONCERN

Agencies of the Lake Erie Committee (LEC) shall manage Lake Erie basin fisheries through science-based collaborative decision making for the benefit of society. The LEC uses consensus-based approaches identified in A Joint Strategic Plan for Management of Great Lakes Fisheries (GLFC 2007), coupled with interagency and university partnerships, stakeholder input, and the best available science, to achieve its vision.

GUIDING PRINCIPLES

The following principles identify core values common among fishery-management agencies of the Lake Erie Committee that guide the development of fish community objectives.

- Individual fish stocks (or populations) are the basic units for conservation and management and should, where feasible, be identified, monitored, and appropriately managed.
- Management and rehabilitation of native and desirable naturalized fish, including individual stocks where appropriate, should serve as the basis for sustainable use of Lake Erie fisheries.
- No agency will approve intentional introductions of non-native species without review by all other agencies on the Lake Erie Committee (LEC), a procedure consistent with A Joint Strategic Plan for Management of Great Lakes Fisheries (GLFC 2007).
- Protection, enhancement, and rehabilitation of critical fish habitat, including tributary and nearshore spawning and nursery habitats, are required to sustain productive fisheries over the long term.
- Rare indigenous fish species add to the richness of a fish community through their ecological importance and intrinsic value.
- Stocked fish can contribute to ecological function of the fish community, support the rehabilitation of native fish species, and provide put-grow-take fishing opportunities.
- Control of deleterious invasive fish (e.g., Sea Lamprey) is essential for proper management of Lake Erie basin fisheries.
- The amount of fish that can be produced and harvested from the Lake Erie basin has ecological limits; sustainable fishery management means working within these limits. Ecological shifts from factors like climate and invasive species affect population dynamics of targeted species, influencing fisheries performance and management options.
- There is an implicit understanding by the LEC agencies that the underlying ecosystem and food web are key components driving the productivity of desirable species.
- Stakeholders contribute critical biological, social, economic, and cultural information to fishery-management agencies in support of coordinated fisheries-management decision making. With decision making comes a duty by stakeholders to share accountability, benefits from the resource, and stewardship.

- The best available knowledge, science, information, and decision support tools are necessary for pragmatic decisions to sustainably manage fisheries.

LAKE ERIE BASIN FISH COMMUNITY OBJECTIVES

Fish community objectives establish the specific and/or clear targets guiding the Lake Erie Committee's (LEC) actions that ultimately support the LEC's vision and the goals in A Joint Strategic Plan for Management of Great Lakes Fisheries (GLFC 2007). The following fish community objectives have been organized into four groups that reflect the level of fishery influence and management. Intensively managed species include several fish populations that support broadly distributed fisheries as well as the invasive Sea Lamprey. Interagency harvest policies may be developed for high-value species that are the target of both commercial and recreational fisheries and that have the potential to impact the trajectory of population abundance. Other managed species include populations that support localized fisheries in the basin. Rehabilitation species are of potential ecological or fishery importance but currently lack self-sustaining populations. Prey fish include largely unfished and unmanaged populations of ecological importance to the fish community.

Intensively Managed Species

1. Objective: Maintain Walleye and Yellow Perch populations that support sustainable commercial and recreational fisheries.

   Status indicator: Maintain populations with sustainable levels of spawning-stock biomass and fisheries harvest consistent with species-specific management plans informed by science and stakeholder input.

2. Objective: Maintain a White Bass population that permits sustainable commercial and recreational exploitation.

   Status indicator: Maintain a population that is typically approximately 20% or more of the unfished spawning-stock biomass that can support sustainable annual lakewide commercial and recreational harvests, understanding that fluctuations will occur based on normal variation in the amount of fishery effort that is targeted towards White Bass.

3. Objective: Manage Lake Whitefish fishery harvest to ensure persistence in the system, recognizing increasingly challenging environmental conditions for this species.

   Status indicator: Maintain an adult Lake Whitefish population with a diverse age structure and spawner biomass above the historically low levels seen between 2014 and 2017.

4. Objective: Suppress abundance of Sea Lamprey to levels that will not impede achievement of any fish community objective, especially for coldwater species of low abundance.

   Status indicator: Reduce Sea Lamprey abundance to levels specified in the Sea Lamprey management plan administered by the Great Lakes Fishery Commission (Slade 2012).

Other Managed Species

1. Objective: Maintain a high-quality Black Bass fishery throughout the Lake Erie basin.

   Status indicator: Maintain catch rates at or above 0.5 fish per hour.

2. Objective: Maintain a high-quality trophy-sized Muskellunge fishery in the St. Clair and Detroit River System (SCDRS), the Upper Niagara River, and selected nearshore areas in Lake Erie.

   Status indicator: Maintain Muskellunge populations to sustain catch rates near the long-term average in selected areas of the system that have historically supported targeted fisheries.

3. Objective: Maintain a put-grow-take Steelhead fishery in suitable Lake Erie tributaries and incidentally in the open lake.

   Status indicator: Maintain tributary catch rates at or above 0.25 fish per hour, recognizing that performance in individual streams will vary.

Rehabilitation Species

1. Objective for Lake Trout: Establish a Lake Trout population consistent with a functional cold-water ecosystem that maintains a fishery in the eastern and central basins.

   Status indicator: Maintain viable adult spawning-stock biomass, as measured by survey catch per effort (see Markham et al. 2008) while maintaining and expanding existing fishing opportunities with a goal of documenting evidence of natural reproduction.

2. Objective for Lake Sturgeon: Support the preservation of existing spawning stock and rehabilitation of spawning stocks in historic spawning locations.

   Status indicator: Maintain or increase adult abundance in existing spawning sites (SCDRS, Upper Niagara River, and Buffalo Harbor) and establish an adult spawning stock in at least one new spawning location.

3. Objective for other species: The LEC acknowledges that other species of interest, such as Sauger and Cisco, may present rehabilitation opportunities, but environmental conditions and fish community status ultimately dictate the feasibility for each species (LEC 2017b, 2018). Any efforts to rehabilitate currently extirpated species should be carefully and collaboratively considered prior to implementation.

   Status indicator: To be determined as opportunities arise.

Prey Fish

1. Objective: Maintain a diverse, abundant prey-fish community that is capable of sustaining abundant warm-, cool-, and cold-water predators and that contributes to ecosystem function and sustainable human use. The LEC recognizes that it cannot directly manage prey-fish populations, even though they are essential to support the Lake Erie basin fisheries. The LEC especially values native prey species but recognizes that naturalized prey species can be an important part of the prey-fish community, predator diets, and targeted fisheries.

   Status indicator: Prey-fish populations support predator condition and growth rates near the long-term average.

THE LAKE ERIE BASIN ECOSYSTEM

The unique features of the Lake Erie basin create a variety of connected tributary, nearshore, and offshore habitats that support a diverse fish community. Inflows from the St. Clair and Detroit River System (SCDRS) and various tributaries interact with wind conditions and bathymetry to form gyres and currents that move nutrients and biota within and among basins (Bolsenga and Herdendorf 1993; Davies et al. 2005). Compared to the other Great Lakes, nearshore regions are highly prevalent in the Lake Erie basin with waters that typically do not thermally stratify in summer. Offshore regions with thermal stratification occur primarily in the central and eastern basins. Coastal wetlands and areas of submerged aquatic vegetation occur in many areas of the Lake Erie basin (e.g., Lake St. Clair, Point Pelee, Long Point, Rondeau Bay, others), but overall they are only a fraction of what existed historically (Kaatz 1955). Generally, nutrient conditions in the Lake Erie basin are the highest of the Great Lakes, with areas ranging from highly productive (eutrophic) regions near river mouths or urban areas to moderately productive (mesotrophic) pelagic waters, supporting warm- and cool-water fish communities, respectively. Nutrient levels of deep (>15 m) offshore areas are lower (oligotrophic) than in nearshore areas, supporting cold-water fish communities.

A variety of fish species entered the Lake Erie basin both during and following glacial periods. Stocks formed over time as fish adapted to various habitats, with many species depending on tributary or nearshore habitats for successful reproduction. Several stocks (Walleye, Lake Whitefish, White Bass, others) move seasonally among the three basins and through the SCDRS into Lake Huron, thereby contributing to the overall ecology of these lakes and to fisheries of multiple jurisdictions (MacLennan et al. 2003). Non-native fish were introduced into the lake after the late 1800s from a variety of pathways. Several of them have established naturalized populations owing to the availability of conducive habitats.

The Lake Erie basin is particularly responsive to weather-induced changes on environmental conditions (e.g., waves, currents, water clarity, water temperature, dissolved oxygen) that, in turn, affect the fish community and fishery. Prolonged periods of strong winds can cause scouring of reefs and other shallow areas, erosion of shorelines, movement of sediments, high turbidity, and seiche-driven changes in lake levels or thermocline stability affecting fish recruitment (Roseman et al. 2001; Steinhart 2004), fish behavior or distribution (Roberts et al. 2009), fish mortality (Rao et al. 2014), and fishery performance. Storm events drive nutrient loadings to Lake Erie via tributary flows, stimulate algal production (Scavia et al. 2014), increase sediment turbidity, and may directly affect fish recruitment (Mion et al. 1998). Extended periods of hot, calm weather can intensify the extent and duration of hypoxia in Lake Erie, particularly in the central basin. Severe winters can result in complete ice cover, affecting lake ecology and fisheries. Extended winters (i.e., cold springs) can affect recruitment for some species. Therefore, shifts in climate are expressed in the environmental conditions, habitats, fish communities, and fisheries of Lake Erie.

Given its unique features, the Lake Erie basin is appealing to societies but also responsive to societal influences. Shipping, recreational boating, tourism, and fisheries in the Lake Erie basin contribute billions of dollars annually. Currently, about 11 million people use Lake Erie as their primary source of drinking water (www.epa.gov/greatlakes/lake-erie). Numerous river mouths and harbors support a variety of benefits as transport access portals. These portals also provide pathways for the entry of non-native species, including harmful invasive organisms, and pathogens. Several non-native species are now prominent components of the basin ecosystem (e.g., Sea Lamprey, dreissenids, Round Goby, common carp) and fisheries (Rainbow Smelt, White Perch). Historically, Lake Erie has responded dramatically to changes in nutrient loadings from human activities and water-quality management efforts mediated by climate shifts that affect basin hydrology (Makarewicz and Bertram 1991; Ludsin et al. 2001; Vandergoot et al. 2019).

Phosphorus concentrations have been artificially increased in Lake Erie since the late 1990s owing to excessive loadings from agriculture and other land uses (Scavia et al. 2014), causing harmful algal blooms and contributing to hypoxic conditions in the central basin. Binational efforts of water-quality managers to regulate phosphorus flowing into Lake Erie have been made since the early 1970s and have continued to the present. Legacy and emerging contaminants from metropolitan areas continue to affect water quality and biota. Habitat degradation and fishery exploitation have historically contributed to the extirpation of several native fish stocks (Cisco, Blue Pike, Sauger, Lake Trout) and to dramatic reductions of other native species (Lake Sturgeon, Walleye, Lake Whitefish), although some stocks have recovered (Regier and Hartman 1973; Ryan et al. 2003; Vandergoot et al. 2019).

THE LAKE ERIE BASIN FOOD WEB

A functional aquatic food web transfers energy from dissolved nutrients (particularly phosphorus and nitrogen) and sunlight into fish biomass. Nutrients enter the Lake Erie basin from the watershed in particulate or dissolved forms and are deposited on the lake bottom for benthic processing or suspended in the water column for pelagic processing by various organisms. Nutrient processing is influenced by the types of biota and the environmental conditions (light, temperature, dissolved oxygen) in nearshore and offshore regions. Groups (e.g., trophic levels) of benthic and pelagic biota in the food web include primary producers (rooted plants or phytoplankton/algae) that grow via photosynthesis, primary consumers of producers (benthic macro-invertebrates like mollusks, crayfish, amphipods, burrowing mayfly, most zooplankton, and some prey fish), predators of primary consumers (amphibians/reptiles, some zooplankton, most prey fish, omnivorous fish), and top predators (fish, birds, reptiles) that primarily eat prey fish. The types and behaviors of predator and prey species affect processing rates and overall efficiency of energy transfer through the food web. Some predators have inherent preferences for certain species or sizes of prey while others are not selective or are omnivorous. Environmental conditions affect feeding behaviors of all organisms and, over time, drive shifts in species composition. A well-functioning food web in the Lake Erie basin consists of organisms in all trophic levels to facilitate benthic and pelagic processing of energy from nutrients through predator-prey interactions in concert with prevailing environmental conditions driven by weather (short-term) and climate shifts (long-term). Native species have filled these predator-prey roles well, given their coexistence and adaptations to the Lake Erie basin ecosystem over thousands of years.

The Lake Erie basin food web has undergone a massive and irreversible transformation since the late 1800s owing to changes in environmental conditions, the loss of key native fish stocks, and establishment of non-native species (Regier and Hartman 1973; Ryan et al. 2003). Degradation of nearshore areas and tributaries, along with overfishing, led to the demise of several stocks of native predators (Lake Trout, Sauger, Blue Pike, and Lake Sturgeon) and a key native planktivore and prey fish (Cisco). Other predators (Walleye, Yellow Perch, and Lake Whitefish) experienced major fluctuations in abundance during the 1900s (Regier and

Hartman 1973). The establishment of key non-native species began with common carp in the late 1800s, followed by Sea Lamprey and Rainbow Smelt (1920s), Alewife (1930s), White Perch (1970s), zebra mussels and spiny water fleas (1980s), and quagga mussels and Round Goby (1990s). These established species have persisted as important participants in the Lake Erie basin food web, serving as primary consumers (dreissenids), lower-level predators (spiny water fleas, Alewife, common carp, Rainbow Smelt, Round Goby, White Perch), prey fish (Rainbow Smelt, Round Goby, Alewife), and top predators (Sea Lamprey, adult White Perch). Filter-feeding dreissenids uniquely fill many roles in the food web. They eat phytoplankton, amplify nutrient concentrations in benthic habitats through excretion and cause a nearshore shunt of energy from offshore areas (Hecky et al. 2004), are prey for many fish (Round Goby, Freshwater Drum, Lake Whitefish, Yellow Perch, others), and act as an agent for contaminant and pathogen transfer to other organisms and trophic levels. Given the recent establishment of these non-native species compared to thousands of years of co-existence for native species, the capacity and efficiency of the modern Lake Erie basin food web to convert nutrients into desired fish biomass is still evolving.

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