Historically, Cisco Coregonus artedi and deepwater ciscoes Coregonus spp. were the most abundant and ecologically important fish species in the Laurentian Great Lakes, but anthropogenic influences caused nearly all populations to collapse by the 1970s. Fishery managers have begun exploring the feasibility of restoring populations throughout the basin, but questions regarding hatchery propagation and stocking remain. We used historical and contemporary stock-recruit parameters previously estimated for Ciscos in Wisconsin waters of Lake Superior, with estimates of age-1 Cisco rearing habitat (broadly defined as total ha ≤ 80 m depth) and natural mortality, to estimate how many fry (5.5 months post-hatch), fall fingerling (7.5 months post-hatch), and age-1 (at least 12 months post-hatch) hatchery-reared Ciscos are needed for stocking in the Great Lakes to mimic recruitment rates in Lake Superior, a lake that has undergone some recovery. Estimated stocking densities suggested that basin-wide stocking would require at least 0.641-billion fry, 0.469-billion fall fingerlings, or 0.343-billion age-1 fish for a simultaneous restoration effort targeting historically important Cisco spawning and rearing areas in Lakes Huron, Michigan, Erie, Ontario, and Saint Clair. Numbers required for basin-wide stocking were considerably greater than current or planned coregonine production capacity, thus simultaneous stocking in the Great Lakes is likely not feasible. Provided current habitat conditions do not preclude Cisco restoration, managers could maximize the effectiveness of available production capacity by concentrating stocking efforts in historically important spawning and rearing areas, similar to the current stocking effort in Saginaw Bay, Lake Huron. Other historically important Cisco spawning and rearing areas within each lake (listed in no particular order) include: (1) Thunder Bay in Lake Huron, (2) Green Bay in Lake Michigan, (3) the islands near Sandusky, Ohio, in western Lake Erie, and (4) the area near Hamilton, Ontario, and Bay of Quinte in Lake Ontario. Our study focused entirely on Ciscos but may provide a framework for describing future stocking needs for deepwater ciscoes.
How Many Ciscoes are Needed for Stocking in the Laurentian Great Lakes?

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Abstract

Historically, Cisco *Coregonus artedi* and deepwater ciscoes *Coregonus* spp. were the most abundant and ecologically important fish species in the Laurentian Great Lakes, but anthropogenic influences caused nearly all populations to collapse by the 1970s. Fishery managers have begun exploring the feasibility of restoring populations throughout the basin, but questions regarding hatchery propagation and stocking remain. We used historical and contemporary stock-recruit parameters previously estimated for Ciscos in Wisconsin waters of Lake Superior, with estimates of age-1 Cisco rearing habitat (broadly defined as total ha ≤ 80 m depth) and natural mortality, to estimate how many fry (5.5 months post-hatch), fall fingerling (7.5 months post-hatch), and age-1 (at least 12 months post-hatch) hatchery-reared Ciscos are needed for stocking in the Great Lakes to mimic recruitment rates in Lake Superior, a lake that has undergone some recovery. Estimated stocking densities suggested that basin-wide stocking would require at least 0.641-billion fry, 0.469-billion fall fingerlings, or 0.343-billion age-1 fish for a simultaneous restoration effort targeting historically important Cisco spawning and rearing areas in Lakes Huron, Michigan, Erie, Ontario, and Saint Clair. Numbers required for basin-wide stocking were considerably greater than current or planned coregonine production capacity, thus simultaneous stocking in the Great Lakes is likely not feasible. Provided current habitat conditions do not preclude Cisco restoration, managers could maximize the effectiveness of available production capacity by concentrating stocking efforts in historically important spawning and rearing areas, similar to the current stocking effort in Saginaw Bay, Lake Huron. Other historically important Cisco spawning and rearing areas within each lake (listed in no particular order) include: (1) Thunder Bay in Lake Huron, (2) Green Bay in Lake Michigan, (3) the islands near Sandusky, Ohio, in western Lake Erie, and (4) the area near Hamilton, Ontario,
and Bay of Quinte in Lake Ontario. Our study focused entirely on Ciscos but may provide a framework for describing future stocking needs for deepwater ciscos.

Keywords: Coregonine stocking, Habitat area, Historical and contemporary abundance, Natural mortality, Stock-recruit parameters

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Introduction

Prior to European settlement, Cisco *Coregonus artedi* (“Cisco” or “Ciscoes”) and deepwater ciscoes *Coregonus* spp. (“deepwater cisco” or “deepwater ciscoes”) were the most abundant and ecologically important fish species in the Laurentian Great Lakes (hereafter “Great Lakes”; Figure 1; Koelz 1926; Smith 1964, 1968). However, nearly all populations were reduced or extirpated basin-wide by the 1970s because of over-exploitation (Koelz 1926; Smith 1968), eutrophication (Beeton 1965; Vollenweider et al. 1974), and non-native species invasions and introductions (Berst and Spangler 1972; Christie 1972; Lawrie and Rahrer 1972; Wells and McLain 1972; Leach and Nepszy 1976). Commercial harvests declined throughout the basin (Figure 2; Baldwin et al. 2018) as these historically important native fishes were replaced by invasive Alewife *Alosa pseudoharengus* and Rainbow Smelt *Osmerus mordax* (Berst and Spangler 1972; Christie 1972; Lawrie and Rahrer 1972; Wells and McLain 1972; Leach and Nepszy 1976). Bloater *C. hoyi* persisted in Lake Michigan and possibly Lake Huron, but all other deepwater ciscoes were extinct, extirpated, or hybridized in Lakes Huron, Michigan, Erie, and Ontario (Eshenroder et al. 2016). In Lake Superior, Bloater, Kiyi *C. kiyi*, and Shortjaw Cisco *C. zenithicus* are extant, whereas Blackfin Cisco *C. nigripinnis* and Shortnose Cisco *C. reighardi* are of uncertain status (Eshenroder et al. 2016). Remnant Cisco populations persisted in Lakes Superior, Huron, Michigan, and Ontario, but with the exception of Lake Superior, contemporary populations are small and isolated (Eshenroder et al. 2016). Cisco partially recovered in Lake Superior after the 1980s (Bronte et al. 2003), but contemporary abundance is likely below historical levels (Rook et al. 2021), and driven by highly variable and sporadic recruitment, with few strong year-classes produced since 1977 (Bronte et al. 2003; Stockwell et al. 2009; Rook et al. 2012, 2013).
More recently (mid-2000s–present), ecological and environmental conditions throughout the Great Lakes are thought to have improved for many native fishes (e.g., Oldenberg et al. 2007; Zimmerman and Krueger 2009; Muir et al. 2012a). Alewife and Rainbow Smelt densities have declined since the late-1990s (USGS 2018), which could lessen negative interactions with Ciscoes and deepwater ciscoes through reduced competition for zooplankton (e.g., Smith 1968; Anderson and Smith 1971) or predation on larvae (e.g., Crowder 1980; Selgeby 1982).

Restrictive commercial fishery regulations (e.g., Brege and Kevern 1978) have reduced or eliminated most, if not all, fishing mortality for many coregonine populations that were heavily exploited prior to the 1970s (Baldwin et al. 2018). Re-oligotrophication has resulted in zooplankton communities and levels of primary production in Lakes Huron, Michigan, and Ontario that more closely resemble those in Lake Superior (Dove 2009; Evans et al. 2011; Barbiero et al. 2012; Dove and Chapra 2015; Fahrenstiel et al. 2016), which currently supports the largest Cisco populations and most diverse coregonine assemblage in the Great Lakes (Eshenroder et al. 2016). Environmental conditions for overwintering eggs, primarily bottom dissolved oxygen (DO) concentrations (see Brooke and Colby 1980), have also improved in historically important nearshore spawning and rearing areas, such as lower Green Bay, Lake Michigan, and may be suitable for reintroducing and restoring coregonine populations in these areas and perhaps elsewhere (Madenjian et al. 2011).

Stocking is expected to play a major role in re-establishing self-sustaining Cisco and deepwater cisco populations in most Great Lakes, especially where species are extirpated, extremely low in abundance, or limited in distribution (e.g., LHTC 2007; Oldenburg et al. 2007). However, questions regarding hatchery propagation and stocking remain research priorities for both United States (U.S.) Department of Interior (DOI) agencies (U.S. Fish and Wildlife Service...
[USFWS] and U.S. Geological Survey [USGS]) and the Great Lakes Fishery Commission (GLFC) before large-scale restoration can proceed (Todd 1986; Zimmerman and Krueger 2009; Muir et al. 2012a; Bronte et al. 2017). Based on experiences from European stocking programs, Todd (1986) suggested that “fry” (< one month old) stocking densities should exceed about 40% of each year-class to achieve a detectible contribution to Lake Whitefish *C. clupeaformis* populations in the Great Lakes, and concluded that stocking programs of this magnitude (billions of fish) were likely too ambitious to succeed. Programs targeting less abundant coregonine forms, such as deepwater ciscoes, or stocking more advanced life stages, such as “fingerlings” (10–11 months old) and “yearlings” (> 12 months old), were suggested as possible alternatives, but the knowledge to implement such programs was not yet available (Todd 1986).

Northern Europeans have a long history of rearing coregonines, such as Vendace *C. albula* (“European cisco”) and European Whitefish *C. lavaretus*, to advanced life stages on a large scale (e.g., Salonen et al. 1996; Wanke et al. 2016), methods of which are being implemented in the Great Lakes. Bloaters from Lake Michigan and Ciscoes from remnant Lake Ontario populations have been reared and stocked in Lake Ontario since 2012 (OMNRF 2016; Bronte et al. 2017), although the Cisco stocking program was recently discontinued. Some of these stocked fish have been recaptured in subsequent fish community surveys (NYSDEC 2019). At the request of the Lake Huron Committee (LHC) of the Great Lakes Fishery Commission, the U.S. Fish and Wildlife Service has stocked at least 750,000 fall fingerling Cisco per year in Saginaw Bay, Lake Huron, since 2018 and stocking is expected to continue through 2027 (LHTC 2018). These stocking programs currently rely on advanced life stages (fall fingerlings or yearlings) that require more care, infrastructure, and time in hatcheries than fry stocking programs (e.g., EIFAC 1994). European studies suggest that yield from stocking (kg
harvested/1,000 fish stocked) generally increases as a function of age/life stage or size stocked for most coregonines, with a nearly 400-fold increase in observed yield between *C. albula* fry and fall fingerlings and about a 20–35-fold increase in observed yield between the same life stages for *C. lavaretus* (EIFAC 1994). However, stocking success is highly variable (e.g., Eckmann et al. 1998; Poczuczynski et al. 2011) and largely dependent on local ecological and environmental conditions (e.g., Bninska 2000). To encourage survival and successful reproduction, fishery managers throughout the Great Lakes may need to carefully evaluate local conditions (e.g., Bninska 2000) and weigh potential costs and benefits associated with rearing individuals to more advanced life stages prior to stocking (e.g., Amtstaetter and Willox 2004).

Densities or numbers of fish required for stocking at different life stages are currently unavailable for most historically important Cisco and deepwater cisco populations, but are necessary for cost-benefit analyses (e.g., Turkowski 1999) to guide future coregonine restoration efforts throughout the basin (Bronte et al. 2017).

In this study, our objective was to estimate numbers of fry, fall fingerling, and age-1 hatchery fish needed for Cisco restoration stocking in the Great Lakes. We assumed fry were 60–70 mm total length (TL) and stocked about 5.5 months post-hatch (summer year of hatching), fall fingerlings were 80–165 mm total length and stocked about 7.5 months post-hatch (October year of hatching), and age-1 fish were greater than 165 mm total length and stocked at least 12 months post-hatch (spring year after hatching). Estimates mimicked historical and contemporary age-1 and adult recruitment rates in Lake Superior, a lake that has undergone some recovery, and were made for three spatial scales, basin-wide, lake-wide, and individual habitat areas. The need for this study was identified during a 2016 workshop by Department of Interior agencies (USFWS and USGS) and the Great Lakes Fishery Commission targeted at identifying
information needs for coregonine restoration throughout the Great Lakes (Bronte et al. 2017).

To that end, lake-specific estimates of natural mortality could be used with existing stock-recruit models for Ciscoes in Lake Superior (e.g., Rook et al. 2021) to inform stocking targets for other Great Lakes (Bronte et al. 2017). Workshop participants also recognized the importance of identifying historically important Cisco spawning and rearing areas (hereafter “habitat area” or “habitat areas”; Figure 3) to prioritize for stocking given limited coregonine production capacity in hatcheries (Bronte et al. 2017). Our study focused entirely on Ciscoes but may provide a framework for describing future stocking needs for deepwater ciscoes.

**Methods**

**Study area**

Lake Superior now contains the most abundant and well-studied Cisco populations in the Great Lakes, and most importantly, previous estimates of historical and contemporary Cisco stock-recruit parameters (Rook et al. 2021) are available to estimate numbers of hatchery fish needed for stocking at the fry, fall fingerling, and age-1 life stages in other Great Lakes.

Carrying capacity related to total area of age-1 Cisco rearing habitat (< 90 m depth; Gorman et al. 2012) was previously found to influence recruitment of Ciscoes in Lake Superior (Rook et al. 2013) and this dynamic may apply throughout the basin. Total phosphorus (TP) levels in Lake Superior were about 3–5-fold greater during the 1950s (~ 10 μg/L TP in 1953; Beeton et al. 1959) than now (~ 2–3 μg/L TP; Dove and Chapra 2015). This suggests the potential to support greater coregonine abundance historically (e.g., Rook et al. 2021). Recent trophic convergence in Lakes Superior, Huron, Michigan, and Ontario (e.g., Dove 2009; Barbiero et al. 2012) suggests that contemporary estimates of abundance and stock-recruit parameters from Cisco populations in Lake Superior can be used to estimate stocking rates for most other Great Lakes.
Despite recent declines, contemporary total phosphorus levels in Lakes Erie and Saint Clair (~13–25 µg/L TP) are higher than in other Great Lakes (~2–7 µg/L TP; Dove and Chapra 2015; Burniston et al. 2018). This suggests that stocking rates based on contemporary Cisco populations in Lake Superior may underestimate those needed for Lakes Erie and Saint Clair, whereas stocking rates based on historical Cisco populations may be more appropriate (e.g., Rook et al. 2021).

**Overall approach**

We estimated numbers of hatchery fish needed for stocking at the fry, fall fingerling, and age-1 life stages in other Great Lakes based on estimates of peak age-1 recruitment $R_{max}$ and the spawning stock size required to produce peak age-1 recruitment $S_{max}$ (Ricker 1975) for historical and contemporary Ciscoes in Wisconsin waters of Lake Superior (Figure 3; Rook et al. 2021). First, lake-specific stocking densities (fish/ha) for each life stage were back-calculated from previous estimates of $R_{max}$ and $S_{max}$ (fish/ha) using estimates of instantaneous natural mortality $M$ (Ricker 1975) derived from historical and contemporary growth parameters $L_{\infty}$ and $K$ for Ciscoes in Wisconsin waters of Lake Superior (Rook et al. 2021) and lake-specific contemporary air temperatures $T$ (°C; Pauly 1980). Second, lake-specific stocking densities were converted to habitat area-specific numbers of fish needed for each life stage using habitat area-specific estimates of age-1 Cisco rearing habitat, which were based on total area (ha) up to 80 m depth (Figure 1; Rook et al. 2013) and published descriptions of historical Cisco spawning and rearing areas from Koelz (1926, 1929), Organ et al. (1979), and Goodyear et al. (1982). Third, habitat area-specific numbers of fish needed for each life stage were “scaled up” to basin-wide and lake-wide numbers of fish by combining estimates for all habitat areas (basin-wide) or all habitat areas within each lake (lake-wide).
Stocking densities and numbers of fish needed for each life stage were estimated using bootstrap methods (Zar 1999) and represent the median (50.0 percentile) of all estimates for each stocking scenario after applying $N = 1,000$ random combinations of $M$ between stocking and the age-1 or adult life stages. The 2.5 and 97.5 percentile confidence intervals (95% CIs) were also estimated and appear in Figures 4–5 and the Supplementary Material (Supplemental Material, Tables S1–S3). For comparison, estimates of $M$, $T$, stocking density, and age-1 Cisco rearing habitat are provided for Lake Superior. However, numbers of fish were not estimated for Lake Superior, because most Cisco populations are self-sustaining and stocking is not necessary (Ebener and Pratt 2021). Because different terminology is used for the fry, fall fingerling, age-1, and adult life stages, we use “equivalents” to refer to fish similar in size and life stage to those in our study when making comparisons with other studies.

**Stock-recruit parameters**

To estimate historical (pre-1955) and contemporary (1992–2016) stock-recruit parameters for Ciscoes in Wisconsin waters of Lake Superior, Rook et al. (2021) used commercial catch, effort, and life-history data from published studies (Dryer and Beil 1964; Selgeby 1982) and agency records (USGS and Wisconsin Department of Natural Resources [WIDNR]) to construct simulation models that mimicked observed historical and contemporary harvests. These models relied on Ricker stock-recruit relationships (Ricker 1975) that were calibrated by systematically adjusting parameters until simulated harvests mimicked observed harvests (Rook et al. 2021). Peak age-1 recruitment $R_{\max}$ (number of age-1 recruits) and the spawning stock size required to produce peak age-1 recruitment $S_{\max}$ (number of adults) were estimated using parameters from calibrated stock-recruit relationships and scaled to total area of age-1 Cisco rearing habitat (total ha $\leq 80$ m depth; Rook et al. 2013) in Wisconsin waters of
Lake Superior (~ 345,000 ha; Rook et al. 2021). Previous estimates of $R_{max}$ and $S_{max}$ were
235.2 age-1 recruits/ha and 82.7 adults/ha for historical populations (2.8 = age-1 recruits/adult) and 27.9 age-1 recruits/ha and 10.8 adults/ha for contemporary populations (2.6 = age-1 recruits/adult; Rook et al. 2021). These estimates of $R_{max}$ and $S_{max}$ were assumed to be reasonable age-1 and adult targets to mimic population densities in Lake Superior.

**Natural mortality**

Instantaneous natural mortality $M$ was estimated using the Pauly equation (Pauly 1980) because it is one of the best-performing estimators of $M$ for information-limited fisheries (Kenchington 2014). The equation was derived from stock-specific estimates of asymptotic total length $L_\infty$ (cm), instantaneous growth rate $K$ (years$^{-1}$), and average annual air or water temperature $T$ ($^\circ$C) for 175 different unexploited or lightly exploited fish stocks distributed across 84 freshwater and marine species to estimate $\log M$ (Pauly 1980):

$$\log M = -0.0066 - 0.279 \log L_\infty + 0.6543 \log K + 0.4634 \log T$$

Previous estimates of $L_\infty$ and $K$ for Ciscoes in Wisconsin waters of Lake Superior were 345 mm (SE = 7.04 mm) and 0.29 years$^{-1}$ (SE = 0.017 years$^{-1}$) for historical populations and 416 mm (SE = 11.86 mm) and 0.19 years$^{-1}$ (SE = 0.015 years$^{-1}$) for contemporary populations (Rook et al. 2021). These estimates of $L_\infty$ and $K$ were applied throughout the basin. Contemporary (1990–2016) summary data for land-based monitoring stations near each lake (Figure 1) were used to estimate lake-specific average annual air temperatures $T$, which ranged 5.5–10.1°C (SE = 0.22–1.08°C; Table 1). Air temperature was used because it provides a reasonable approximation of water temperature for freshwater fishes (Pauly 1980). Bootstrap methods and a stochastic version of the Pauly equation that treated $L_\infty$, $K$, and $T$ as normally distributed random variables...
(mean ± standard error) were used to generate N = 1,000 random lake- and year-specific estimates of $M$. These were used to back-calculate lake-specific stocking densities (fish/ha) for fry, fall fingerling, and age-1 fish using previous estimates of $R_{max}$ and $S_{max}$ for historical and contemporary Ciscoes in Wisconsin waters of Lake Superior (Rook et al. 2021). Random lake- and year-specific estimates of $M$ represented a range of mortalities experienced by each life stage stocked between stocking and the age-1 or adult life stages. Median estimates of $M$ for each lake ranged 0.36–0.48 for historical populations and 0.26–0.35 for contemporary populations (Table 1). Because the same approach was used to estimate $M$ for all three life stages stocked, potential mortality experienced by fry was likely underestimated, whereas potential mortality experienced by fall fingerlings and age-1 fish was likely more accurate (see Fluchter 1982).

**Habitat areas**

As with Rook et al. (2013), potential age-1 Cisco rearing habitat (ha) was estimated using 80-m depth contours (Figure 1). Habitat area-specific polygons were delineated within each lake using ArcMap (Environmental Systems Research Institute, Redlands, California) and published descriptions of historical Cisco spawning and rearing areas from Koelz (1926, 1929), Organ et al. (1979), and Goodyear et al. (1982). Overlay procedures in ArcMap were used to extract bathymetric data and estimate total area up to 80 m depth within each polygon (Supplemental Material, Shapefiles S1–S7). Individual habitat areas within each lake were delineated by grouping historical spawning and rearing areas. Proximity and location within an embayment or surrounding a point or group of islands were the primary factors used for grouping. Habitat-area specific polygons were delineated by circular arcs that extended about 25 km away from shore towards the middle of each lake. This is the distance within which most tagged adult Ciscoes were recovered in Lake Michigan (Smith and Van Oosten 1940) and allowed historical spawning
and rearing areas from multiple sources to be combined. Where riverine and offshore spawning and rearing areas were present historically, this distance was adjusted accordingly (< 25 km for riverine and > 25 km for offshore). Lakes Huron, Michigan, Erie, and Ontario each contained eight to 14 habitat areas that ranged 30–190 km measured at the widest point (Table 2; Figure 3). Because of its size (50 km measured at the widest point; see Table 2 and Figure 3), Lake Saint Clair was treated as both a lake and single habitat area. Basin-wide and lake-wide estimates represent “scaled up” values for all habitat areas combined (basin-wide) or all habitat areas within each lake combined (lake-wide). This approach assumed Ciscoes would not be limited by unsuitable oxythermal or other ecological and environmental conditions, an assumption that may not be true in some areas, such as in Lake Erie (e.g., Schmitt et al. 2020).

Stocking estimates

A three-step process was used to estimate numbers of hatchery fish needed for stocking at each life stage. First, lake-specific stocking densities (fish/ha) for the fry $D_{fry}$, fall fingerling $D_{ff}$, and age-1 $D_{age-1}$ life stages were back-calculated from $R_{max}$ and $S_{max}$ using bootstrap methods and $N = 1,000$ random lake- and year-specific estimates of $M$ (see Table 1). These estimates represented potential mortality combinations experienced in years one to six ($M_1$–$M_6$) between stocking and the age-1 or adult life stages, where up to six annual mortality estimates ($M_1$, $M_2$, $M_3$, $M_4$, $M_5$, and $M_6$) were used for back-calculations. Lake-specific stocking densities were estimated separately for each stocking scenario (i.e., historical or contemporary periods and age-1 or adult restoration targets). For stocking densities based on historical and contemporary $R_{max}$, $D_{fry}$, $D_{ff}$, and $D_{age-1}$ were estimated as:

\[ D_{fry} = R_{max} \left( \frac{1}{e^{-M_1}} \right) \left( \frac{1}{e^{-M_2}} \right); \]
$D_{ff} = R_{max} \left( \frac{1}{e^{-M_1}} \right)$; and

$D_{age-1} = R_{max}$

where $D_{age-1}$ was assumed to be equivalent to $R_{max}$ and $M_1 - M_2$ were random estimates of $M$ experienced in the one to two years between stocking and age-1 (i.e., no mortality for age-1 fish, one year of mortality for fall fingerlings, and two years of mortality for fry). Similar methods were used to back-calculate stocking densities based on $S_{max}$, but period-specific (historical or contemporary) fractional mortality terms ($0.2M$ or $0.5M$) were used to mimic weighted average adult age structures (4.2 years or 5.5 years) in Wisconsin waters of Lake Superior (Rook et al. 2021), which would be similar to those expected in other Great Lakes following Cisco restoration. For stocking densities based on historical $S_{max}$ (average adult age = 4.2 years), $D_{fr}, D_{ff}$, and $D_{age-1}$ were estimated as:

$D_{fr} = S_{max} \left( \frac{1}{e^{-0.2M}} \right) \left( \frac{1}{e^{-M_1}} \right) \cdots \left( \frac{1}{e^{-M_5}} \right)$;

$D_{ff} = S_{max} \left( \frac{1}{e^{-0.2M}} \right) \left( \frac{1}{e^{-M_2}} \right) \cdots \left( \frac{1}{e^{-M_4}} \right)$; and

$D_{age-1} = S_{max} \left( \frac{1}{e^{-0.2M}} \right) \left( \frac{1}{e^{-M_1}} \right) \cdots \left( \frac{1}{e^{-M_3}} \right)$

where $0.2M$ was a fractional estimate of random mortality based on fractional age (0.2 years) and $M_1 - M_5$ were random estimates of $M$ experienced in the one to five years between stocking and age-4 (i.e., 3.2 years of mortality for age-1 fish, 4.2 years of mortality for fall fingerlings, and 5.2 years of mortality for fry). For stocking densities based on contemporary $S_{max}$ (average adult age = 5.5 years), $D_{fr}, D_{ff}$, and $D_{age-1}$ were estimated as:
\[ D_{fr} = S_{max} \left( \frac{1}{e^{-0.5M}} \right) \left( \frac{1}{e^{-M_1}} \right) \cdots \left( \frac{1}{e^{-M_6}} \right); \]

\[ D_{ff} = S_{max} \left( \frac{1}{e^{-0.5M}} \right) \left( \frac{1}{e^{-M_1}} \right) \cdots \left( \frac{1}{e^{-M_5}} \right); \]

\[ D_{age-1} = S_{max} \left( \frac{1}{e^{-0.5M}} \right) \left( \frac{1}{e^{-M_1}} \right) \cdots \left( \frac{1}{e^{-M_4}} \right) \]

where \( 0.5M \) was a fractional estimate of random mortality based on fractional age (0.5 years) and \( M_1-M_6 \) were random estimates of \( M \) experienced in the one to six years between stocking and age-5 (i.e., 4.5 years of mortality for age-1 fish, 5.5 years of mortality for fall fingerlings, and 6.5 years of mortality for fry). This approach effectively assumed one additional year of mortality for fry compared to fall fingerlings and fall fingerlings compared to age-1 fish. However, only about two to five months separated each successive life stage stocked. Second, lake-specific stocking densities \( D_{fr} \), \( D_{ff} \), and \( D_{age-1} \) were converted to habitat area-specific numbers of fish needed for the fry \( N_{fr} \), fall fingerling \( N_{ff} \), and age-1 \( N_{age-1} \) life stages using habitat area-specific estimates of age-1 Cisco rearing habitat \( A \) (total ha \( \leq 80 \) m depth; see Figures 1 and 3; Rook et al. 2013):

\[ N_{fr} = D_{fr} \times A; \]

\[ N_{ff} = D_{ff} \times A; \]

\[ N_{age-1} = D_{age-1} \times A \]

where all terms are as previously defined. Similar to lake-specific stocking densities, habitat area-specific numbers for each life stage (fry, fall fingerling, and age-1) were estimated separately for each period (historical or contemporary) and life stage (age-1 or adult) used to establish restoration targets. Third, numbers of fish needed for each life stage \( N_{fr} \), \( N_{ff} \), and...
\( N_{age-1} \) were “scaled up” to basin-wide and lake-wide numbers of fish by combining estimates for individual habitat areas at the spatial scale of interest (basin-wide or lake-wide). The bootstrap median and 95% confidence intervals were estimated for each stocking scenario, although 95% confidence intervals only appear in Figures 4–5 and the Supplementary Material (Supplemental Material, Tables S1–S3).

**Results**

**Habitat areas**

At the habitat area scale, age-1 Cisco rearing habitat ranged 0.014–0.650-million ha in Lake Huron, 0.083–0.628-million ha in Lake Michigan, 0.032–0.463-million ha in Lake Erie, and 0.033–0.137-million ha in Lake Ontario (Table 2; Figures 1 and 3). Lake-wide totals were greatest in Lake Huron (3.574-million ha), followed by Lake Michigan (2.242-million ha), Lake Erie (1.455-million ha), Lake Ontario (0.601-million ha), and Lake Saint Clair (0.115-million ha), with a basin-wide total of 7.987-million ha (Table 2). Habitat areas contained the greatest proportions of age-1 Cisco rearing habitat in Lakes Erie and Saint Clair (100%), followed by Lake Huron (89%), Lake Michigan (76%), and Lake Ontario (74%), with a basin-wide average of 86% (Table 2).

**Stocking estimates**

Cisco stocking densities ranged 78–1,553 fry/ha, 58–959 fall fingerlings/ha, and 43–593 age-1 fish/ha in Lakes Huron, Michigan, Erie, Ontario, and Saint Clair (Table 3; Figure 4). Stocking scenarios that mimicked contemporary age-1 recruitment rates required the lowest stocking densities, whereas those that mimicked historical adult recruitment rates required the highest stocking densities (Table 3; Figure 4). Stocking densities for historical targets ranged
7.5–11.0-fold greater than those for contemporary targets, whereas stocking densities for adult targets ranged 1.1–1.8-fold greater than those for age-1 targets (Table 3; Figure 4). At the habitat area scale, stocking numbers ranged 0.001–0.765-billion for fry, 0.001–0.496-billion for fall fingerlings, and 0.001–0.321-billion for age-1 fish (Tables 4–5). Lake-wide totals were greatest in Lake Huron (0.153–3.942-billion fish), followed by Lake Michigan (0.096–2.734-billion fish), Lake Erie (0.062–2.264-billion fish), Lake Ontario (0.026–0.798-billion fish), and Lake Saint Clair (0.005–0.171-billion fish), with a basin-wide range of 0.343–9.908-billion fish (Tables 4–5; Figure 5). Basin-wide estimates of the total number of Ciscos needed for stocking ranged 0.641–9.908-billion for fry, 0.469–6.387-billion for fall fingerlings, and 0.343–4.121-billion for age-1 fish (Tables 4–5; Figure 5).

**Discussion**

**Habitat areas**

Lake-wide totals for age-1 Cisco rearing habitat suggested that total Cisco biomass or abundance (production) and subsequent yield (kg harvested) should be greatest in Lake Huron, followed by Lake Michigan, Lake Erie, Lake Ontario, and Lake Saint Clair (see Table 2). However, historical records indicate that Cisco yield was greatest in Lake Erie (22.2-million kg), followed by Lake Michigan (12.4-million kg), Lake Huron (4.9-million kg), Lake Ontario (1.1-million kg), and Lake Saint Clair (0.4-million kg; Baldwin et al. 2018). We suggest that lake-specific Cisco production is likely determined by a combination of age-1 Cisco rearing habitat, primary production (e.g., Eckmann et al. 2007; Rook et al. 2012, 2013), and lake- or habitat area-specific variability in natural mortality and potential recruitment bottlenecks (e.g., Madenjian et al. 2011), whereas yield is defined by fishing effort applied to Cisco production. Consequently, fishery managers may need to adjust stocking estimates on a lake- or habitat area-specific basis.
after the survival of stocked Cisco is evaluated. As stated before, recent trophic convergence in Lakes Superior, Huron, Michigan, and Ontario (e.g., Dove 2009; Barbiero et al. 2012) suggests that our estimates could be reasonably applied throughout most of the basin. Additional monitoring data may be especially useful in lakes where primary productivity or total phosphorus levels differ from Lake Superior, such as Lakes Erie and Saint Clair (Dove and Chapra 2015; Burniston et al. 2018).

**Stocking estimates**

Cisco stocking densities estimated here were similar to those applied in European Coregonus spp. stocking programs. In an unpublished review of stocking densities used, mostly for *C. albula* and *C. lavaretus*, values averaged 2,533 fry equivalents/ha (range = 1–20,537 fish/ha), 344 fall fingerling equivalents/ha (range = 1–3,536 fish/ha), and 25 age-1 equivalents/ha (range = 1–92 fish/ha; Supplemental Material, Data S2). For *C. albula*, a pelagic planktivore similar to Cisco, published stocking densities averaged 3,764 fry equivalents/ha (range = 541–10,365 fish/ha; Supplemental Material, Data S2) and 387 fall fingerling equivalents/ha (range = 5–1,500 fish/ha; EIFAC 1994; Salonen et al. 1996). The only published stocking density available for age-1 equivalents was 92 fish/ha (Huuskonen et al. 2004).

Except for the fry life stage, Cisco stocking densities presented here can be considered “bookends” on those for other Coregonus spp., where estimates based on historical recruitment rates were generally higher and those based on contemporary recruitment rates were generally lower than for European species (see Table 3, Figure 4, and Supplemental Material, Data S2). Differences between period-specific stocking densities were likely related to differences in primary production and corresponding carrying capacity for Ciscos in Lake Superior (e.g., Rook et al. 2021). Similar differences between historical and contemporary primary productivity
have been observed in other Great Lakes (e.g., Schelske 1991; Schelske et al. 2006; Estepp and
Reavie 2015). Period-specific stocking densities suggest that primary production and coregonine
carrying capacity in many European lakes is intermediate between historical and contemporary
conditions in Lake Superior (see Supplemental Material, Data S2 and Rook et al. 2021).

Cisco stocking densities estimated for the fry life stage were lower than most published
stocking densities for European Coregonus spp. (see Table 3, Figure 4, and Supplemental
Material, Data S2). These differences were likely related to how estimates of natural mortality
were applied to densities of age-1 and adult fish to back-calculate numbers of fish needed for
stocking at the fry life stage. Evidence from Pilsen Lake, Germany, suggests that survival of C.
lavaretus fall fingerling equivalents is about 1,500-fold greater than that of fry equivalents
(Fluchter 1982). Similarly, survival from the fry to age-1 life stages is lower than that from the
age-1 to adult life stages for Ciscoes in Lake Superior (Stockwell et al. 2009). Therefore, our
methods likely underestimated natural mortality between the fry and fall fingerling life stages.
Consequently, we suggest that fishery managers use published stocking densities for related
European species for the fry life stage (average = 2,533 fish/ha for all species and 3,764 fish/ha
for C. albula; Supplemental Material, Data S2).

To date, fall fingerlings and advanced summer fingerlings equivalent in size to fall
fingerlings have been used by federal, state, provincial, and tribal agencies in pilot stocking
programs throughout the basin (Fischer et al. 2016; OMNRF 2016; Bronte et al. 2017; Johnson
et al. 2017). Our findings suggest that basin-wide Cisco restoration stocking would require a
minimum of 0.469-billion fall fingerlings to mimic recruitment rates in Lake Superior (Tables 4–
5; Figure 5). This estimate is based on stocking scenarios that mimicked contemporary age-1
recruitment rates, which required the lowest stocking densities (Table 3; Figure 4). The
estimated long-term maximum coregonine production capacity for all federal, state, provincial, and tribal hatcheries throughout the Great Lakes is about 4.5-million fall fingerlings (Bronte et al. 2017). The Jordan River National Fish Hatchery (USFWS) in Elmira, Michigan, currently supplies about half of this production capacity (2.1-million fall fingerlings; Bronte et al. 2017). As stated before, the U.S. Fish and Wildlife Service has begun to stock at least 750,000 fall fingerling Cisco per year in Saginaw Bay, Lake Huron, with stocking expected to continue through 2027 (LHTC 2018). Using Lake Huron and Saginaw Bay as examples, our minimum stocking estimates for fall fingerling Ciscos suggest that numbers of fish needed for all of Lake Huron and only Saginaw Bay are about 98-fold and 12-fold greater than the current federal production capacity and about 46-fold and 6-fold greater than the estimated long-term maximum production capacity for the entire basin (see Table 5). Therefore, to meet minimum stocking needs at the habitat area scale, further stocking requests would require substantial and likely unattainable investments in hatchery production capacity.

Reductions in Pacific salmon Oncorhynchus spp. (O. tshawytscha and O. kisutch) and Lake Trout Salvelinus namaycush stocking rates in most of the Great Lakes have resulted in potential excess raceway rearing capacity in some federal and state hatcheries (Muir et al. 2012a). There are adequate methods for rearing Ciscos in traditional flow-through raceway systems (e.g., Johnson et al. 2017) and this excess rearing capacity may be able to augment some Cisco production needs (Muir et al. 2012a). For example, the total number of Pacific salmon and Lake Trout (total fingerling equivalents) stocked in Lake Huron by all agencies combined has declined by about 4.1-million fish (36%), from a maximum of 11.3-million fish in 2000 to an average of 7.2-million fish during 2013–2017, with similar declines of 7.0-million fish in Lake Michigan (36%), 6.4-million fish in Lake Erie (92%), and 5.1-million fish in Lake Ontario (58%;
Supplemental Material, Data S3). This potential excess rearing capacity could augment some Cisco production needs, particularly in smaller habitat areas, but is unlikely to meet production needs at basin-wide or even lake-wide scales (see Tables 4–5 and Figure 5).

**Management Implications**

Simultaneous Cisco restoration stocking in the Great Lakes, similar in magnitude to that of the Lake Trout restoration program (Hansen 1999; Muir et al. 2012b), is likely not feasible within current or future coregonine production capacities (e.g., Bronte et al. 2017). Commercial harvest data suggest that historical Cisco populations relied on relatively few important spawning and rearing areas within each lake to sustain lake-wide adult populations (e.g., Muir et al. 2012a). For example, Green Bay contributed 90% to total Cisco harvest in Lake Michigan during 1920–1960, whereas Saginaw Bay contributed 65% to total Cisco harvest in Lake Huron during the same period (Muir et al. 2012a; Baldwin et al. 2018). Provided current habitat conditions do not preclude Cisco restoration, managers could maximize the effectiveness of available production capacity by concentrating stocking efforts in historically important spawning and rearing areas, similar to the current stocking effort in Saginaw Bay, Lake Huron (LHTC 2018). Other historically important Cisco spawning and rearing areas within each lake (listed in no particular order) include: (1) Thunder Bay in Lake Huron (H-13 in Figure 3), (2) Green Bay in Lake Michigan (M-5 in Figure 3), (3) the islands near Sandusky, Ohio, in western Lake Erie (E-7 in Figure 3), and (4) the area near Hamilton, Ontario, and Bay of Quinte in Lake Ontario (O-1 and O-4 in Figure 3). These areas were described as having the largest commercial fisheries and greatest historical yields by Koelz (1926, 1929), Organ et al. (1979), and Goodyear et al. (1982). Establishing self-sustaining Cisco populations in historically important spawning and rearing areas may lead to colonization of additional areas and thereby reduce the need for
further stocking. Successful re-establishment of self-sustaining populations will likely depend on local ecological and environmental conditions (e.g., Bninska 2000) and fishery managers may need to evaluate the overall suitability of each area before and after stocking efforts have been initiated, regardless of the life stage stocked.

Our study focused entirely on Ciscoes but may provide a framework for describing future stocking needs for deepwater ciscoes. The availability of commercial harvest records is sporadic prior to the early-1900s (Baldwin et al. 2018), and databases containing basin-wide fishery statistics did not differentiate most deepwater cisco species prior to population collapses (Eshenroder et al. 2016), so historical commercial harvest records cannot provide useful information for generating stocking estimates. However, as we demonstrated here, estimates of habitat area and data from remnant populations in one lake could be used to inform restoration efforts in other lakes. For example, Bloater populations in Lake Michigan could be used to inform stocking efforts in Lake Ontario. In cases where contemporary data for deepwater cisco species are unavailable, data from ecologically similar species could be used as a surrogate. Basic knowledge and life-history data are limited for most deepwater cisco populations (see Eshenroder et al. 2016) and the generalized approach used in our study may be the best available approach to generate stocking estimates for restoration efforts throughout the basin.

**Supplemental Material**

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Data S1. Microsoft Excel (Microsoft Corporation, Redmond, Washington) workbook containing contemporary (1990–2016) estimates of average annual air temperature $T$ ($^\circ$C) for land-based monitoring stations near Lakes Huron, Michigan, Erie, Ontario, and Saint Clair (see Table 1 and Figure 1; Station-Specific Data Available: https://www.ncdc.noaa.gov/cdo-web/datatools/findstation [October 2021]). This workbook contains worksheets (tabs) for each...
lake (Lake Huron, Lake Michigan, Lake Erie, Lake Ontario, and Lake Saint Clair) that contain
station-specific estimates of \( T \). The first row in each worksheet contains column headings
corresponding to year (YEAR), notes (NOTES), and the names of land-based monitoring stations
in Figure 1. Rows 2–28 contain the year (1990–2016), notes, and station-specific estimates of \( T \).
In some cases, linear regression (Zar 1999) was used to estimate missing values (\( T \)) from
nearest-neighbor stations (identified by shaded cells; linear regression \( R^2 \) range = 0.75–0.96).
The nearest-neighbor stations used to estimate missing values (\( T \)) and linear regression \( R^2 \) values
are provided in the NOTES column ("N/A" indicates linear regression was not necessary).
Station-specific estimates of \( T \) were used to generate lake-specific estimates of \( T \) and
corresponding standard errors (SEs) used for estimating instantaneous natural mortality \( M \) (see
Table 1; Ricker 1975). Estimates of \( T \) (average and SE) from Rook et al. (2021) were used for
Lake Superior and are provided in Table 1. Land-based monitoring stations near Lake Superior
used by Rook et al. (2021) are provided in Figure 1. Stations were selected for each lake based
on “broad” spatial coverage and data availability (i.e., relatively few missing values).

**Data S2.** Microsoft Excel (Microsoft Corporation, Redmond, Washington) workbook
containing coregonine stocking densities (fish/ha) from published European studies. This
workbook contains one worksheet (tab) for stocking density (Stocking Density) that contains
lake-, country-, and region-specific stocking densities for a variety of Coregonus spp. and life
stages stocked. The data were part of a separate, unpublished literature review provided by co-
author C. Bronte (United States [U.S.] Fish and Wildlife Service [USFWS], Green Bay Fish and
Wildlife Conservation Office [FWCO]). The first row in the worksheet contains column
headings corresponding to reference (REFERENCE), lake name (LAKE_NAME), country
(COUNTRY), region (REGION), Coregonus spp. (SPECIES), life stage stocked

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STAGE_STOCKED), and density stocked (DENSITY_STOCKED). Rows 2–164 contain data sources (REFERENCE) and corresponding data from each source (LAKE_NAME, COUNTRY, REGION, SPECIES, STAGE_STOCKED, and DENSITY_STOCKED; “N/A” indicates data were unavailable). Data are sorted by STAGE_STOCKED (youngest to oldest) and then alphabetically by SPECIES. Summary density values (average, minimum, and maximum) for SPECIES and STAGE_STOCKED were used for comparisons. For simplicity, we treated categories in the STAGE_STOCKED column as equivalent to the “fry”, “fall fingerling”, or “age-1” life stages in our study: (1) “Larvae” = fry (60–70 mm total length [TL] and stocked about 5.5 months post-hatch); (2) “Summer Fry” and “Autumn Fry” = fall fingerlings (80–165 mm TL and stocked about 7.5 months post-hatch); and (3) “Yearlings” = age-1 fish (greater than 165 mm TL and stocked at least 12 months post-hatch). These groupings are not entirely accurate, but can be used to provide a range of stocking densities for life stages similar to those in our study, which can then be compared to estimated stocking densities (see Table 3).

**Data S3.** Microsoft Excel (Microsoft Corporation, Redmond, Washington) workbook containing summary data for numbers of Pacific salmon *Oncorhynchus* spp. (*O. tshawytscha* and *O. kisutch*) and Lake Trout *Salvelinus namaycush* stocked in Lakes Huron, Michigan, Erie, and Ontario during 1980–2017 (all three species combined; Lake-Specific Data Available: [http://www.glfc.org/fishstocking/index.htm](http://www.glfc.org/fishstocking/index.htm) [October 2021]). This workbook contains one worksheet (tab) for stocking number (Stocking Number) that contains lake-specific stocking numbers for a variety of life stages stocked. The first row in the worksheet contains column headings corresponding to year (YEAR), lake (LAKE), age-2 fish (AGE_2), age-0 fingerlings (FINGERLING_0), age-0 fall fingerlings (FALL_FINGERLING_0), age-0 spring fingerlings (SPRING_FINGERLING_0), age-0 summer fingerlings (SUMMER_FINGERLING_0), age-1
yearlings (AGE_1), and total fingerling equivalents (TOT_FINGERLING_EQ). Rows 2–191 contain the year (1980–2017), lake (Huron, Michigan, Erie, and Ontario), and corresponding numbers of each life stage stocked in each lake (AGE_2, FINGERLING_0, FALL_FINGERLING_0, SPRING_FINGERLING_0, SUMMER_FINGERLING_0, AGE_1, and TOT_FINGERLING_EQ; “N/A” indicates life stage was not stocked). Data are sorted by LAKE and then by YEAR. Year- and lake-specific values for TOT_FINGERLING_EQ were estimated by adding year- and lake-specific values for all other life stage columns after applying appropriate correction factors (3 × AGE_2 and 2 × AGE_1; age-2 fish and age-1 yearlings assumed to require three-fold and two-fold greater rearing capacity than fingerlings). These assumptions are not entirely accurate, but can be used to provide estimates of potential excess rearing capacity for total fingerling equivalents in hatcheries throughout the Great Lakes, which can then be compared to stocking numbers for fall fingerlings estimated in our study (see Tables 4–5). For comparisons, excess rearing capacity was estimated as the difference between lake-specific maximum values of TOT_FINGERLING_EQ during 1980–2017 and lake-specific average values of TOT_FINGERLING_EQ during 2013–2017 (i.e., peak number of fish stocked vs. average number of fish stocked during the most recent five-year period).

**Shapefile S1.** Zip file containing ArcMap (Environmental Systems Research Institute, Redlands, California) shapefile with bathymetry contours (m depth) for Lake Superior provided by L. Evrard (United States [U.S.] Geological Survey [USGS], Lake Superior Biological Station [LSBS]). This contour shapefile was converted to raster form (2.5 km square grids) using ArcMap. Overlay procedures in ArcMap were then used to extract raster depth data for Wisconsin waters of Lake Superior (one area; see Figures 1 and 3 and Supplemental Material, Shapefile S7). As with Rook et al. (2013), area up to 80 m depth (ha) was estimated using 80-m
depth contours (see Table 2). These areas are generally near shorelines in Lake Superior (unshaded [white] areas in Figure 1). The depth data contained in this shapefile are equivalent to the data displayed in Figure 1.

Shapefile S2. Zip file containing ArcMap (Environmental Systems Research Institute, Redlands, California) shapefile with bathymetry contours (m depth) for Lake Huron (Shapefile Available: https://www.ngdc.noaa.gov/mgg/greatlakes/greatlakes.html [October 2021]). This contour shapefile was converted to raster form (2.5 km square grids) using ArcMap. Overlay procedures in ArcMap were then used to extract raster depth data for individual Cisco *Coregonus artedi* habitat areas within Lake Huron (14 areas; see Figures 1 and 3 and Supplemental Material, Shapefile S7). As with Rook et al. (2013), area up to 80 m depth (ha) was estimated using 80-m depth contours (see Table 2). These areas are generally near shorelines in Lake Huron (unshaded [white] areas in Figure 1). The depth data contained in this shapefile are equivalent to the data displayed in Figure 1.

Shapefile S3. Zip file containing ArcMap (Environmental Systems Research Institute, Redlands, California) shapefile with bathymetry contours (m depth) for Lake Michigan (Shapefile Available: https://www.ngdc.noaa.gov/mgg/greatlakes/greatlakes.html [October 2021]). This contour shapefile was converted to raster form (2.5 km square grids) using ArcMap. Overlay procedures in ArcMap were then used to extract raster depth data for individual Cisco *Coregonus artedi* habitat areas within Lake Michigan (eight areas; see Figures 1 and 3 and Supplemental Material, Shapefile S7). As with Rook et al. (2013), area up to 80 m depth (ha) was estimated using 80-m depth contours (see Table 2). These areas are generally near shorelines in Lake Michigan (unshaded [white] areas in Figure 1). The depth data contained in this shapefile are equivalent to the data displayed in Figure 1.
**Shapefile S4.** Zip file containing ArcMap (Environmental Systems Research Institute, Redlands, California) shapefile with bathymetry contours (m depth) for Lake Erie (Shapefile Available: [https://www.ngdc.noaa.gov/mgg/greatlakes/greatlakes.html](https://www.ngdc.noaa.gov/mgg/greatlakes/greatlakes.html) [October 2021]). This contour shapefile was converted to raster form (2.5 km square grids) using ArcMap. Overlay procedures in ArcMap were then used to extract raster depth data for individual Cisco *Coregonus artedi* habitat areas within Lake Erie (eight areas; see Figures 1 and 3 and Supplemental Material, Shapefile S7). As with Rook et al. (2013), area up to 80 m depth (ha) was estimated using 80-m depth contours (see Table 2). These areas include all of Lake Erie (unshaded [white] areas in Figure 1). The depth data contained in this shapefile are equivalent to the data displayed in Figure 1. It is worth noting this shapefile also has bathymetry contours for Lake Saint Clair, but only contours for Lake Erie were used for analyses.

**Shapefile S5.** Zip file containing ArcMap (Environmental Systems Research Institute, Redlands, California) shapefile with bathymetry contours (m depth) for Lake Ontario (Shapefile Available: [https://www.ngdc.noaa.gov/mgg/greatlakes/greatlakes.html](https://www.ngdc.noaa.gov/mgg/greatlakes/greatlakes.html) [October 2021]). This contour shapefile was converted to raster form (2.5 km square grids) using ArcMap. Overlay procedures in ArcMap were then used to extract raster depth data for individual Cisco *Coregonus artedi* habitat areas within Lake Ontario (eight areas; see Figures 1 and 3 and Supplemental Material, Shapefile S7). As with Rook et al. (2013), area up to 80 m depth (ha) was estimated using 80-m depth contours (see Table 2). These areas are generally near shorelines in Lake Ontario (unshaded [white] areas in Figure 1). The depth data contained in this shapefile are equivalent to the data displayed in Figure 1.

**Shapefile S6.** Zip file containing ArcMap (Environmental Systems Research Institute, Redlands, California) shapefile with bathymetry contours (m depth) for Lake Saint Clair
This contour shapefile was converted to raster form (2.5 km square grids) using ArcMap. Overlay procedures in ArcMap were then used to extract raster depth data for individual Cisco *Coregonus artedi* habitat areas within Lake Saint Clair (entire lake; one area; see Figures 1 and 3 and Supplemental Material, Shapefile S7). As with Rook et al. (2013), area up to 80 m depth (ha) was estimated using 80-m depth contours (see Table 2). These areas include all of Lake Saint Clair (unshaded [white] areas in Figure 1). The depth data contained in this shapefile are equivalent to the data displayed in Figure 1. It is worth noting this shapefile also has bathymetry contours for Lake Erie, but only contours for Lake Saint Clair were used for analyses.

**Shapefile S7.** Zip file containing ArcMap (Environmental Systems Research Institute, Redlands, California) shapefile with polygons delineated for Wisconsin waters of Lake Superior (one area) and individual Cisco *Coregonus artedi* habitat areas within Lakes Huron (14 areas), Michigan (eight areas), Erie (eight areas), Ontario (eight areas), and Saint Clair (entire lake; one area; see Figure 3). In the attribute table, the AREA_LABEL column corresponds to labels used for each area in Figure 3. Overlay procedures in ArcMap were used to extract raster depth data for each area after converting contour shapefiles (Supplemental Material, Shapefiles S1–S6) to raster form (2.5 km square grids) using ArcMap (see Figures 1 and 3). As with Rook et al. (2013), area up to 80 m depth (ha) was estimated using 80-m depth contours (see Table 2). These areas are generally near shorelines in Lakes Superior, Huron, Michigan, and Ontario, but include all of Lakes Erie and Saint Clair (unshaded [white] areas in Figure 1). Habitat area-specific polygons were delineated within each lake by grouping historical spawning and rearing areas from Koelz (1926, 1929), Organ et al. (1979), and Goodyear et al. (1982). Proximity and
location within an embayment or surrounding a point or group of islands were the primary
factors used for grouping. Habitat-area specific polygons were delineated by circular arcs that
extended about 25 km away from shore towards the middle of each lake. This is the distance
within which most tagged adult Ciscoes were recovered in Lake Michigan (Smith and Van
Oosten 1940) and allowed historical spawning and rearing areas from multiple sources to be
combined. Where riverine and offshore spawning and rearing areas were present historically,
this distance was adjusted accordingly (< 25 km for riverine and > 25 km for offshore). Because
of its small size, Lake Saint Clair was treated as both a lake and single habitat area. This
approach assumed Ciscoes would not be limited by unsuitable oxythermal or other ecological
and environmental conditions, an assumption that may not be true in some areas, such as in Lake
Erie (e.g., Schmitt et al. 2020). The polygons contained in this shapefile are equivalent those
displayed in Figure 3. It is worth noting this shapefile also has polygons outlining each lake,
which are labeled with the lake name in the AREA_LABEL column. These polygons were used
for mapping.

**Table S1.** Lake-specific estimates of fry (Fry), fall fingerling (Fingerling), and age-1
(Age-1) stocking densities (fish/ha) used to determine the number of Ciscoes *Coregonus artedi*
needed for stocking in the Laurentian Great Lakes to mimic historical and contemporary age-1
and adult recruitment rates in Wisconsin waters of Lake Superior. Values are provided in
descending order for stocking density (all life stages) and are equivalent to those in Table 3 and
Figure 4. Lake Superior is only included for comparison. Values were estimated using bootstrap
methods (Zar 1999) and represent the median density of each life stage (fry, fall fingerling, or
age-1) needed to mimic historical or contemporary peak age-1 recruitment $R_{max}$ (Age-1
Equivalents) or the spawning stock size required to produce peak age-1 recruitment $S_{max}$ (Adult
Equivalents) after applying 1,000 random combinations of instantaneous natural mortality $M$ (Ricker 1975) between stocking and the age-1 or adult life stages. Upper and lower 95% confidence intervals (95% CIs) for each median value are also provided (U95 and L95). These values were converted to numbers of fish using estimates of area up to 80 m depth (ha; see Figures 1 and 3). Values for $R_{max}$ and $S_{max}$ were based on historical (pre-1955) and contemporary (1992–2015) Ricker stock-recruit relationships (Ricker 1975) previously estimated for Ciscoes in Wisconsin waters of Lake Superior and are provided in the Methods section (Rook et al. 2021). Values of “N/A” for U95 and L95 correspond to median estimates where no back-calculations were used (i.e., median values equivalent to previously reported values from Rook et al. 2021).

**Table S2.** Habitat area-specific numbers of fry (Fry), fall fingerling (Fingerling), and age-1 (Age-1) Ciscoes *Coregonus artedi* (billions of fish) needed for stocking in the Laurentian Great Lakes to mimic historical and contemporary adult recruitment rates in Wisconsin waters of Lake Superior. The first column (Lake or Habitat Area) corresponds to cities, towns, or geographic features near each area, whereas the second column (Figure 3 Label) corresponds to labels used for each area in Figure 3 (H = Huron, M = Michigan, E = Erie, and O = Ontario). Because of its small size, Lake Saint Clair was treated as both a lake and single habitat area. Values were estimated using bootstrap methods (Zar 1999) and represent the median density of each life stage (fry, fall fingerling, or age-1) needed to mimic historical or contemporary spawning stock size required to produce peak age-1 recruitment $S_{max}$ (Adult Equivalents) after conversion to numbers of fish using estimates of area up to 80 m depth (ha; see Figures 1 and 3). Upper and lower 95% confidence intervals (95% CIs) for each median value are also provided (U95 and L95). Values for $S_{max}$ were based on historical (pre-1955) and contemporary (1992–
2015) Ricker stock-recruit relationships (Ricker 1975) previously estimated for Ciscoes in Wisconsin waters of Lake Superior and are provided in the Methods section (Rook et al. 2021). Basin-wide (except Lake Superior) and lake-wide values for numbers of fish are equivalent to “scaling up” or combining individual habitat areas at the spatial scale of interest (basin-wide or lake-wide). All values are equivalent to those in Table 4 and Figure 5.

Table S3. Habitat area-specific numbers of fry (Fry), fall fingerling (Fingerling), and age-1 (Age-1) Ciscoes Coregonus artedi (billions of fish) needed for stocking in the Laurentian Great Lakes to mimic historical and contemporary age-1 recruitment rates in Wisconsin waters of Lake Superior. The first column (Lake or Habitat Area) corresponds to cities, towns, or geographic features near each area, whereas the second column (Figure 3 Label) corresponds to labels used for each area in Figure 3 (H = Huron, M = Michigan, E = Erie, and O = Ontario). Because of its small size, Lake Saint Clair was treated as both a lake and single habitat area. Values were estimated using bootstrap methods (Zar 1999) and represent the median density of each life stage (fry, fall fingerling, or age-1) needed to mimic historical or contemporary peak age-1 recruitment $R_{\text{max}}$ (Age-1 Equivalents) after conversion to numbers of fish using estimates of area up to 80 m depth (ha; see Figures 1 and 3). Upper and lower 95% confidence intervals (95% CIs) for each median value are also provided (U95 and L95). Values for $R_{\text{max}}$ were based on historical (pre-1955) and contemporary (1992–2015) Ricker stock-recruit relationships (Ricker 1975) previously estimated for Ciscoes in Wisconsin waters of Lake Superior and are provided in the Methods section (Rook et al. 2021). Basin-wide (except Lake Superior) and lake-wide values for numbers of fish are equivalent to “scaling up” or combining individual habitat areas at the spatial scale of interest (basin-wide or lake-wide). All values are equivalent to those in Table 5 and Figure 5. Values of “N/A” for U95 and L95 correspond to median
estimates where no back-calculation calculations were used (i.e., median values equivalent to previously reported values from Rook et al. 2021).

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**Table Captions**

**Table 1.** Lake-specific estimates of average annual air temperature $T$ ($^\circ$C), with standard errors (SE; $^\circ$C), and corresponding estimates of historical and contemporary instantaneous
natural mortality $M$ (Ricker 1975) used to determine the number of Ciscoes *Coregonus artedi* needed for stocking in the Laurentian Great Lakes to mimic historical and contemporary age-1 and adult recruitment rates in Wisconsin waters of Lake Superior. Values are provided in descending order for $T$ and thus $M$. Lake Superior is only included for comparison (values from Rook et al. 2021). Contemporary (1990–2016) summary data for land-based monitoring stations near each lake (see Figure 1) were used to estimate $T$. Bootstrap methods (Zar 1999) and a stochastic version of the Pauly equation (Pauly 1980) that treated all parameters $L_\infty$, $K$, and $T$ as normally distributed random variables (mean ± standard error) were used to estimate $M$. Values provided for $M$ are median bootstrap estimates based on historical (pre-1955) and contemporary (1992–2015) growth parameters $L_\infty$ and $K$ previously estimated for Ciscoes in Wisconsin waters of Lake Superior (values and standard errors for $L_\infty$ and $K$ are provided in the Methods section; Rook et al. 2021). Air temperature monitoring data used to generate this table are available in the Supplementary Material (Supplemental Material, Data S1).

**Table 2.** Habitat areas within each lake used to determine the number of Ciscoes *Coregonus artedi* needed for stocking in the Laurentian Great Lakes to mimic historical and contemporary age-1 and adult recruitment rates in Wisconsin waters of Lake Superior. Lake Superior and Wisconsin waters of Lake Superior (Wisc.) are only included for comparison. The first column (Lake or Habitat Area) corresponds to cities, towns, or geographic features near each area, whereas the second column (Figure 3 Label) corresponds to labels used for each area in Figure 3 (H = Huron, M = Michigan, E = Erie, and O = Ontario). Because of its small size, Lake Saint Clair was treated as both a lake and single habitat area. Estimates of width measured at the widest point (Width; km) and area up to 80 m depth (millions of ha and proportion [%]) are also provided for the entire basin (except Lake Superior), each lake, and individual habitat.
areas within each lake (see Figures 1 and 3). Basin-wide and lake-wide values for area up to 80 m depth represent historical Cisco spawning and rearing areas and are equivalent to “scaling up” or combining individual habitat areas at the spatial scale of interest (basin-wide or lake-wide).

Shapefiles used to generate this table are available in the Supplementary Material (Supplemental Material, Shapefiles S1–S7).

**Table 3.** Lake-specific estimates of fry (Fry), fall fingerling (Fingerling), and age-1 (Age-1) stocking densities (fish/ha) used to determine the number of Ciscos *Coregonus artedi* needed for stocking in the Laurentian Great Lakes to mimic historical and contemporary age-1 and adult recruitment rates in Wisconsin waters of Lake Superior. Values are provided in descending order for stocking density (all life stages) and are equivalent to those in Figure 4. Lake Superior is only included for comparison. Values were estimated using bootstrap methods (Zar 1999) and represent the median density of each life stage (fry, fall fingerling, or age-1) needed to mimic historical or contemporary peak age-1 recruitment $R_{max}$ (Age-1 Equivalents) or the spawning stock size required to produce peak age-1 recruitment $S_{max}$ (Adult Equivalents) after applying 1,000 random combinations of instantaneous natural mortality $M$ (Ricker 1975) between stocking and the age-1 or adult life stages. These values were converted to numbers of fish using estimates of area up to 80 m depth (ha; see Figures 1 and 3). Values for $R_{max}$ and $S_{max}$ were based on historical (pre-1955) and contemporary (1992–2015) Ricker stock-recruit relationships (Ricker 1975) previously estimated for Ciscos in Wisconsin waters of Lake Superior and are provided in the Methods section (Rook et al. 2021). Confidence intervals (95% CIs) for each median value are provided in the Supplementary Material (Supplemental Material, Table S1).
Table 4. Habitat area-specific numbers of fry (Fry), fall fingerling (Fingerling), and age-1 (Age-1) Ciscoes *Coregonus artedi* (billions of fish) needed for stocking in the Laurentian Great Lakes to mimic historical and contemporary adult recruitment rates in Wisconsin waters of Lake Superior. The first column (Lake or Habitat Area) corresponds to cities, towns, or geographic features near each area, whereas the second column (Figure 3 Label) corresponds to labels used for each area in Figure 3 (H = Huron, M = Michigan, E = Erie, and O = Ontario). Because of its small size, Lake Saint Clair was treated as both a lake and single habitat area. Values were estimated using bootstrap methods (Zar 1999) and represent the median density of each life stage (fry, fall fingerling, or age-1) needed to mimic historical or contemporary spawning stock size required to produce peak age-1 recruitment $S_{\text{max}}$ (Adult Equivalents) after conversion to numbers of fish using estimates of area up to 80 m depth (ha; see Figures 1 and 3). Values for $S_{\text{max}}$ were based on historical (pre-1955) and contemporary (1992–2015) Ricker stock-recruit relationships (Ricker 1975) previously estimated for Ciscoes in Wisconsin waters of Lake Superior and are provided in the Methods section (Rook et al. 2021). Basin-wide (except Lake Superior) and lake-wide values for numbers of fish are equivalent to “scaling up” or combining individual habitat areas at the spatial scale of interest (basin-wide or lake-wide). All basin-wide values are equivalent to those in Figure 5. Confidence intervals (95% CIs) for each median value are provided in the Supplementary Material (Supplemental Material, Table S2).

Table 5. Habitat area-specific numbers of fry (Fry), fall fingerling (Fingerling), and age-1 (Age-1) Ciscoes *Coregonus artedi* (billions of fish) needed for stocking in the Laurentian Great Lakes to mimic historical and contemporary age-1 recruitment rates in Wisconsin waters of Lake Superior. The first column (Lake or Habitat Area) corresponds to cities, towns, or geographic features near each area, whereas the second column (Figure 3 Label) corresponds to labels used...
for each area in Figure 3 (H = Huron, M = Michigan, E = Erie, and O = Ontario). Because of its small size, Lake Saint Clair was treated as both a lake and single habitat area. Values were estimated using bootstrap methods (Zar 1999) and represent the median density of each life stage (fry, fall fingerling, or age-1) needed to mimic historical or contemporary peak age-1 recruitment \( R_{\text{max}} \) (Age-1 Equivalents) after conversion to numbers of fish using estimates of area up to 80 m depth (ha; see Figures 1 and 3). Values for \( R_{\text{max}} \) were based on historical (pre-1955) and contemporary (1992–2015) Ricker stock-recruit relationships (Ricker 1975) previously estimated for Ciscoes in Wisconsin waters of Lake Superior and are provided in the Methods section (Rook et al. 2021). Basin-wide (except Lake Superior) and lake-wide values for numbers of fish are equivalent to “scaling up” or combining individual habitat areas at the spatial scale of interest (basin-wide or lake-wide). All basin-wide values are equivalent to those in Figure 5. Confidence intervals (95% CIs) for each median value are provided in the Supplementary Material (Supplemental Material, Table S3).

**Figure Captions**

**Figure 1.** Study area and land-based air temperature monitoring stations (labeled points) used to determine the number of Ciscoes *Coregonus artedi* needed for stocking in the Laurentian Great Lakes to mimic historical and contemporary age-1 and adult recruitment rates in Wisconsin waters of Lake Superior. Major latitude and longitude lines are identified by tic marks along the border of the figure. States (United States [U.S.]) and provinces (Canada) are identified by their standard two-letter postal abbreviations (MN = Minnesota, IA = Iowa, WI = Wisconsin, IL = Illinois, MI = Michigan, IN = Indiana, ON = Ontario, OH = Ohio, PA = Pennsylvania, NY = New York, and QC = Quebec). As with previous studies, area up to 80 m depth (ha) was estimated using 80-m depth contours (Rook et al. 2013), which include all
unshaded (white) areas within each lake (see Supplemental Material, Shapefiles S1–S6). These areas are generally near shorelines in Lakes Superior, Huron, Michigan, and Ontario, but include all of Lakes Erie and Saint Clair. Contemporary (1990–2016) summary data for land-based monitoring stations near each lake were used to estimate lake-specific average annual air temperatures $T$ ($\degree C$; see Supplemental Material, Data S1). Stations near Lake Superior are those used by Rook et al. (2021). Lake-specific estimates of $T$, bootstrap methods (Zar 1999), and a stochastic version of the Pauly equation (Pauly 1980) were used to estimate instantaneous natural mortality $M$ (see Table 1; Ricker 1975).

**Figure 2.** Combined commercial harvest (millions of kg) of Ciscos *Coregonus artedi* and deepwater ciscoes *Coregonus* spp. in Lakes Superior, Huron, Michigan, Erie, Ontario, and Saint Clair during 1880–2015 (Baldwin et al. 2018). Commercial fishery records were sporadic prior to the early-1900s. Data are for all jurisdictions within each lake combined. All $y$-axes are different to better show lake-specific declines. Nearly all Cisco and deepwater cisco populations in the Laurentian Great Lakes were reduced or extirpated basin-wide by the 1970s.

**Figure 3.** Study area and individual habitat areas within each lake used to determine the number of Ciscos *Coregonus artedi* needed for stocking in the Laurentian Great Lakes to mimic historical and contemporary age-1 and adult recruitment rates in Wisconsin waters of Lake Superior. Major latitude and longitude lines are identified by tic marks along the border of the figure. States (United States [U.S.]) and provinces (Canada) are identified by their standard two-letter postal abbreviations (MN = Minnesota, IA = Iowa, WI = Wisconsin, IL = Illinois, MI = Michigan, IN = Indiana, ON = Ontario, OH = Ohio, PA = Pennsylvania, NY = New York, and QC = Quebec). Labels used for each area correspond to the second column (Figure 3 Label) in Tables 2 and 4–5 (H = Huron, M = Michigan, E = Erie, and O = Ontario). Because of its small
size, Lake Saint Clair was treated as both a lake and single habitat area. Estimates of area up to 80 m depth (ha; see Table 2) were generated by overlaying habitat area-specific polygons in this figure with bathymetry data in Figure 1 using ArcMap (Environmental Systems Research Institute, Redlands, California). Habitat area-specific polygons were delineated within each lake based on published descriptions of historical Cisco spawning and rearing areas from Koelz (1926, 1929), Organ et al. (1979), and Goodyear et al. (1982). The shapefile used to generate this figure is available in the Supplementary Material (Supplemental Material, Shapefile S7).

**Figure 4.** Lake-specific estimates of fry (Fry), fall fingerling (Fingerling), and age-1 (Age-1) stocking densities (fish/ha) used to determine the number of Ciscoes *Coregonus artedi* needed for stocking in the Laurentian Great Lakes to mimic historical and contemporary age-1 and adult recruitment rates in Wisconsin waters of Lake Superior. Values are provided in descending order for stocking density (all life stages) and are equivalent to those in Table 3. Lake Superior is only included for comparison. Values were estimated using bootstrap methods (Zar 1999) and represent the median density of each life stage (fry, fall fingerling, or age-1) needed to mimic historical (Hist.) or contemporary (Cont.) peak age-1 recruitment $R_{\text{max}}$ (Age-1 Equivalents) or the spawning stock size required to produce peak age-1 recruitment $S_{\text{max}}$ (Adult Equivalents) after applying 1,000 random combinations of instantaneous natural mortality $M$ (Ricker 1975) between stocking and the age-1 or adult life stages. These values were converted to numbers of fish using estimates of area up to 80 m depth (ha; see Figures 1 and 3). Values for $R_{\text{max}}$ and $S_{\text{max}}$ were based on historical (pre-1955) and contemporary (1992–2015) Ricker stock-recruit relationships (Ricker 1975) previously estimated for Ciscoes in Wisconsin waters of Lake Superior and are provided in the Methods section (Rook et al. 2021). Error bars represent upper and lower 95% confidence intervals for median values (95% CIs; U95 and L95),
which are provided in the Supplementary Material (Supplemental Material, Table S1). Error bars are not provided for historical or contemporary age-1 stocking densities in the lower panel because estimates were equivalent to previously reported values (Rook et al. 2021) and no back-calculations were used.

**Figure 5.** Basin-wide (except Lake Superior) numbers of fry (Fry), fall fingerling (Fingerling), and age-1 (Age-1) Ciscoes *Coregonus artedi* (billions of fish) needed for stocking in the Laurentian Great Lakes to mimic historical and contemporary age-1 and adult recruitment rates in Wisconsin waters of Lake Superior. Values are provided in descending order for numbers of fish (all life stages). Values were estimated using bootstrap methods (Zar 1999) and represent the median density of each life stage (fry, fall fingerling, or age-1) needed to mimic historical (Hist.) or contemporary (Cont.) peak age-1 recruitment $R_{max}$ (Age-1 Equivalents) or the spawning stock size required to produce peak age-1 recruitment $S_{max}$ (Adult Equivalents) after conversion to numbers of fish using estimates of area up to 80 m depth (ha; see Figures 1 and 3). Values for $R_{max}$ and $S_{max}$ were based on historical (pre-1955) and contemporary (1992–2015) Ricker stock-recruit relationships (Ricker 1975) previously estimated for Ciscoes in Wisconsin waters of Lake Superior and are provided in the Methods section (Rook et al. 2021). Basin-wide (except Lake Superior) values for numbers of fish are equivalent to “scaling up” or combining individual habitat areas at the basin-wide scale. All basin-wide values are equivalent to those in Tables 4–5. Error bars represent upper and lower 95% confidence intervals for median values (95% CIs; U95 and L95), which are provided in the Supplementary Material (Supplemental Material, Tables S2–S3). Error bars are not provided for historical or contemporary age-1 stocking densities for age-1 equivalents because estimates were equivalent to previously reported values (Rook et al. 2021) and no back-calculations were used.
Table 1.

| Lake  | Air Temperature $T$ $^\circ$C | SE $^\circ$C | Historical $M$ | Contemporary $M$ |
|-------|-------------------------------|-------------|----------------|------------------|
| Erie  | 10.1                          | 0.80        | 0.48           | 0.35             |
| Saint Clair | 9.8     | 0.90        | 0.47           | 0.34             |
| Ontario | 8.8       | 0.86        | 0.45           | 0.32             |
| Michigan | 8.1     | 1.08        | 0.43           | 0.31             |
| Huron  | 7.4                           | 0.95        | 0.42           | 0.30             |
| Superior | 5.5     | 0.22        | 0.36           | 0.26             |
Table 2.

| Lake or Habitat Area                  | Figure 3 Label | Width (km) | Area ≤ 80 m Depth (millions of ha) | Area ≤ 80 m Depth (%) |
|---------------------------------------|----------------|------------|-------------------------------------|-----------------------|
| Lake Superior                         | Lake Superior  | 600        | 2.030                               | 25                    |
| Wisconsin                             | Wisc.          | 170        | 0.344                               | 65                    |
| Basin-Wide                            | N/A            | N/A        | 7.987                               | 86                    |
| Lake Huron                            | Lake Huron     | 420        | 3.574                               | 89                    |
| Cheboygan/St. Ignace                  | H-1            | 70         | 0.179                               | 94                    |
| West North Channel                    | H-2            | 85         | 0.172                               | 100                   |
| East North Channel                    | H-3            | 120        | 0.259                               | 100                   |
| Drummond/Manitoulin                   | H-4            | 150        | 0.206                               | 65                    |
| South Bay                             | H-5            | 30         | 0.014                               | 100                   |
| North Georgian Bay                    | H-6            | 120        | 0.593                               | 87                    |
| South Georgian Bay                    | H-7            | 140        | 0.650                               | 78                    |
| Southampton/Stokes Bay                | H-8            | 125        | 0.221                               | 67                    |
| Goderich                              | H-9            | 70         | 0.128                               | 98                    |
| Port Huron                            | H-10           | 80         | 0.293                               | 100                   |
| Harbor Beach                          | H-11           | 65         | 0.139                               | 100                   |
| Saginaw Bay                           | H-12           | 130        | 0.457                               | 100                   |
| Thunder Bay                           | H-13           | 75         | 0.167                               | 89                    |
| Rogers City                           | H-14           | 65         | 0.096                               | 72                    |
| Lake Michigan                         | Lake Michigan  | 525        | 2.242                               | 76                    |
| Chicago/Gary/Michigan City            | M-1            | 100        | 0.399                               | 94                    |
| Waukegan                              | M-2            | 80         | 0.166                               | 79                    |
| Milwaukee/Sheboygan                   | M-3            | 155        | 0.236                               | 61                    |
| Kewaunee/Algoma                       | M-4            | 75         | 0.083                               | 44                    |
| Green Bay                             | M-5            | 190        | 0.628                               | 83                    |
| Manistique                            | M-6            | 115        | 0.295                               | 98                    |
| Traverse City/Petoskey                | M-7            | 100        | 0.154                               | 74                    |
| Holland/Muskegon                      | M-8            | 165        | 0.280                               | 73                    |
| Lake Erie                             | Lake Erie      | 405        | 1.455                               | 100                   |
| Detroit River                         | E-1            | 35         | 0.052                               | 100                   |
| Leamington/Wheatley                   | E-2            | 65         | 0.125                               | 100                   |
| Rondeau/Stanley/Burwell               | E-3            | 135        | 0.331                               | 100                   |
| Long Point Bay                        | E-4            | 100        | 0.261                               | 100                   |
| Dunkirk                               | E-5            | 35         | 0.051                               | 100                   |
| Erie                                  | E-6            | 70         | 0.140                               | 100                   |
| Sandusky/Cleveland                    | E-7            | 175        | 0.463                               | 100                   |
| Maumee Bay                            | E-8            | 25         | 0.032                               | 100                   |
| Lake Ontario                          | Lake Ontario   | 315        | 0.601                               | 74                    |
| Location                          | Code | Depth | Concentration | Temperature |
|----------------------------------|------|-------|---------------|-------------|
| Hamilton                         | O-1  | 35    | 0.054         | 85          |
| Toronto                          | O-2  | 35    | 0.033         | 65          |
| Brighton                         | O-3  | 75    | 0.137         | 97          |
| Bay of Quinte                    | O-4  | 85    | 0.076         | 100         |
| Chaumont Bay                     | O-5  | 45    | 0.083         | 100         |
| Nine Mile/North Pond             | O-6  | 55    | 0.084         | 62          |
| Irondequoit/Sodus                 | O-7  | 95    | 0.086         | 40          |
| St. Catharines/Niagra/Wilson     | O-8  | 60    | 0.049         | 45          |
| **Lake Saint Clair**             |      | 50    | **0.115**     | **100**     |
### Table 3.

| Lake      | Stocking Density (fish/ha) - Adult ($S_{max}$) Equivalents | Stocking Density (fish/ha) - Age-1 ($R_{max}$) Equivalents |
|-----------|------------------------------------------------------------|------------------------------------------------------------|
|           | Historical Fry | Historical Fingerling | Historical Age-1 | Contemporary Fry | Contemporary Fingerling | Contemporary Age-1 |
| Erie      | 1,553          | 959                  | 593             | 156             | 111                    | 78                |
| Saint Clair | 1,490          | 927                  | 578             | 151             | 107                    | 76                |
| Ontario   | 1,327          | 846                  | 538             | 136             | 99                     | 71                |
| Michigan  | 1,221          | 791                  | 512             | 126             | 92                     | 67                |
| Huron     | 1,101          | 727                  | 480             | 115             | 85                     | 63                |
| Superior  | 838            | 583                  | 406             | 90              | 70                     | 54                |
| Erie      | 948            | 585                  | 362             | 86              | 61                     | 43                |
| Saint Clair | 931            | 580                  | 362             | 85              | 60                     | 43                |
| Ontario   | 891            | 567                  | 362             | 82              | 59                     | 43                |
| Michigan  | 865            | 559                  | 362             | 80              | 59                     | 43                |
| Huron     | 828            | 548                  | 362             | 78              | 58                     | 43                |
| Superior  | 748            | 520                  | 362             | 72              | 56                     | 43                |
Table 4.

| Lake or Habitat Area                  | Figure 3 Label | Historical Adult ($S_{max}$) Equivalents (billions of fish) | Contemporary Adult ($S_{max}$) Equivalents (billions of fish) |
|--------------------------------------|----------------|-------------------------------------------------------------|-------------------------------------------------------------|
|                                      |                | Fry   | Fingerling | Age-1   | Fry   | Fingerling | Age-1   |
| Basin-Wide                           | N/A            | 9.908 | 6.387     | 4.121   | 1.021 | 0.744      | 0.543   |
| Lake Huron                           | Lake Huron     | 3.942 | 2.602     | 1.719   | 0.411 | 0.305      | 0.227   |
|                                      |                | H-1   | 0.197     | 0.130    | 0.086 | 0.021      | 0.015   | 0.011   |
|                                      |                | H-2   | 0.190     | 0.125    | 0.083 | 0.020      | 0.015   | 0.011   |
|                                      |                | H-3   | 0.285     | 0.188    | 0.124 | 0.030      | 0.022   | 0.016   |
|                                      |                | H-4   | 0.227     | 0.150    | 0.099 | 0.024      | 0.018   | 0.013   |
|                                      |                | H-5   | 0.015     | 0.010    | 0.007 | 0.002      | 0.001   | 0.001   |
|                                      |                | H-6   | 0.654     | 0.432    | 0.285 | 0.068      | 0.051   | 0.038   |
|                                      |                | H-7   | 0.717     | 0.473    | 0.313 | 0.075      | 0.055   | 0.041   |
|                                      |                | H-8   | 0.244     | 0.161    | 0.106 | 0.025      | 0.019   | 0.014   |
|                                      |                | H-9   | 0.142     | 0.093    | 0.062 | 0.015      | 0.011   | 0.008   |
|                                      |                | H-10  | 0.323     | 0.213    | 0.141 | 0.034      | 0.025   | 0.019   |
|                                      |                | H-11  | 0.153     | 0.101    | 0.067 | 0.016      | 0.012   | 0.009   |
|                                      |                | H-12  | 0.504     | 0.332    | 0.220 | 0.053      | 0.039   | 0.029   |
|                                      |                | H-13  | 0.184     | 0.122    | 0.080 | 0.019      | 0.014   | 0.011   |
|                                      |                | H-14  | 0.106     | 0.070    | 0.046 | 0.011      | 0.008   | 0.006   |
| Lake Michigan                        | Lake Michigan  | 2.734 | 1.770     | 1.146   | 0.282 | 0.207      | 0.151   |
|                                      |                | M-1   | 0.486     | 0.315    | 0.204 | 0.050      | 0.037   | 0.027   |
|                                      |                | M-2   | 0.203     | 0.131    | 0.085 | 0.021      | 0.015   | 0.011   |
|                                      |                | M-3   | 0.288     | 0.187    | 0.121 | 0.030      | 0.022   | 0.016   |
|                                      |                | M-4   | 0.102     | 0.066    | 0.043 | 0.010      | 0.008   | 0.006   |
|                                      |                | M-5   | 0.765     | 0.496    | 0.321 | 0.079      | 0.058   | 0.042   |
|                                      |                | M-6   | 0.359     | 0.233    | 0.151 | 0.037      | 0.027   | 0.020   |
|                                      |                | M-7   | 0.188     | 0.122    | 0.079 | 0.019      | 0.014   | 0.010   |
|                                      |                | M-8   | 0.342     | 0.221    | 0.143 | 0.035      | 0.026   | 0.019   |
| Lake Erie                            | Lake Erie      | 2.264 | 1.399     | 0.865   | 0.228 | 0.161      | 0.114   |
|                                      |                | E-1   | 0.081     | 0.050    | 0.031 | 0.008      | 0.006   | 0.004   |
|                                      |                | E-2   | 0.195     | 0.120    | 0.074 | 0.020      | 0.014   | 0.010   |
|                                      |                | E-3   | 0.515     | 0.318    | 0.197 | 0.052      | 0.037   | 0.026   |
|                                      |                | E-4   | 0.406     | 0.251    | 0.155 | 0.041      | 0.029   | 0.020   |
|                                      |                | E-5   | 0.079     | 0.049    | 0.030 | 0.008      | 0.006   | 0.004   |
|                                      |                | E-6   | 0.218     | 0.135    | 0.083 | 0.022      | 0.016   | 0.011   |
|                                      |                | E-7   | 0.720     | 0.445    | 0.275 | 0.072      | 0.051   | 0.036   |
|                                      |                | E-8   | 0.050     | 0.031    | 0.019 | 0.005      | 0.004   | 0.003   |
| Lake Ontario                         | Lake Ontario   | 0.798 | 0.508     | 0.324   | 0.082 | 0.059      | 0.043   |
|                                      |                | O-1   | 0.072     | 0.046    | 0.029 | 0.007      | 0.005   | 0.004   |
| Location                        | O-2 | O-3 | O-4 | O-5 | O-6 | O-7 | O-8 | O-9 | O-10 | O-11 | O-12 | O-13 | O-14 | O-15 | O-16 |
|--------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Toronto                        | 0.043 | 0.028 | 0.018 | 0.004 | 0.003 | 0.002 | | | | | | | | | |
| Brighton                       | 0.182 | 0.116 | 0.074 | 0.019 | 0.013 | 0.010 | | | | | | | | | |
| Bay of Quinte                  | 0.101 | 0.064 | 0.041 | 0.010 | 0.007 | 0.005 | | | | | | | | | |
| Chaumont Bay                   | 0.110 | 0.070 | 0.045 | 0.011 | 0.008 | 0.006 | | | | | | | | | |
| Nine Mile/North Pond           | 0.111 | 0.071 | 0.045 | 0.011 | 0.008 | 0.006 | | | | | | | | | |
| Irondequoit/Sodus               | 0.114 | 0.073 | 0.046 | 0.012 | 0.008 | 0.006 | | | | | | | | | |
| St. Catharines/Niagra/Wilson   | 0.064 | 0.041 | 0.026 | 0.007 | 0.005 | 0.003 | | | | | | | | | |
| Lake Saint Clair               | 0.171 | 0.106 | 0.066 | 0.017 | 0.012 | 0.009 | | | | | | | | | |
### Table 5.

| Lake or Habitat Area | Figure 3 Label | Historical Age-1 ($R_{max}$) Equivalents (billions of fish) | Contemporary Age-1 ($R_{max}$) Equivalents (billions of fish) |
|----------------------|----------------|-------------------------------------------------------------|-------------------------------------------------------------|
|                      |                | Fry | Fingerling | Age-1 | Fry | Fingerling | Age-1 |
| Basin-Wide           | N/A           | 6.916 | 4.469 | 2.892 | 0.641 | 0.469 | 0.343 |
| Lake Huron           | Lake Huron    | 2.961 | 1.957 | 1.294 | 0.278 | 0.206 | 0.153 |
| Cheboygan/St. Ignace  | H-1           | 0.148 | 0.098 | 0.065 | 0.014 | 0.010 | 0.008 |
| West North Channel   | H-2           | 0.143 | 0.094 | 0.062 | 0.013 | 0.010 | 0.007 |
| East North Channel   | H-3           | 0.214 | 0.142 | 0.094 | 0.020 | 0.015 | 0.011 |
| Drummond/Manitoulin  | H-4           | 0.171 | 0.113 | 0.075 | 0.016 | 0.012 | 0.009 |
| South Bay            | H-5           | 0.011 | 0.007 | 0.005 | 0.001 | 0.001 | 0.001 |
| North Georgian Bay   | H-6           | 0.491 | 0.325 | 0.215 | 0.046 | 0.034 | 0.025 |
| South Georgian Bay   | H-7           | 0.538 | 0.356 | 0.235 | 0.051 | 0.038 | 0.028 |
| Southampton/Stokes Bay| H-8         | 0.183 | 0.121 | 0.080 | 0.017 | 0.013 | 0.010 |
| Goderich             | H-9           | 0.106 | 0.070 | 0.046 | 0.010 | 0.007 | 0.006 |
| Port Huron           | H-10          | 0.243 | 0.160 | 0.106 | 0.023 | 0.017 | 0.013 |
| Harbor Beach         | H-11          | 0.115 | 0.076 | 0.050 | 0.011 | 0.008 | 0.006 |
| Saginaw Bay          | H-12          | 0.378 | 0.250 | 0.165 | 0.035 | 0.026 | 0.020 |
| Thunder Bay          | H-13          | 0.138 | 0.092 | 0.061 | 0.013 | 0.010 | 0.007 |
| Rogers City          | H-14          | 0.079 | 0.052 | 0.035 | 0.007 | 0.006 | 0.004 |
| Lake Michigan        | Lake Michigan | 1.935 | 1.251 | 0.812 | 0.179 | 0.131 | 0.096 |
| Chicago/Gary/Michigan City | M-1   | 0.344 | 0.223 | 0.144 | 0.032 | 0.023 | 0.017 |
| Waukegan             | M-2           | 0.144 | 0.093 | 0.060 | 0.013 | 0.010 | 0.007 |
| Milwaukee/Sheboygan  | M-3           | 0.204 | 0.132 | 0.086 | 0.019 | 0.014 | 0.010 |
| Kewaunee/Algoma      | M-4           | 0.072 | 0.046 | 0.030 | 0.007 | 0.005 | 0.004 |
| Green Bay            | M-5           | 0.542 | 0.350 | 0.227 | 0.050 | 0.037 | 0.027 |
| Manistique           | M-6           | 0.254 | 0.165 | 0.107 | 0.024 | 0.017 | 0.013 |
| Traverse City/Petoskey| M-7         | 0.133 | 0.086 | 0.056 | 0.012 | 0.009 | 0.007 |
| Holland/Muskegon     | M-8           | 0.242 | 0.156 | 0.101 | 0.022 | 0.016 | 0.012 |
| Lake Erie            | Lake Erie     | 1.378 | 0.853 | 0.527 | 0.125 | 0.088 | 0.062 |
| Detroit River        | E-1           | 0.049 | 0.030 | 0.019 | 0.004 | 0.003 | 0.002 |
| Leamington/Wheatley  | E-2           | 0.119 | 0.073 | 0.045 | 0.011 | 0.008 | 0.005 |
| Rondeau/Stanley/Burwell| E-3         | 0.314 | 0.194 | 0.120 | 0.028 | 0.020 | 0.014 |
| Long Point Bay       | E-4           | 0.247 | 0.153 | 0.095 | 0.022 | 0.016 | 0.011 |
| Dunkirk              | E-5           | 0.048 | 0.030 | 0.018 | 0.004 | 0.003 | 0.002 |
| Erie                 | E-6           | 0.133 | 0.082 | 0.051 | 0.012 | 0.009 | 0.006 |
| Sandusky/Cleveland   | E-7           | 0.438 | 0.271 | 0.168 | 0.040 | 0.028 | 0.020 |
| Maumee Bay           | E-8           | 0.030 | 0.019 | 0.012 | 0.003 | 0.002 | 0.001 |
| Lake Ontario         | Lake Ontario  | 0.536 | 0.341 | 0.218 | 0.049 | 0.036 | 0.026 |
| Hamilton             | O-1           | 0.048 | 0.031 | 0.020 | 0.004 | 0.003 | 0.002 |
| Location                          | Code | O-2 | O-3  | O-4  | O-5  | O-6  | O-7  | O-8  | Lake Saint Clair |
|----------------------------------|------|-----|------|------|------|------|------|------|-----------------|
| Toronto                          | O-2  | 0.029 | 0.019 | 0.012 | 0.003 | 0.002 | 0.001 |
| Brighton                         | O-3  | 0.122 | 0.078 | 0.050 | 0.011 | 0.008 | 0.006 |
| Bay of Quinte                    | O-4  | 0.068 | 0.043 | 0.027 | 0.006 | 0.005 | 0.003 |
| Chaumont Bay                     | O-5  | 0.074 | 0.047 | 0.030 | 0.007 | 0.005 | 0.004 |
| Nine Mile/North Pond             | O-6  | 0.075 | 0.048 | 0.030 | 0.007 | 0.005 | 0.004 |
| Irondequoit/Sodus                 | O-7  | 0.077 | 0.049 | 0.031 | 0.007 | 0.005 | 0.004 |
| St. Catharines/Niagra/Wilson     | O-8  | 0.043 | 0.028 | 0.018 | 0.004 | 0.003 | 0.002 |
| Lake Saint Clair                 | Lake Saint Clair | 0.107 | 0.067 | 0.041 | 0.010 | 0.007 | 0.005 |
Figure 1.
Figure 2.
Figure 3.
Figure 4.
Figure 5.
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