Dissolved Oxygen Tolerance Guilds of Adult and Juvenile Great Lakes Fish Species

Rex W.K. Tang, Susan E. Doka, Erin L. Gertzen, and Leah M. Neigum

Fisheries and Oceans Canada
Central and Arctic Region (Fisheries Ecology Section)
Great Lakes Laboratory for Fisheries and Aquatic Sciences
867 Lakeshore Road
Burlington, Ontario L7S 1A1

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DISSOLVED OXYGEN TOLERANCE GUILDS OF ADULT AND JUVENILE GREAT LAKES FISH SPECIES

by

Rex W.K. Tang, Susan E. Doka, Erin L. Gertzen, and Leah M. Neigum

Central and Arctic Region
Fisheries Ecology Section
Great Lakes Laboratory for Fisheries and Aquatic Sciences
867 Lakeshore Road
Burlington, ON
L7S 1A1

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Tang, R.W.K., Doka, S.E., Gertzen, E.L., Neigum, L.M. 2020. Dissolved oxygen tolerance guilds of adult and juvenile Great Lakes fish species. Can. Manuscr. Rep. Fish. Aquat. Sci. 3193: viii + 69 p.

Habitat suitability matrices (HSM) for calculating habitat supply have long been an irreplaceable tool in fish habitat assessments. A key component in HSM is defining fish guild assemblages. We selected dissolved oxygen (DO) tolerance as the essential factor to characterize fish guild assemblages for fish habitat assessments in the Great Lakes. Hypoxia is a form of habitat loss that can cause physiological stress on fish and lead to widespread mortality and changes in fish community assemblages. To determine “sensitive,” “mesotolerant,” and “tolerant” DO tolerance guilds for Great Lakes fish species, we conducted a one-dimensional k-means cluster analysis using mean DO tolerance levels extracted from the literature. To verify our “HABLAB" results, we assigned confidence values to our classifications based on a weight of evidence approach. Our results were further refined by combining with other known indices of general and DO fish tolerances (Barbour et al. 1999; Meador and Carlisle 2007; Trebitz et al. 2007; Eakins 2019) using a weighted average approach (Method 1) and a majority rule approach (Method 2). The final guild classification was decided using a decision tree, which took into account a combination of the lines of evidence provided by our HABLAB dataset and other reported tolerance indices. Of the 164 Great Lakes freshwater fish species considered in this study, 43 (27%), 81 (50%), and 20 (12%) species were assigned to the sensitive, mesotolerant, and tolerant guilds, respectively. To our knowledge, this study is the first to use a weight of evidence approach incorporating summarized information from literature and existing guild classification in sorting DO tolerance fish guilds. The results from this study can further provide a foundational framework to inform future fish habitat assessments in the Great Lakes.

RÉSUMÉ

Tang, R.W.K., Doka, S.E., Gertzen, E.L., Neigum, L.M. 2020. Dissolved oxygen tolerance guilds of adult and juvenile Great Lakes fish species. Can. Manuscr. Rep. Fish. Aquat. Sci. 3193: viii + 69 p.

Les matrices de convenance de l'habitat (MCH) pour le calcul de l'habitat disponible sont depuis longtemps un outil irremplaçable dans les évaluations de l'habitat du poisson. Un élément clé des MCH est la définition des assemblages de guildes de poissons. Nous avons choisi la tolérance à la teneur en oxygène dissous comme facteur essentiel pour caractériser les assemblages de guildes de poissons pour les évaluations de l'habitat du poisson dans les Grands Lacs. L'hypoxie est une forme de perte d'habitat qui peut provoquer un stress physiologique chez les poissons et entraîner une mortalité et des changements en grande échelle dans les assemblages de communautés de poissons. Pour déterminer les guildes de tolérance à la teneur en oxygène dissous « sensible », « à tolérance moyenne » et « tolérante » pour les espèces de poissons des Grands Lacs, nous avons effectué une analyse unidimensionnelle de classification automatique à K moyennes en utilisant les niveaux de tolérance moyens à la teneur en oxygène dissous puisés dans la documentation. Pour vérifier nos résultats « HABLAB », nous avons attribué des valeurs de confiance à nos classifications en nous basant sur une approche du poids de la preuve. Nos résultats ont été affinés en les combinant avec d'autres indices connus de tolérance générale et de tolérance des poissons à la teneur en oxygène dissous (Barbour *et al*., 1999; Meador et Carlisle, 2007; Trebitz *et al*., 2007; Eakins, 2019) en utilisant une approche fondée sur une moyenne pondérée (méthode 1) et une approche fondée sur la règle de la majorité (méthode 2). La classification finale des guildes a été établie à l'aide d'un arbre décisionnel, qui a pris en compte une combinaison des sources de données fournies par notre ensemble de données HABLAB et d'autres indices de tolérance signalés. Sur les 164 espèces de poissons d'eau douce des Grands Lacs considérées dans cette étude, 43 (27 %), 81 (50 %) et 20 (12 %) espèces ont été classées dans les guildes sensible, à tolérance moyenne et tolérante, respectivement. À notre connaissance, cette étude est la première à utiliser une approche du poids de la preuve tenant compte des données sommaires tirées de la documentation et de la classification existante des guildes pour le tri des guildes de poissons tolérants à la teneur en oxygène dissous. Les résultats de cette étude peuvent en outre fournir un cadre de base pour orienter les futures évaluations de l'habitat du poisson dans les Grands Lacs.

INTRODUCTION

FISH ASSEMBLAGE AND GUILDS

Fish assemblage characterization based on biological criteria and quantitative indices has been an integral part of biological assessment (Meador and Carlisle 2007), providing a qualitative measure of fish species' tolerance to environmental stressors, as well as a mode of comparison in habitat modelling (Minns et al. 2001). One example includes habitat suitability matrices (HSMs)—a set of rules and criteria applied in aggregate with habitat suitabilities for evaluating the ability of an ecoregion's to support fish. In the past, studies have classified fish species assemblages into functional fish guilds (Barbour et al. 1999; Elliott et al. 2007; Pegg et al. 2014; Eakins 2019) to characterize fish's tolerance to different environmental stressors.

Shelford's law of tolerance (Shelford 1912), which bases the limit for growth and distribution of an individual on the abundance and scarcity of an essential factor, is often applied to these classifications in conjunction with professional judgement (Meador and Carlisle 2007). Therefore, these tolerance guilds are often subjective in their classification and vary among studies, and have been criticized because of their qualitative nature (Aarts and Nienhuis 2003; Pegg et al. 2014; Eakins 2019).

A more recent approach has been to consolidate specific environmental factors—such as habitat tolerance, water quality, general tolerance (subjective assignment by Eakins (Eakins 2019) based on tolerance to a wide range of variables), and anthropogenic stress—into tolerance indicator values (TIV) and calculate relationships among TIVs to assign a tolerance class (Meador and Carlisle 2007). This approach is more empirical in nature and less subjective to professional judgement. However, fish classifications are highly dependent on the selection of essential factors, and covariation among factors is often a challenge.

DISSOLVED OXYGEN TOLERANCE

Supply of oxygen is an essential factor in the metabolic and life history processes of aerobic aquatic organisms. Hypoxia (depletion of dissolved oxygen [DO] in water) negatively affects the lives and diversity of aquatic organisms through widespread mortality (Davis 1975), physiological stress (Carlson et al. 1974; Bushnell et al. 1984; Zweifel et al. 2010), changes in fish community assemblages, and habitat loss (Davis 1975; Chapman 1986). Consequently, understanding spatial and temporal distribution dynamics of oxygen in water is fundamental for determining the distribution, behaviour, survival, and growth of fish in lakes (Wetzel 2001).

The solubility of oxygen in water is affected by water temperature. Water bodies with higher temperatures hold less DO and have increased likelihood of anoxic or hypoxic conditions than those with lower temperatures (Elshout et al. 2013). Studies have shown that fish mortality and avoidance behaviour can be a result of discrepancies between oxygen demand and oxygen supply (Pörtner and Knust 2007). Since the solubility of DO decreases with higher temperatures (Wetzel 2001), there is generally a loose association of low-DO sensitive species (e.g. Salmonidae) with cooler water temperatures. Inversely, low-DO tolerant species such as the Common Carp (*Cyprinus carpio*) are usually associated with higher water temperatures. The selection of habitat areas by fish is likely related to the combination of the optimal DO concentration and water temperature required for the overall metabolism of the fish, rather than these factors being individual habitat considerations.

Negative physiological effects and mortality in fish due to low DO concentrations in water depends on the DO tolerance of the individual and its ability to avoid hypoxic environments (Elshout et al. 2013). DO tolerance is linked to factors such as life stage and hypoxic adaptation. The ability to avoid averse conditions such as hypoxic environments is a behavioural response linked to a number of environmental stressors, such as overall water quality (including chlorophyll, ammonia, nitrate, turbidity, etc.), seasonal temperature changes, waterbody attributes (such as flow rates, proximity to wetlands and estuaries, waterbody shape), and the fish's ability to move away from the less ideal conditions.

Fish in earlier life stages (such as embryos and eggs) are known to be the least tolerant of low-DO environments because they have limited surface area for respiration and an inability to avoid hypoxic areas (Graham 2006; Elshout et al. 2013). In addition, fish egg and embryo development is often negatively affected when spawning beds in streams and small rivers are impacted by sedimentation (Soulsby et al. 2001), which can cause anoxia at the sediment-water interface.

Aquatic surface respiration (ASR) of fishes is an adaptive behavioural response that plays a role in increasing DO tolerance under hypoxic conditions, where some fish species move to the air-water interface for aquatic respiration (Kramer 1987). Even when water is mostly hypoxic, rapid oxygen diffusion occurs at a very thin zone near the surface, allowing fish to respire there (Kramer 1987). ASR is often a widespread adaptation to survive extreme hypoxia in tropical freshwater fishes (Kramer and McClure 1982). Since DO saturation in water is related to water temperature, the availability of access to the water surface to perform ASR had been shown to significantly increase critical thermal maxima (CTMax) (Rutledge and Beitinger 1989). This suggests that available DO is a stronger limiting factor than water temperature. Hence, DO tolerance in a given individual is affected by interacting biotic and abiotic factors and can vary among different species.

It is unclear whether DO tolerance is affected by fish size (Doudoroff and Shumway 1970; Pörtner and Knust 2007; Nilsson and Östlund-Nilsson 2008; Everett and Crawford 2010). A review investigating the DO tolerance of northwestern European freshwater fish species (Elshout et al. 2013) found that the mean DO lowest-observed-effect-concentrations (LOECs) of juvenile fish classes were lower than found for adult fish classes. Alternatively, Nilsson and Östlund-Nilsson (2008) also reviewed data for a range of families (Cichlidae, Cyprinidae, Centrachidae, Percidae, Sparidae, Salmonidae) and found that individual body sizes seemed to have little to no impact on DO uptake during hypoxic conditions. Over a wide fish-size range, they found that the respiratory surface area usually matched fish metabolic rates and concluded that if there were any size-related differences in the ability for oxygen uptake in fish, it was likely a reflection of adaptation in specific life-history processes (Nilsson and Östlund-Nilsson 2008).

SCOPE OF STUDY/ OBJECTIVES

To prepare for fish habitat assessment modelling in the lower Great Lakes using DO tolerance as our essential habitat suitability factor, we conducted an extensive literature review to compile widely scattered data on DO tolerances of Great Lakes fish species. Extensive reviews and primary research on fish DO tolerances were considered in our review, and tolerances were summarized by species and life stages.

Our objectives were to:

1. Compile DO tolerance data to categorize fish species from the Great Lakes into DO tolerance guild clusters, and

2. Use the compiled information to generate DO suitability curves for each DO tolerance guild to inform future fish habitat assessments.

METHODS

DO TOLERANCE LITERATURE REVIEW AND DATABASE COMPILATION

Our review of literature on Great Lakes fish species' DO tolerance focused on the DO tolerance guilds of adult, egg, embryo, fry, and juvenile Great Lakes fish species. A complete species list for Lake Ontario was provided by the Ontario Ministry of Natural Resources and Forestry. The keywords used for literature searches were:

1) species, genus, or common name,
2) Great Lakes,
3) DO, hypoxia, hypoxic, anoxia, and anoxic,
4) tolerance, and loss of equilibrium

Data extracted from each article were categorized by species (common name and scientific name), species' presence in the Great Lakes, life stage (adult, juvenile, young-of-the-year, and embryo and fry), sampling location, experimental methods, length of the study, experimental endpoints (lethal, sublethal), DO tolerance levels (mg/L), experimental temperatures, source of the reference, and the percent of sample negatively affected (Figure 1; Appendix Tables A1–A3; Supplementary material). For data extracted from literature reviews, the original source was recorded and cross-validated, and any repeated or duplicated data were removed from the initial dataset (Supplementary material). Where possible, DO tolerance level was reported in mg/L and temperature was reported in degrees Celsius (°C). Conversions were made from percent saturation, torrs, and partial pressure where enough information (e.g., temperature, pressure) was presented in the original source; otherwise, the information was discarded. Juvenile life stages were defined as older than young-of-the-year, but not reaching sexual maturity.

Previous studies have observed that DO tolerances of fish exposed to DO conditions below 100% lethal concentrations (LC_{100}) were not different between juvenile and adults (Elshout et al. 2013); however, the same study showed that juveniles had been observed to have a significantly lower mean LOEC (Elshout et al. 2013). Others found no effect of size on the tolerance to hypoxia in Atlantic Cod (*Gadus morhua;* Plante et al. 1998). In addition, past studies have shown that body size has little to no impact on the fishes' ability for DO uptake; this was attributed to respiratory surface areas generally matching metabolic rates (Nilsson and Östlund-Nilsson 2008). Adult and juvenile data were therefore combined into the same life-stage group to increase data availability for analysis.

With the assumption that DO tolerances are similar for the two life stages, and for the purpose of assessing fish habitat suitability, we aimed to capture an average tolerance. For the Great Lakes studies that did not have well-defined endpoints—and where fish could not be classified within one of the percent-of-individuals-negatively-affected categories (as shown in Figure 1)—the data were also excluded from the dataset. For example, in some studies or reviews, DO tolerance was described as the point where the initial negative effects were observed (e.g., fish started to display avoidance behaviour); this information was recorded as "starting effects" in the database. However, starting effects were never used for subsequent analyses due to ambiguity in translating individuals that were negatively affected. For consistent categorization of research conditions, when a study provided a range of DO tolerance levels (mg/L) across consistent conditions with the same experimental endpoint, the mean DO tolerance was taken.

Mean adult and juvenile fish DO tolerances (mg/L) were extracted from the compiled dataset based on the percentage of individuals negatively affected. Under this circumstance, 80% of individuals were considered to be negatively affected. The majority of studies we encountered assigned a percentage for negatively affected individuals based on exposure to DO concentrations associated with 50 or 100% mortality (LC_{50} and LC_{100}, respectively). Therefore, the percentage of responses that were negatively affected were categorized accordingly (< 50% or ≥ 50%, respectively).

LETHAL AND SUBLETHAL EXPERIMENTAL ENDPOINT GROUPINGS

Mean DO tolerance for each species was then further consolidated into two experimental endpoint subgroups: lethal and sublethal (Figure 1). The former group was defined by negative effects that caused fish mortality or the loss of equilibrium (LOE: defined as the inability of fish to maintain an upright position within the water column). The sublethal group was defined by impacts that included negative effects on fish ability for ASR, and on avoidance behaviour, metabolism, feeding, swimming, reproduction, and other toxic effects (Figure 1). Summarized information of the compiled dataset can be found in the appendix of this report (Tables A1–A10; Supplementary material).

Freshwater fish that utilize ASR have been known to increase their "perceived" tolerance to hypoxia (Kramer and McClure 1982). Therefore, we excluded any experimental data in our analysis where fish were given access to the surface. Since DO saturation is affected by temperature (Elshout et al. 2013), studies testing for DO tolerance at CTMax or critical thermal minima (CTMin) were also removed from the final dataset.

The dataset was partitioned into three subgroups based on experimental endpoints. Two subgroup categories were mentioned earlier: lethal and sublethal (Figure 1). To further investigate the possibility of overlap between lethal and sublethal DO tolerance levels, when species-specific data were available from both the lethal and sublethal experimental endpoint groups, the data were bootstrapped to create a third dataset: the "combination" group, which was not exclusive of the lethal and sublethal categories. This dataset allowed clustering of fish species with both lethal and sublethal DO tolerance levels, and helped inform final guild decisions (Supplementary material).

To validate our lethal and sublethal data partition, based on our sorting criteria described above, we tested for normality using the Shapiro-Wilk normality test (Shapiro.test function; R Software version 3.1.0, 2014) followed by a Kruskal-Wallis rank sum test (kruskal.test function; R Software version 3.1.0, 2014) across all species means of DO tolerances between lethal and sublethal groups for datasets where ≥ 50% of adults or juveniles were negatively affected. Statistical significance was set at $p < 0.05$.

"HABLAB" CLUSTER ANALYSIS

A three-guild classification scheme of tolerances to various environmental conditions for fish has been widely accepted: tolerant, moderate, and intolerant or sensitive (Halliwell et al. 1999). On occasion, however, fish are classified into four or five tolerance guilds (tolerant, moderately tolerant, moderately intolerant, and intolerant; Meador and Carlisle 2007). To maximize comparability between most studies, and because we felt the underlying data did not have adequate resolution for more breadth, DO tolerances were partitioned into three groups in this study; our initial results were deemed "HABLAB" clusters defined by "tolerant," "mesotolerant," and "sensitive" classifications.

We conducted k-means cluster analysis for the three guild clusters using the mean DO concentrations at the ≥ 50% negatively affected levels for juveniles and adults. K-means analysis is a prototype-based, partitional clustering technique that partitions observations into k groups, where the observations' sum of squares and their assigned cluster centroids are at a minimum (Hartigan and Wong 1979; Tan et al. 2013). Since k-means centroids were chosen randomly by default, one-dimension k-means cluster analysis (Ckmeans.1d.dp; R 3.1.0) was used for both the lethal and sublethal datasets. This clustering method partitions one-dimensional data using a dynamic programming algorithm that ensures repeatability and optimality of the analysis (Wang and Song 2011). Since the combination dataset was in two dimensions, a standard k-means analysis was used instead of one-dimensional cluster analysis (kmeans; R 3.1.0). We generated 25 initial configurations for the clustering and reported on the best possible guild sorting solution. Cluster analysis was performed across all available fish species (Supplementary material)

GUILD ASSIGNMENT CONSIDERATIONS

HABLAB verification: weight of evidence

To verify DO tolerance guild assignments for individual fish species from our cluster analyses (named "HABLAB" clusters), a "weight of evidence" approach was used (Webb et al. 2013). Confidence values were assigned to each fish species based on a number of criteria: 1) sample size, 2) reference diversity, and 3) relative standard deviation (Table 1). Sample size describes the total number of species-specific levels extracted from literature to determine the mean DO tolerance level; a higher confidence weight was assigned when more mean DO levels were available (Table 1). Reference diversity is the number of unique literature DO tolerance levels, where a higher confidence weight described a wider range of literature used to develop the mean levels (Table 1). Standard deviation describes whether the species-specific DO tolerance mean was within one standard deviation of the guild mean that was assigned using cluster analysis (Table 1). This criterion helped identify DO tolerance levels that were outliers to the specific guild. The total weight of the assigned guild was calculated as the sum of all three criteria for HABLAB clusters. The maximum weight of evidence for a specific guild assignment based on the three criteria for HABLAB clusters was 4.5 points (Table 1).

To verify our cluster assignments (HABLAB clusters), we compared our results with five other known indices of general environmental and DO tolerances in literature (Barbour et al. 1999; Meador and Carlisle 2007; Trebitz et al. 2007; Eakins 2019; Table 2). Indices from other literature were assigned a maximum weight of one.

1. The Barbour tolerance classification (Barbour et al. 1999) is a trophic and tolerance designation for selected fish species in the United States developed by the United States Environmental Protection Agency for environmental monitoring and bioassessment; tolerance classifications were relevant to non-specific stressors based on cited literature across the United States (Barbour et al. 1999).

2. Eakin's tolerance classification (Eakins 2019) was extracted from the Ontario Freshwater Fishes Life History Database. A species-specific tolerance class was defined to include species able to adapt to environmental perturbations or anthropogenic stresses and was based on *Freshwater Fishes of Canada* (Scott and Crossman 1985) and other supporting literature (Eakins 2019).

3. The Meador and Carlisle tolerance classification (Meador and Carlisle 2007) is based on tolerance indicator values (TIVs) calculated from weighted averaging inference models of 10 physicochemical variables across 773 stream sites collected as part of the U.S. Geological Survey's National Water-Quality Assessment Program.

4. We also included Meador and Carlisle's DO classification (Meador and Carlisle 2007) as an additional index from the water quality variables. Meador's DO classification defined ordinal ranks (1–10) where a rank of 1 represents the lowest 10% of TIVs, and a rank of 10 represents the highest 10% of TIVs. Ordinal ranks

were then further assigned to tolerance classifications based on their average scores where 1 to 4 = sensitive, > 4 to < 7 = mesotolerant, and 7 to 10 = tolerant (Meador and Carlisle 2007).

5. Trebitz's tolerance (Trebitz et al. 2007) is a fish guild tolerance assignment based on number of fish occurrences at varying turbidity in the Great Lakes coastal wetlands. Turbidity levels were measured in nephelometric turbidity units (NTU) and levels were set at 10, 25, and 50 NTUs, corresponding thresholds to the United States water quality criteria. Fish species were then classified into four distinct guilds based on their turbidity tolerance and occurrences (Trebitz et al. 2007; Table 2): occurrence at 10 NTU = intolerant; occurance across a turbidity gradient or no decline in relative abundance > 50 NTU = tolerant; multiple occurrences at > 10 NTU or one occurrence at > 25 NTU = moderately intolerant; and multiple occurrencs at > 25 NTU or reduced relative abundance > 50 NTU = moderately tolerant.

With the exception of the Meador DO tolerance indicies, other indices also included environmental and physicochemical factors (e.g., turbidity, pH, ammonia, phosphorus, chloride and nitrate). Therefore, an assumption was made that fish species that are sensitive to hypoxia are also sensitive to other environmental and physicochemical factors investigated from other indices. For example, Trebitz et al. (2007) tolerance classifications were classified based on species-specific turbidity tolerance. Turbidity is indirectly related to DO (Wetzel 2001), where high turbidity may increase light absorption in water and therefore also increase temperature and decrease DO saturation. While this assumption is not ideal (since some environmental factors in some indices may have more leverage), it provided this study a multi-layered systematic approach to verify the classifications. Additional sorting criteria were also applied to the final guild assignments to address discrepancy and disagreements between indices systematically, as described below.

Two methods were used to consolidate the weight of evidence from the HABLAB clusters and other indices to validate our final DO guild assignments.

Method 1 used a "weighted average approach," in which guild assignments from both HABLAB clusters and other indices were converted to scalar values (SClass), where 3 = sensitive guild (S), 2 = mesotolerant guild (M), and 1 = tolerant guild (T). Guild assignments from other indices with interim guilds were assigned ±0.5 points as necessary. For example, species assigned as in-between mesotolerant and tolerant (MT) were assigned a scalar value of 1.5. Next, the weighted mean guild was calculated based on the following equation:

$$G = \frac{\sum W_i * S_j}{\sum W_i} \qquad (1)$$

where G is the weight of evidence based guild assignment, W is the weight of evidence currently assigned to each guild assignment *i* (S, M, or T), and $SClass_j$ (S, M, or T) is the DO tolerance guild converted to a scalar value *j*. The guild assignment for this method was determined by rounding G to the nearest whole scalar value.

For Method 2, a “majority rule” approach was used, in which we used the sum-of-weights for each guild to determine the final guild assignment:

$$G_i = \sum W_{i,j} \qquad (2)$$

where G is the weight-of-evidence-based guild assignment, W is the weight assigned for each guild assignment “ *i* ” (S, M, or T) and for each index “ *j* “ (HABLAB, Barbour, Meador, Trebitz, Eakins). Guild assignment using Method 2 was based on a majority rule, where the final guild for each species was assigned based on G_i with the highest weight of evidence support. In cases where weights have equal support for two or more guilds, an in-between guild was assigned instead (e.g., mesotolerant/tolerant = MT, sensitive/mesotolerant = SM). For guild assignments with equal support for all 3 guilds ($G_S = G_M = G_T$), or considered to be conflicting (e.g., $G_S = G_T$), the results were considered inconclusive and needing more information for a final guild assignment (Figure 2).

Decision Tree and Final Guild Assignments

To combine our weight of evidence approach using Method 1 and Method 2, and to account for cases where limited information was available, a decision tree approach was used (Figure 2). The decision tree was developed using the following rules:

1) When the compiled data from our initial literature review were available, or when guild assignments between indices were not in conflict (conflict = difference between guild scalar values ≥ 1.5), the Method 1 weight of evidence approach was used for the final guild assignment (Figure 2). Otherwise, the species was classified as “additional information required.”

2) When HABLAB data were not available, and guild assignments from other indices were in conflict, the decision tree checks for the number of available indices (index count); if the count was ≥ 5, Method 2 was used as the final guild assignment, using the majority rule method. Otherwise, the species was classified as “additional information required.”

3) Any species with an index count of only 1 was automatically sorted as “additional information required.”

The decision tree method ensured that conflicting guild assignments between indices could be equally represented in the final guild assignment.

We examined the differences in guild assignments across methodologies with distribution and kernel density estimation (KDE). KDE is a non-parametric technique used to visualize distribution of a continuous random variable (Vokoun 2003). This method provided a way to visualize probability distribution overlaps between fish guild assignments. Smoothing bandwidths for each combination of guild classification, experimental effect (lethal, sublethal), and assignment method were chosen automatically based on the Silverman's rule-of-thumb Gaussian KDE (Silverman 2018).

Results for each DO guild sorting criteria and steps can be found in the Appendixes and Supplementary material provided in this report.

RESULTS

VERIFICATION OF LETHAL AND SUBLETHAL GROUPINGS

Of the 164 Great Lakes freshwater species considered in this study, 56 species were available with sufficient data for cluster analysis (Tables A1–A3). Two species were removed from the final species list (Deepwater Cisco, *Coregonus johannae* and Blue Pike/ Blue Walleye, *Sander Vitreus glaucus*) due to their 'extinct' status—as identified by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC)—in the Great Lakes region. Using the final database, we compared mean and median DO tolerances for the negatively affected groups of all species of adult and juvenile fish showing lethal and sublethal endpoints (Table 3). For all negatively affected groups, the mean lethal DO tolerance ranged from 1.20 to 3.85 mg/L, and the mean sublethal DO tolerance ranged from 0.80 to 5.83 mg/L (Table 3).

Sublethal effects of ASR showed the lowest overall combined mean and median DO tolerance for both the $< 50\%$ and $\geq 50\%$ negatively affected groups (Table 3). This indicates fish performing ASR have an adaptive advantage to low DO conditions and are generally more tolerant (Rutledge and Beitinger 1989). With the removal of ASR effects, DO tolerance level for all negatively affected groups of adults and juveniles ranged from 1.58 to 3.85 mg/L and 1.83 to 5.83 mg/L for lethal and sublethal effects groups, respectively.

Lethal and sublethal DO tolerances were not normally distributed (Shapiro-Wilk test; lethal, $W = 0.87$, $n = 41$, $p < 0.01$; sublethal, $W = 0.92$, $n = 36$, $p = 0.01$), so a Kruskal-Wallis rank sum test was performed to compare lethal and sublethal groups. DO tolerance of lethal and sublethal groups were significantly different ($X2 = 6.85$, $df = 1$, $p < 0.01$; Figure 3).

HABLAB CLUSTER ANALYSIS

A total of 56 species were available for k-means clustering for HABLAB clusters across datasets using the ≥50% negatively affected adults and juveniles DO tolerance data. There were 41 species available for cluster analysis in the lethal dataset, 36 species in the sublethal dataset, and 19 species in the combination dataset (Figures 4 and 5; Table 3). Between sum of squares and total sum of squares ranged from 74.7 to 89.6% for all datasets (Table 4), which indicates a good separation between DO tolerance guilds. For HABLAB guild assignments, clustering from the combination dataset was prioritized, followed by lethal or sublethal datasets where data were available (Table 4). For the HABLAB guild assignments, 3 (5.17%), 28 (48.28%), and 27 (46.55%) fish species were assigned to S, M, and T guilds, respectively (Table 5).

Final guild assignments generally agreed with other indices in other environmental tolerances, where the percentages of agreement were generally higher than disagreements (Tables 6 and 7). Comparing the clustering of this report (HABLAB) with the final guild assignments, HABLAB guilds only had a moderate agreement (Table 6). Among all DO guild indices considered for this study, Eakins (2019) had the highest percentage of agreement with our final guild classifications (Table 6; 75%), while Barbour's tolerance (1999) also showed good agreement with our final guild sorting (Table 6; 65%). However, Meador and Carlisle DO (2007) had a low agreement percentage (Table 6; 23%), but not with Meador general tolerance (Table 6; 46%). Trebitz turbidity tolerance index (2007) had 4 classifications and therefore cannot be directly compared with our final guild assignments, unless some classification are grouped (Table 7). The highest agreement between final guild assignments and Trebitz et al.'s (2007) turbidity tolerance index was 21% when the mesotolerant guilds were grouped (SM-MT: 21%), and the lowest agreement was when the sensitive guilds were grouped (S-SM: 15%). Percentage of species sorted into conflicting classifications (where a species is presumed to be within a tolerant guild but was classified as sensitive species or vice versa), were generally low (Tables 4–7; ~ 0 to 4%).

Weight of evidence and final decision tree guild assignments

Fish DO tolerance guilds were reassigned independently using a weighted average method (Method 1) and a majority rule method (Method 2). Additional species previously not available for HABLAB clustering were included in this part of the analysis due to their availability in other indices. For Method 1, 48 (29.63), 94 (58.02%), and 20 (12.35%) fish species were sorted into the S, M, and T guilds, respectively (Table 8). While for Method 2, 34 (20.99%), 16 (9.88%), 87 (53.70%), 2 (1.23%), 22 (13.58%), and 1 (0.62%) fish species were sorted into the S, SM, M, MT, T, and sensitive/tolerant (ST) guild assignments, respectively (Table 6 and Table 7).

Using the DO tolerance guild classification information from HABLAB guild, Method 1 and Method 2, a decision tree was incorporated to determine final DO tolerance guild classifications (Figure 2). A total of 43 (26.54%) species were assigned as the S guild, 81 (50.00%) species were assigned to the M guild, and 20 (12.35%) species were assigned to the T guild. Based on the results from the decision tree, 18 species will require additional information for guild assignment (Table 8).

KDE between DO tolerance guilds had considerable overlap for lethal DO levels for all clustering assignment methods (Figures 6–7). Kernel density for all guild combinations in the lethal group showed slight bimodal relationships across all clustering methods (Figure 7), and this was most evident in the HABLAB guilds. The highest probability density for the lethal groups range from 1.5 to 2.5 mg/L, indicating the range for a general lethal effects threshold for all guilds. Sublethal DO levels for all cluster assignment methods showed a much wider overall distribution (Figure 6–7), with the exception of the sublethal tolerant guilds, which showed a narrower distribution. This is expected because sublethal effects in our initial sorting covered a wide range of negative effects (Figure 1). Tolerant guilds in both lethal and sublethal groupings showed a narrow DO tolerance distribution (Figure 7), which suggests with decreasing

DO, there is a narrow window before tolerant fish species transition from experiencing sublethal to lethal effects. Generally, distributions across all combinations were better “smoothed” after applying the decision tree for final guild classification (Figure 7).

DISCUSSION

Employing a weight of evidence approach, we assigned a large number of fish species to the M guild and very few to the S guild (Table 5). We investigated the initial species’ sorting in the lethal and sublethal groups. Although lethal and sublethal groupings were significantly different (Figure 4), some species with combined information showed lower mean sublethal DO tolerance levels than the lethal group (Figure 5). This discrepancy can likely be attributed to the variation in study design, location, and local population of the fish used for the study. In addition, lethal and sublethal effects can also be hard to differentiate when approaching hypoxia, where a sublethal response can be a precursor to LOE or death shortly after (Table A1). For example, fathead minnows (*Pimephales promelas*) from southern Manitoba, Canada showed sublethal opercula movement response at 0.85 mg/L (Gee et al. 1978), but in another study, lethal tolerance of fathead minnow in Ontario, Canada was shown to be 2 mg/L.

Our final guild assignments generally agree with other indices in other environmental tolerances, where the percentage of agreement was higher than disagreements with a few minor exceptions (Tables 6 and 7). This is expected since each index used different sorting methods and parameters (Table 2) in the final guild decision. The combined weight of evidence approach provided a way to classify guilds based on existing information, accounting for the confidence values assigned based on sample size, reference diversity, and standard deviation of DO tolerance levels (Table 1). This was further compared with other supporting indices to increase classification confidence (Figure 2).

Where conflicting guild assignments existed, the weight of evidence approach allowed us to make systematic judgements on guild assignments. For example, Freshwater Drum (*Aplodinotus grunniens*) was classified as a sensitive species in the HABLAB guild clustering where only one mean DO tolerance level was extracted from the literature. Other indices classified it as a tolerant or mesotolerant species (Barbour et al. 1999; Meador and Carlisle 2007; Trebitz et al. 2007; Eakins 2019). Due to limited line of evidence from the HABLAB guild in the present study, classifications from other indices were favoured for the final guild assignment (Table 6, 33% disagreement with final guild assignments). This is especially evident in species with a designated COSEWIC status (Table 5) where only limited data is available, thereby requiring additional information from the other indices (Table 5).

In another example, Cisco was classified as a sensitive species by the HABLAB guild, where 10 mean DO tolerance levels were extracted from the literature for both lethal and sublethal datasets across two references. For other comparing indices, only classification from Eakins (2019) and Barbour et al. (1999) were available. Therefore, the HABLAB guild assignment was favoured in this scenario. We believe that by using this multi-layered weight of evidence approach, our DO tolerance guild classification provides a quantitative approach and valuable information in classifying fish DO guilds in Ontario.

DO tolerance levels were extracted from mean tolerance levels across various literature sources with varying methods and were compared with other guild classification indices for general environmental indices. It was assumed that fish species that are sensitive to hypoxia are also sensitive to other environmental and physicochemical factors investigated from other indices (e.g., turbidity, pH, ammonia, phosphorus, chloride, nitrate). However, this may not be the case since, for some indices, DO may not be the main driver for characterizing the other variables considered (Table 2).

Meador and Carlisle (2007) used tolerance indicator values (TIVs) to classify fish species tolerance to environmental disturbance and showed that water temperature, DO, and pH may not be as important in guild classifications compared to physical environmental factors such as stream flow and physical habitat. Although the inclusion of other environmental tolerance indices may not be ideal, the process allowed verification in this multi-layered analysis, using a complex decision tree to resolve conflicted classifications (Figure 2). Species classified using only information from other tolerance indices should be interpreted with additional care (Table 6). When additional information is available, the same process can be applied to reclassify fish species.

Professional judgement continues to be a component in guild classifications among published literature in fish guild classification (Meador and Carlisle 2007). There is no standardized number for DO tolerance classes, which can vary from 1 to 5 classes, depending on methodology and classification approach (Whittier and Hughes 1998; Meador and Carlisle 2007). In the past, Karr (1981) suggested that 5–10% of the most intolerant species should be classified as the S guild, though in the same study, they reported 16.6% of their species as intolerant (sensitive). Meador and Carlisle (2007), classified 17 species as intolerant (sensitive) which accounted for 16.20% of the number of species investigated. In our final guild classification, 43 species were assigned to the S guild, which accounts for 26.54% of all species examined. However, when only HABLAB classifications were considered with no influence from other indices, only three species were classified as S guild, which accounts for 1.85% of the fish species considered (Table 8).

Salmonidae are generally considered a sensitive species, affected by a number of environmental factors, including low DO levels (Doudoroff and Shumway 1970, Eakins 2019). Since Hamilton Harbour RAP has a DO target for cisco (Bowlby et al. 2010; Gertzen et al. 2016), it is important to examine the classification of Salmonidae in this report. The majority of Salmonidae with HABLAB data were assigned to the M guild (Table 4) including species like Atlantic Salmon, Brown Trout, Chinook Salmon, Coho Salmon, Lake Trout, Lake Whitefish, and Rainbow Trout (Table 4). As expected, Cisco was assigned the S guild (Table 4). Salmonidae are considered metabolic conformers with the ability to decrease their metabolic rate under hypoxic conditions after a critical threshold is reached (Marvin and Heath 1968; Hughes 1973; Barnes et al. 2011). Barnes et al. (2011) showed that Atlantic Salmon displayed a high degree of hypoxia tolerance by regulating metabolic rates under low DO conditions. In addition, juvenile Rainbow Trout have been shown to consistently perform ASR behaviour under hypoxic conditions (Dean and Richardson 1999). Furthermore, Sockeye Salmon (*Oncorhynchus nerka*) have been shown to have prolonged swimming and recovery under moderate hypoxia (Farrell et al. 1998). Therefore, based on the guild assignments in this study, juvenile and adult salmonids may be more tolerant to general hypoxic conditions than formerly presumed by many other guild classifications.

There are a number of species that require additional information before a guild classification can be assigned (Table 4; Table 5). These are species that either had limited information or conflicting classifications among indices. Locating DO tolerance information for some species remains a constant challenge; examples include fish species that are rarely studied or have 'species at risk' designations. Caveats or biases exist in all classification studies, where the constantly growing pool of information and studies can always be used to inform guild classification results. However, by approaching guild classification systematically in this study, we hoped to decrease the experimental bias among studies, improve the reliance on evidence-based guild classification instead of expert opinion, and create guild classifications from extracted information.

CONCLUSION

To our knowledge, this study is the first to incorporate summarized information from literature and existing guild classifications in a weight of evidence approach for classifying DO tolerance fish guilds. Although thus far, fish guild classification tends to be judgment based and/or encompasses a wide range of variables. We believe that by combining information from multiple sources as well as focusing on specific variables, we can provide a greater understanding of hypoxia tolerance in fish of the Great Lakes. This information can also be applied to specific areas of the Great Lakes to improve existing habitat suitability models to help inform on the productive capacity and quality or types of fish habitat. For example, the results from this study can further provide a foundational framework for our Hamilton Harbour fish habitat model. In Hamilton Harbour, anoxia is a major habitat modifier and the DO fish guild information can be used to develop habitat suitability curves for DO tolerance as part of a suite of HSIs.

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SUPPLEMENTARY MATERIALS

Supplementary material included in the methodology and data analysis is available upon request.

TABLES

Table 1. Weight-of-evidence confidence values (Weight) assigned for verifying HABLAB dissolved oxygen (DO) guild clustering analysis.

Category	**Condition**	**Weight(W)**	**Description**
Sample size (n)	0–1	0	Number of species-specific DO tolerance levels (mg/L) extracted from literature to determine mean DO tolerance
	2–4	1	
	≧ 5	2	
Reference diversity	≤ 1	0	Number of unique DO tolerance levels extracted from literature, per species
	= 2	1	
	> 2	2	
Species DO mean within ±1 SD of guild DO mean	Yes	0.5	Mean reported species-specific DO tolerance within ±1 standard deviation of HABLAB Guild DO mean
	No	0	

Table 2. Review of the other studies' dissolved oxygen tolerance indices used in guild classification; No. of class. = number of classifications

Reference	Location or reference cited	Variables used in ranking	No. of class.	Classification details
Barbour et al. (1999)	Literature search included the following studies: • Midwestern United States (Karr 1981) • Ohio (Ohio EPA 1987) • Midwestern United States (Plafkin 1989) • Central Corn Belt Plain (Simon 1991) • Wisconsin Warmwater (Lyons 1992) • Maryland Coastal Plain (Hall et al. 1996) • Northeastern United States (Halliwell et al. 1999)	General environmental tolerance	3	**Tolerance designations (relevant to non-specific stressors):** Intolerant (I) – Species sensitive to environmental and anthropogenic stressors Intermediate (M) – Species moderately sensitive to environmental and anthropogenic stressors Tolerant (T) – Species insensitive or resilient t to environmental and anthropogenic stressors
Eakins (2019)	Ontario Fish species • Includes a large number of references from literature depending on species • Scott and Crossman (1985)	General environmental tolerance	3	**Tolerance classification: ability of a species to adapt to environmental perturbations or anthropogenic stresses:** Intolerant (I) – Species sensitive to environmental or anthropogenic stresses Intermediate (M) – Species neither particularly sensitive nor insensitive to environmental or anthropogenic stresses Tolerant (T) – Species fairly insensitive or adaptive to environmental or anthropogenic stresses
Meador and Carlisle (2007)	773 stream sites sampled from major river basins across the United States	Water quality variables • ammonia • chloride • dissolved oxygen • nitrite plus nitrate • pH • phosphorus • specific conductance • sulfate • suspended sediment • water temperature	3	**General Tolerance:** On a scale of 1–10, 1 being intolerant, 10 being most tolerant, weighted average estimates were transformed into ordinal ranks, the ordinal ranks (1–10) of each species were assigned based on the percentiles of tolerance indicator values (TIVs) across all species for each water quality (WQ) variable: where 1-4 = intolerant; > 4 to < 7 = moderate; 7–10 = tolerant Intolerant (I) – Species sensitive to environmental and anthropogenic stressors Intermediate (M) – Species moderately sensitive to environmental and anthropogenic stressors Tolerant (T) – Species insensitive or resilient to environmental and anthropogenic stressors

Reference	Location or reference cited	Variables used in ranking	No. of class.	Classification details
Meador and Carlisle (2007)	773 stream sites sampled from major river basins across the United States, DO ranks are available. DO was measured directly from the stream using hand-held probes	Dissolved oxygen	3	**DO Tolerance:** On a scale of 1–10, 1 being intolerant, 10 being most tolerant, weighted average estimates were transformed into ordinal ranks, the ordinal ranks (1–10) of each species were assigned based on the percentiles of tolerance indicator values (TIVs) across all species for each water quality (WQ) variable: where 1–4 = intolerant; > 4 to < 7 = moderate; 7–10 = tolerant Intolerant (I) – Species sensitive to environmental and anthropogenic stressors Intermediate (M) – Species moderately sensitive to environmental and anthropogenic stressors Tolerant (T) – Species insensitive or resilient t to environmental and anthropogenic stressors
Trebitz et al. (2007)	Great Lakes coastal wetlands • Data collected over summers of 2002–2004 at Great Lakes coastal wetlands • Additional data from 1990s in Lake Michigan's Green Bay (turbidity declined over time)	Turbidity or nephelometric turbidity units (NTU)	4	**Tolerance to turbidity:** Intolerant (I) – At most one occurrence at turbidity > 10 NTU Tolerant (T) – Occurring across the turbidity gradient or No decline in relative abundance above 50 NTU Moderately intolerant (MI) – Multiple occurrences at turbidity > 10 NTU or At most one occurrence at turbidity > 25 NTU Moderately tolerant (MT) – Multiple occurrences at turbidity > 25 NTU or shift from present to absent or reduced relative abundance above 50 NTU turbidity

Table 3. Summary data of dissolved oxygen (DO) tolerance levels for all species of adult and juvenile fish by the percentage of negatively affected groups (starting effects [S], and < 50% and ≥ 50% affected) for lethal and sublethal endpoints. Lethal effects were defined by fish mortality/death (D) and the loss of equilibrium (LOE), while sublethal negative effects were defined by aquatic surface respiration (ASR), avoidance (A), and effects on behaviour (B), metabolism (M), feeding (F) swimming (Sw).

Experimental endpoint groups	Negative effect groups	% Negatively affected	DO tolerance level (mg/L)		SD	n
			Mean	Median		
Lethal	D, ASR [a]	≥ 50	1.20	0.95	0.91	4
	LOE	≥ 50	1.58	1.93	0.81	8
	D	≥ 50	1.97	1.50	1.69	96
	D	S	1.98	2.25	1.31	8
	D, LOE	≥ 50	2.05	2.11	0.57	16
	D	< 50	2.39	1.68	1.73	8
	D, LOE	< 50	3.53	3.53		1
	LOE	S	3.85	3.85		1
Sublethal	ASR	< 50	0.80	0.80	0.00	2
	M, ASR	≥ 50	1.20	1.20		1
	ASR	≥ 50	1.25	1.00	1.02	51
	B	≥ 50	1.83	1.82	0.83	30
	A	≥ 50	3.38	4.00	1.84	23
	Sw	≥ 50	3.47	2.80	1.90	13
	A	S	3.64	4.50	1.70	7
	M	≥ 50	3.78	2.85	1.92	17
	M, Sw	≥ 50	3.80	3.00	1.10	5
	B	S	3.88	3.88	1.24	2
	Sw	< 50	4.47	3.11	2.53	9
	M	< 50	4.73	5.00	1.52	71
	A	< 50	4.75	4.75	0.65	4
	Sw	S	5.25	4.75	1.19	4
	M	S	5.83	5.40	1.46	22

[a] A number of studies (Appendix A7-A9) showed fish conducting ASR at specific DO tolerance levels, but died shortly after at the same DO tolerance level (thus D, ASR). Although ASR was not considered as part of the lethal experimental endpoint group in our original sorting criteria, it is shown here to demonstrate the differences in mean and median DO tolerance levels between fish with and without access to the surface to perform ASR. These studies were not included in the final guild sorting analysis as ASR can increase fish resilience to hypoxic conditions.

Table 4. Summary of k-mean clusters of dissolved oxygen tolerance guilds from lethal, sublethal, and combination datasets. "w/n SS" represents within-group sums of squares, and "BwSS/TotSS" represents between sum of squares / total sum of squares.

<table>
<tr><th></th><th></th><th colspan="4">Dataset</th></tr>
<tr><th rowspan="2">Guild cluster</th><th rowspan="2">Clustering statistics</th><th rowspan="2">Lethal</th><th rowspan="2">Sublethal</th><th colspan="2">Combination</th></tr>
<tr><th>Lethal</th><th>Sublethal</th></tr>
<tr><td>Sensitive</td><td>Centroid</td><td>3.98</td><td>6.74</td><td>2.80</td><td>5.57</td></tr>
<tr><td></td><td>w/n SS</td><td>0.20</td><td>0.00</td><td colspan="2">4.21</td></tr>
<tr><td></td><td>n</td><td>2</td><td>1</td><td colspan="2">2</td></tr>
<tr><td>Mesotolerant</td><td>Centroid</td><td>1.98</td><td>3.56</td><td>1.75</td><td>2.55</td></tr>
<tr><td></td><td>w/n SS</td><td>1.29</td><td>3.25</td><td colspan="2">5.00</td></tr>
<tr><td></td><td>n</td><td>23</td><td>13</td><td colspan="2">11</td></tr>
<tr><td>Tolerant</td><td>Centroid</td><td>1.06</td><td>1.58</td><td>1.71</td><td>1.16</td></tr>
<tr><td></td><td>w/n SS</td><td>0.69</td><td>6.74</td><td colspan="2">1.45</td></tr>
<tr><td></td><td>n</td><td>16</td><td>22</td><td colspan="2">6</td></tr>
<tr><td>BwSS / TotSS (%)</td><td></td><td>89.6</td><td>83.7</td><td colspan="2">74.7</td></tr>
</table>

Table 5. Dissolved Oxygen (DO) guild sorting for various methods and indices for sensitive (S), sensitive-mesotolerant (SM), mesotolerant (M), mesotolerant-tolerant (MT) and tolerant (T) classification. Species not classified in the analysis were indicated with a "-", and a "X" represents species that require more information before a guild can be assigned in the final classification. An asterisk (*) represents species that are known to perform aquatic surface respiration (ASR) and therefore may increase its DO tolerance. An exclamation mark (!) represent species that were sorted with the absence of HABLAB guild information. COSEWIC = Committee on the Status of Endangered Wildlife in Canada.

Common name	Scientific name	COSEWIC [a] status (2018)	HABLAB guild	Eakins [b] tolerance	Meador [c] DO tolerance	Meador [c] general tolerance	Barbour [d] tolerance	Trebitz [e] turbitity tolerance	*Method 1*	*Method 2*	Final guild assignment	Note
Alewife	*Alosa pseudoharengus*		M	M	-	-	M	T	M	M	M	
American Brook Lamprey	*Lethenteron appendix*		-	S	-	-	S	-	S	S	S	!
American Eel	*Anguilla rostrata*	Threatened	-	M	M	M	M	-	M	M	M	!
American Shad	*Alosa sapidissima*		-	M	-	-	M	-	M	M	M	!
Arctic Char	*Salvelinus alpinus*		-	S	-	-	S	-	S	S	S	!
Atlantic Salmon	*Salmo salar*		M	S	-	-	M	-	M	M	M	
Aurora Trout	*Salvelinus fontinalis timagamiensis*		-	S	-	-	-	-	S	S	X	
Banded Killifish	*Fundulus diaphanus*	Not at Risk	T	T	-	-	T	MT	T	T	T	
Bigmouth Buffalo	*Ictiobus cyprinellus*	Non-active	-	M	-	-	M	MT	M	M	M	!
Black Buffalo	*Ictiobus niger*	Data Deficient	-	M	-	-	M	-	M	M	M	!
Black Bullhead	*Ameiurus melas*		M	M	M	M	M	MT	M	M	M	*
Black Crappie	*Pomoxis nigromaculatus*		M	T	T	T	M	MT	M	M	M	
Black Redhorse	*Moxostoma duquesneii*	Threatened	-	S	S	S	S	-	S	S	S	!
Blackchin Shiner	*Notropis heterodon*	Not at Risk	-	S	-	-	S	S	S	S	S	!
Blackfin Cisco	*Coregonus nigripinnis*	Data Deficient	-	S	-	-	S	-	S	S	S	!
Blacknose Dace	*Rhinichthys atratulus*		T	M	S	M	T	-	M	M	M	*
Blacknose Shiner	*Notropis heterolepis*		-	S	-	-	S	SM	S	S	S	!
Blackside Darter	*Percina maculata*		T	M	M	M	M	-	M	M	M	*
Blackstripe Topminnow	*Fundulus notatus*	Special Concern	-	T	T	T	M	-	T	T	T	*!
Bloater	*Coregonus hoyi*	Not at Risk	-	S	-	-	M	-	S	SM	S	!
Bluegill	*Lepomis macrochirus*		T	M	T	M	M	MT	T	T	T	*
Bluntnose Minnow	*Pimephales notatus*	Not at Risk	T	M	S	M	T	MT	M	M	M	
Bowfin	*Amia calva*		-	M	T	M	M	T	M	M	M	*!
Brassy Minnow	*Hybognathus hankinsoni*		M	M	-	-	M	-	M	M	M	*
Bridle Shiner	*Notropis bifrenatus*	Special Concern	-	S	-	-	S	-	S	S	S	!
Brindled Madtom	*Noturus miurus*	Not at Risk	-	S	-	-	S	-	S	S	S	!
Brook Silverside	*Labidesthes sicculus*	Not at Risk	-	M	T	M	M	T	M	M	M	!
Brook Stickleback	*Culaea inconstans*		M	M	-	-	M	S	M	M	M	*
Brook Trout	*Salvelinus fontinalis*		S	S	S	S	M	-	S	S	S	

Common name	Scientific name	COSEWIC [a] status (2018)	HABLAB guild	Eakins [b] tolerance	Meador [c] DO tolerance	Meador [c] general tolerance	Barbour [d] tolerance	Trebitz [e] turbitity tolerance	*Method 1*	*Method 2*	Final guild assignment	Note
Brown Bullhead	*Ameiurus nebulosus*		T	M	T	M	T	MT	T	T	T	
Brown Trout	*Salmo trutta*		M	S	S	S	M	-	M	M	M	
Burbot	*Lota lota*		M	M	-	-	M	-	M	M	M	
Central Mudminnow	*Umbra limi*		-	T	-	-	T	SM	M	T	X	!
Central Stoneroller	*Campostoma anomalum*	Not at Risk	M	M	S	M	M	-	M	M	M	
Chain Pickerel	*Esox niger*		-	M	T	M	M	-	M	M	M	!
Channel Catfish	*Ictalurus punctatus*		M	T	S	T	M	T	M	M	M	
Channel Darter	*Percina copelandi*	Non-active	-	S	-	-	S	-	S	S	S	!
Chestnut Lamprey	*Ichthyomyzon castaneus*		-	M	-	-	M	-	M	M	M	!
Chinook Salmon	*Oncorhynchus tshawytscha*		M	S	-	-	M	-	M	M	M	*
Cisco	*Coregonus artedi*		S	S	-	-	M	-	S	S	S	
Coho Salmon	*Oncorhynchus kisutch*		M	S	-	-	M	-	M	M	M	
Common Carp	*Cyprinus carpio*		T	T	S	T	T	T	T	T	T	*
Common Shiner	*Luxilus cornutus*		T	M	S	M	M	T	M	T	M	*
Creek Chub	*Semotilus atromaculatus*		M	M	S	M	T	SM	M	M	M	*
Creek Chubsucker	*Erimyzon oblongus*		-	-	T	M	M	-	M	M	M	!
Cutlip Minnow	*Exoglossum maxillingua*	Special Concern	-	S	-	-	S	-	S	S	S	!
Deepwater Sculpin	*Myoxocephalus thompsonii*	Non-active	-	S	-	-	-	-	S	S	X	!
Eastern Sand Darter	*Ammocrypta pellucida*	Threatened	-	S	-	-	S	-	S	S	S	!
Eastern Silvery Minnow	*Hybognathus regius*	Not at Risk	-	S	-	-	M	-	S	SM	S	!
Emerald Shiner	*Notropis atherinoides*		M	M	M	T	M	T	M	M	M	*
Fallfish	*Semotilus corporalis*		-	M	M	M	M	-	M	M	M	!
Fantail Darter	*Etheostoma flabellare*		M	S	S	S	M	-	S	S	S	
Fathead Minnow	*Pimephales promelas*		T	T	S	T	T	MT	T	T	T	*
Finescale Dace	*Chrosomus neogaeus*		T	M	-	-	M	-	M	M	M	
Flathead Catfish	*Pylodictis olivaris*		-	T	M	T	M	-	M	MT	M	!
Fourhorn Sculpin	*Myoxocephalus quadricornis*		-	M	-	-	-	-	M	M	X	!
Fourspine Stickleback	*Apeltes quadracus*		-	M	-	-	M	-	M	M	M	!
Freshwater Drum	*Aplodinotus grunniens*		S	T	T	T	M	T	T	T	T	
Freshwater Tubenose Goby	*Proterorhinus semilunaris*		-	M	-	-	-	-	M	M	X	!
Ghost Shiner	*Notropis buchanani*	Not at Risk	-	M	-	-	M	-	M	M	M	!
Gizzard Shad	*Dorosoma cepedianum*		T	T	T	T	M	T	T	T	T	
Golden Redhorse	*Moxostoma erythrurum*	Not at Risk	-	M	S	M	M	T	M	M	M	!
Golden Shiner	*Notemigonus crysoleucas*		T	M	T	M	T	MT	T	T	T	*
Goldeye	*Hiodon alosoides*		-	S	-	-	S	-	S	S	S	!

Common name	Scientific name	COSEWIC [a] status (2018)	HABLAB guild	Eakins [b] tolerance	Meador [c] DO tolerance	Meador [c] general tolerance	Barbour [d] tolerance	Trebitz [e] turbitity tolerance	*Method 1*	*Method 2*	Final guild assignment	Note
Grass Carp	*Ctenopharyngodon idella*		-	T	-	-	M	-	M	MT	M	!
Grass Pickerel	*Esox americanus vermiculatus*	Special Concern	-	M	T	M	M	SM	M	M	M	!
Gravel Chub	*Erimystax x-punctatus*	Extirpated	-	S	-	-	M	-	S	SM	S	!
Greater Redhorse	*Moxostoma valenciennesi*		-	S	-	-	S	-	S	S	S	!
Green Sunfish	*Lepomis cyanellus*	Not at Risk	T	T	T	T	T	T	T	T	T	*
Greenside Darter	*Etheostoma blennioides*	Not at Risk	M	M	M	M	M	-	M	M	M	
Hornyhead Chub	*Nocomis biguttatus*	Not at Risk	T	M	M	M	S	SM	M	M	M	*
Iowa Darter	*Etheostoma exile*		T	M	-	-	M	-	M	M	M	*
Johnny Darter	*Etheostoma nigrum*		T	T	T	T	M	MT	T	T	T	*
Kiyi	*Coregonus kiyi*	Non-active	-	S	-	-	M	-	S	SM	S	!
Lake Chub	*Couesius plumbeus*		-	M	-	-	M	-	M	M	M	!
Lake Chubsucker	*Erimyzon sucetta*	Endangered	T	M	-	-	M	-	M	M	M	
Lake Sturgeon	*Acipenser fulvescens*	Threatened	-	M	-	-	M	-	M	M	M	!
Lake Trout	*Salvelinus namaycush*		M	S	-	-	M	-	M	M	M	
Lake Whitefish	*Coregonus clupeaformis*	Data Deficient	T	S	-	-	M	-	M	SM	M	
Largemouth Bass	*Micropterus salmoides*		M	T	T	T	M	MT	M	M	M	*
Least Darter	*Etheostoma microperca*	Not at Risk	-	S	-	-	M	-	S	SM	S	!
Logperch	*Percina caprodes*		-	S	T	S	M	MT	M	S	S	!
Longear Sunfish	*Lepomis megalotis*		-	M	T	M	S	-	M	M	X	!
Longnose Dace	*Rhinichthys cataractae*		T	M	S	M	S	MT	M	M	M	*
Longnose Gar	*Lepisosteus osseus*		-	T	T	T	M	T	T	T	T	*!
Longnose Sucker	*Catostomus catostomus*		-	M	S	M	M	-	M	M	M	!
Margined Madtom	*Noturus insignis*	Data Deficient	-	M	S	M	M	-	M	M	M	!
Mimic Shiner	*Notropis volucellus*		-	M	T	M	S	SM	M	M	M	!
Mooneye	*Hiodon tergisus*		-	S	-	-	S	-	S	S	S	!
Mottled Sculpin	*Cottus bairdii*		-	M	-	-	-	-	M	M	X	!
Muskellunge	*Esox masquinongy*		-	M	-	-	M	MT	M	M	M	!
Ninespine Stickleback	*Pungitius pungitius*		M	M	-	-	M	-	M	M	M	*
Nipigon Cisco	*Coregonus nipigon*		-	S	-	-	-	-	S	S	X	!
Northern Brook Lamprey	*Ichthyomyzon fossor*	Non-active	-	S	-	-	S	-	S	S	S	!
Northern Hog Sucker	*Hypentelium nigricans*		-	M	S	M	S	-	S	SM	S	!
Northern Madtom	*Noturus stigmosus*	Endangered	-	S	-	-	S	-	S	S	S	!
Northern Pearl Dace	*Margariscus nachtriebi*		-	M	-	-	-	-	M	M	X	!
Northern Pike	*Esox lucius*		M	M	M	M	M	MT	M	M	M	*

Common name	**Scientific name**	**COSEWIC [a] status (2018)**	**HABLAB guild**	**Eakins [b] tolerance**	**Meador [c] DO tolerance**	**Meador [c] general tolerance**	**Barbour [d] tolerance**	**Trebitz [e] turbitity tolerance**	***Method 1***	***Method 2***	**Final guild assignment**	**Note**
Northern Redbelly Dace	*Phoxinus eos*		-	M	-	-	-	-	M	M	X	*!
Northern Sunfish	*Lepomis peltastes*	Special Concern	-	M	-	-	-	-	M	M	X	!
Orangespotted Sunfish	*Lepomis humilis*	Non-active	T	T	T	T	M	MT	T	T	T	*
Paddlefish	*Polyodon spathula*	Extirpated	-	S	-	-	S	-	S	S	S	!
Pearl Dace	*Margariscus margarita*		T	M	-	-	M	-	T	T	T	*
Pink Salmon	*Oncorhynchus gorbuscha*		-	S	-	-	M	-	S	SM	S	!
Pirate Perch	*Aphredoderus sayanus*		-	-	T	M	M	-	M	M	M	!
Pugnose Minnow	*Opsopoeodus emiliae*	Threatened	-	S	-	-	S	-	S	S	S	!
Pugnose Shiner	*Notropis anogenus*	Threatened	-	S	-	-	S	-	S	S	S	!
Pumpkinseed	*Lepomis gibbosus*		M	M	T	M	M	MT	M	M	M	
Pygmy Whitefish	*Prosopium coulterii*	Threatened	-	S	-	-	-	-	S	S	X	!
Quillback	*Carpiodes cyprinus*		-	M	M	M	M	T	M	M	M	!
Rainbow Darter	*Etheostoma caeruleum*		M	S	S	S	M	-	S	S	S	
Rainbow Smelt	*Osmerus mordax*		-	M	-	-	M	-	M	M	M	!
Rainbow Trout	*Oncorhynchus mykiss*		M	S	S	S	M	-	M	M	M	*
Redfin Shiner	*Lythrurus umbratilis*	Not at Risk	-	M	-	-	M	-	M	M	M	!
Redside Dace	*Clinostomus elongatus*	Endangered	-	S	-	-	S	-	S	S	S	!
River Chub	*Nocomis micropogon*	Not at Risk	-	M	S	M	S	-	S	SM	S	!
River Darter	*Percina shumardi*	Endangered	-	M	-	-	M	-	M	M	M	!
River Redhorse	*Moxostoma carinatum*	Special Concern	-	S	-	-	S	-	S	S	S	!
River Shiner	*Notropis blennius*		-	S	-	-	M	-	S	SM	S	!
Rock Bass	*Ambloplites rupestris*		M	M	S	M	M	MT	M	M	M	*
Rosyface Shiner	*Notropis rubellus*	Not at Risk	-	M	S	M	S	-	S	SM	S	!
Round Goby	*Neogobius melanostomus*		-	M	-	-	-	MT	M	M	M	!
Round Whitefish	*Prosopium cylindraceum*		-	S	-	-	M	-	S	SM	S	!
Rudd	*Scardinius erythrophthalmus*		-	T	-	-	T	-	T	T	T	!
Ruffe	*Gymnocephalus cernua*		-	M	-	-	-	SM	M	M	M	!
Sand Shiner	*Notropis ludibundus*		-	M	S	M	M	MT	M	M	M	!
Sauger	*Sander canadensis*		-	M	-	-	-	-	M	M	X	!
Sea Lamprey	*Petromyzon marinus*		-	M	-	-	M	-	M	M	M	!
Shorthead Redhorse	*Moxostoma macrolepidotum*		-	M	S	M	M	SM	M	M	M	!
Shortjaw Cisco	*Coregonus zenithicus*	Threatened	-	S	-	-	M	-	S	SM	S	!
Shortnose Cisco	*Coregonus reighardi*	Endangered	-	S	-	-	S	-	S	S	S	!
Silver Chub	*Macrhybopsis storeriana*	Non-active	-	S	-	-	M	-	S	SM	S	!
Silver Lamprey	*Ichthyomyzon unicuspis*	Special Concern	-	M	-	-	M	-	M	M	M	!

Common name	**Scientific name**	**COSEWIC [a] status (2018)**	**HABLAB guild**	**Eakins [b] tolerance**	**Meador [c] DO tolerance**	**Meador [c] general tolerance**	**Barbour [d] tolerance**	**Trebitz [e] turbitity tolerance**	***Method 1***	***Method 2***	**Final guild assignment**	**Note**
Silver Redhorse	*Moxostoma anisurum*		-	M	M	M	M	SM	M	M	M	!
Silver Shiner	*Notropis photogenis*	Threatened	-	S	S	S	S	-	S	S	S	!
Silverjaw Minnow	*Notropis buccatus*		-	-	M	M	M	-	M	M	M	!
Slimy Sculpin	*Cottus cognatus*		-	S	-	-	M	-	S	SM	S	!
Smallmouth Bass	*Micropterus dolomieu*		M	M	M	M	M	MT	M	M	M	
Smallmouth Buffalo	*Ictiobus bubalus*		-	T	T	T	M	-	T	T	T	!
Splake (Backcross)	*Salvelinus fontinalis x s. namaycush*		-	S	-	-	-	-	S	S	X	!
Spoonhead Sculpin	*Cottus ricei*	Not at Risk	-	S	-	-	M	-	S	SM	S	!
Spotfin Shiner	*Cyprinella spiloptera*		-	M	S	M	M	T	M	M	M	!
Spottail Shiner	*Notropis hudsonius*		T	M	S	M	M	T	M	M	M	*
Spotted Gar	*Lepisosteus oculatus*	Endangered	-	M	T	M	M	-	M	M	M	!
Spotted Sucker	*Minytrema melanops*	Special Concern	-	M	T	M	M	MT	M	M	M	!
Stonecat	*Noturus flavus*		-	T	S	T	S	-	M	ST	X	!
Striped Shiner	*Luxilus chrysocephalus*	Not at Risk	-	M	M	M	M	-	M	M	M	!
Tadpole Madtom	*Noturus gyrinus*		T	M	M	M	M	SM	M	M	M	*
Tessellated Darter	*Etheostoma olmstedi*	Not at Risk	-	M	S	M	M	-	M	M	M	!
Threespine Stickleback	*Gasterosteus aculeatus*		M	M	-	-	M	SM	M	M	M	
Tiger Muskellunge (Norlunge)	*Esox lucius x e. masquinongy*		-	M	-	-	-	-	M	M	X	!
Trout-Perch	*Percopsis omiscomaycus*		-	M	-	-	M	SM	M	M	M	!
Tubenose Goby	*Proterorhinus marmoratus*		-	M	-	-	-	-	M	M	X	!
Walleye	*Sander vitreus*		M	M	-	-	-	MT	M	M	M	
Warmouth	*Lepomis gulosus*	Endangered	T	M	T	M	M	SM	M	M	M	*
Western Blacknose Dace	*Rhinichthys obtusus*		-	S	-	-	-	-	S	S	X	!
White Bass	*Morone chrysops*		-	T	T	T	M	T	T	T	T	!
White Crappie	*Pomoxis annularis*		T	T	T	T	M	-	T	T	T	*
White Perch	*Morone americana*		-	M	-	-	M	T	M	M	M	!
White Sucker	*Catostomus commersonii*		-	T	-	-	-	MT	T	T	T	*!
Yellow Bullhead	*Ameiurus natalis*		-	T	T	T	T	T	T	T	T	!
Yellow Perch	*Perca flavescens*		M	M	T	M	M	T	M	M	M	*

[a] COSEWIC 2018
[b] Eakins 2019
[c] Meador and Carlisle 2007
[d] Barbour et al. 1999
[e] Trebitz et al. 2007

Table 6. Comparisons of the percentage (%) of agreement of the final guild assignments with other indices considered in the assignment process, for three classifications: sensitive (S), mesotolerant (M) and tolerant (T). An "X" classification represents species that require additional information for classification assignment and a "—" represents fish species not assigned or not considered in the index. DO = dissolved oxygen.

	HABLAB				
Final Guild	**S**	**M**	**T**	**—**	**Total**
S	24.07%	1.23%	1.23%	0.00%	26.54%
M	25.93%	16.05%	0.00%	8.02%	50.00%
T	4.32%	0.00%	0.62%	7.41%	12.35%
X	11.11%	0.00%	0.00%	0.00%	11.11%
Total	65.43%	17.28%	1.85%	15.43%	100.00%
Agreement:	**40.74%**				
Disagreement:	**32.72%**				
Unsorted:	**26.54%**				

	Eakins [a]				
Final Guild	**S**	**M**	**T**	**—**	**Total**
S	24.69%	1.85%	0.00%	0.00%	26.54%
M	4.32%	40.74%	3.09%	1.85%	50.00%
T	0.00%	2.47%	9.88%	0.00%	12.35%
X	3.70%	6.17%	1.23%	0.00%	11.11%
Total	32.72%	51.23%	14.20%	1.85%	100.00%
Agreement:	**75.31%**				
Disagreement:	**11.73%**				
Unsorted:	**12.96%**				

	Meador DO [b]				
Final Guild	**S**	**M**	**T**	**—**	**Total**
S	4.94%	0.00%	0.62%	20.99%	26.54%
M	11.11%	9.26%	8.64%	20.99%	50.00%
T	1.23%	0.00%	8.64%	2.47%	12.35%
X	0.62%	0.00%	0.62%	9.88%	11.11%
Total	17.90%	9.26%	18.52%	54.32%	100.00%
Agreement:	**22.84%**				
Disagreement:	**21.60%**				
Unsorted:	**55.56%**				

	Meador General [b]				
Final Guild	**S**	**M**	**T**	**—**	**Total**
S	20.99%	1.85%	3.70%	0.00%	26.54%
M	20.99%	24.69%	1.23%	3.09%	50.00%
T	2.47%	1.85%	0.00%	8.02%	12.35%
X	9.88%	0.62%	0.00%	0.62%	11.11%
Total	54.32%	29.01%	4.94%	11.73%	100.00%
Agreement:	**45.68%**				
Disagreement:	**32.10%**				
Unsorted:	**22.22%**				

	Barbour Tolerance				
Final Guild	**S**	**M**	**T**	**—**	**Total**
S	16.05%	10.49%	0.00%	0.00%	26.54%
M	1.85%	44.44%	1.85%	1.85%	50.00%
T	0.00%	6.79%	4.94%	0.62%	12.35%
X	1.23%	0.00%	0.62%	9.26%	11.11%
Total	19.14%	61.73%	7.41%	11.73%	100.00%
Agreement:	**65.43%**				
Disagreement:	**20.99%**				
Unsorted:	**13.58%**				

[a] Eakins 2019
[b] Meador and Carlisle 2007
[c] Barbour et al. 1999

Table 7. Comparisons of the percentage (%) of agreement of the final guild assignments with Trebitz et al. (2007) turbidity classifications. Since the final guild classifications we chose consist of three guilds (sensitive, S; mesotolerant, M; and tolerant, T) and the Trebitz et al. (2007) turbidity classifications are in four guilds (sensitive, S; sensitive-mesotolerant, SM; mesolertant-tolerant, MT; tolerant T), different combinations of classifications are presented below. An “X” classification indicates guild assignment that require additional information and a “-“ represent fish species not assigned or considered in the index.

	Trebitz Turbidity Tolerance					
Final Guild	**S**	**SM**	**MT**	**T**	**—**	**Total**
S	0.62%	0.62%	0.62%	0.00%	24.69%	26.54%
M	0.62%	6.79%	9.26%	7.41%	25.93%	50.00%
T	0.00%	0.00%	4.94%	4.32%	3.09%	12.35%
X	0.00%	0.62%	0.00%	0.00%	10.49%	11.11%
Total	1.23%	8.02%	14.81%	11.73%	64.20%	100.00%

	Trebitz Turbidity Tolerance			
Final Guild	**S-SM**	**MT-T**	**—**	**Total**
S	1.23%	0.62%	24.69%	26.54%
M	7.41%	16.67%	25.93%	50.00%
T	0.00%	9.26%	3.09%	12.35%
X	0.62%	0.00%	10.49%	11.11%
Total	9.26%	26.54%	64.20%	100.00%

	Trebitz Turbidity Tolerance				
Final Guild	**S-SM**	**MT**	**T**	**—**	**Total**
S	1.23%	0.62%	0.00%	24.69%	26.54%
M	7.41%	9.26%	7.41%	25.93%	50.00%
T	0.00%	4.94%	4.32%	3.09%	12.35%
X	0.62%	0.00%	0.00%	10.49%	11.11%
Total	9.26%	14.81%	11.73%	64.20%	100.00%
Agreement:	**14.81%**				
Disagreement:	**20.37%**				
Unsorted:	**64.81%**				

	Trebitz Turbidity Tolerance				
Final Guild	**S**	**SM-MT**	**T**	**—**	**Total**
S	0.62%	1.23%	0.00%	24.69%	26.54%
M	0.62%	16.05%	7.41%	25.93%	50.00%
T	0.00%	4.94%	4.32%	3.09%	12.35%
X	0.00%	0.62%	0.00%	10.49%	11.11%
Total	1.23%	22.84%	11.73%	64.20%	100.00%
Agreement:	**20.99%**				
Disagreement:	**14.20%**				
Unsorted:	**64.81%**				

	Trebitz Turbidity Tolerance				
Final Guild	**S**	**SM**	**MT-T**	**—**	**Total**
S	0.62%	0.62%	0.62%	24.69%	26.54%
M	0.62%	6.79%	16.67%	25.93%	50.00%
T	0.00%	0.00%	9.26%	3.09%	12.35%
X	0.00%	0.62%	0.00%	10.49%	11.11%
Total	1.23%	8.02%	26.54%	64.20%	100.00%
Agreement:	**16.67%**				
Disagreement:	**18.52%**				
Unsorted:	**64.81%**				

Table 8. Summary of the number of fish species (n) and percent (%) sorted into various guilds by different methods and indices. S, SM, M, MT, T, ST represents sensitive, sensitive/mesotolerant, mesotolerant, mesotolerant/tolerant, tolerant, sensitive/tolerant guilds respectively. RMI/NA represents "requires more information / not available".

	Guild assignment method																	
Guild assignment	**HABLAB**		**Eakins** [a]		**Meador** [b] **DO tolerance**		**Meador** [b] **general tolerance**		**Barbour** [c] **tolerance**		**Trebitz** [d] **turbidity tolerance**		**Method 1**		**Method 2**		**Final guild**	
	n	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
S	3	1.85%	53	32.72%	29	17.90%	8	4.94%	31	19.14%	2	1.23%	48	29.63%	34	20.99%	43	26.54%
SM											13	8.02%			16	9.88%		
M	28	17.28%	83	51.23%	15	9.26%	47	29.01%	100	61.73%			94	58.02%	87	53.70%	81	50.00%
MT											24	14.81%			2	1.23%		
T	25	15.43%	23	14.20%	30	18.52%	19	11.73%	12	7.41%	19	11.73%	20	12.35%	22	13.58%	20	12.35%
ST															1	0.62%		
RMI/ NA	106	65.43%	3	1.85%	88	54.32%	88	54.32%	19	11.73%	104	64.20%	0	0.00%	0	0.00%	18	11.11%

[a] Eakins 2019
[b] Meador and Carlisle 2007
[c] Barbour et al. 1999
[d] Trebitz et al. 2007

FIGURES

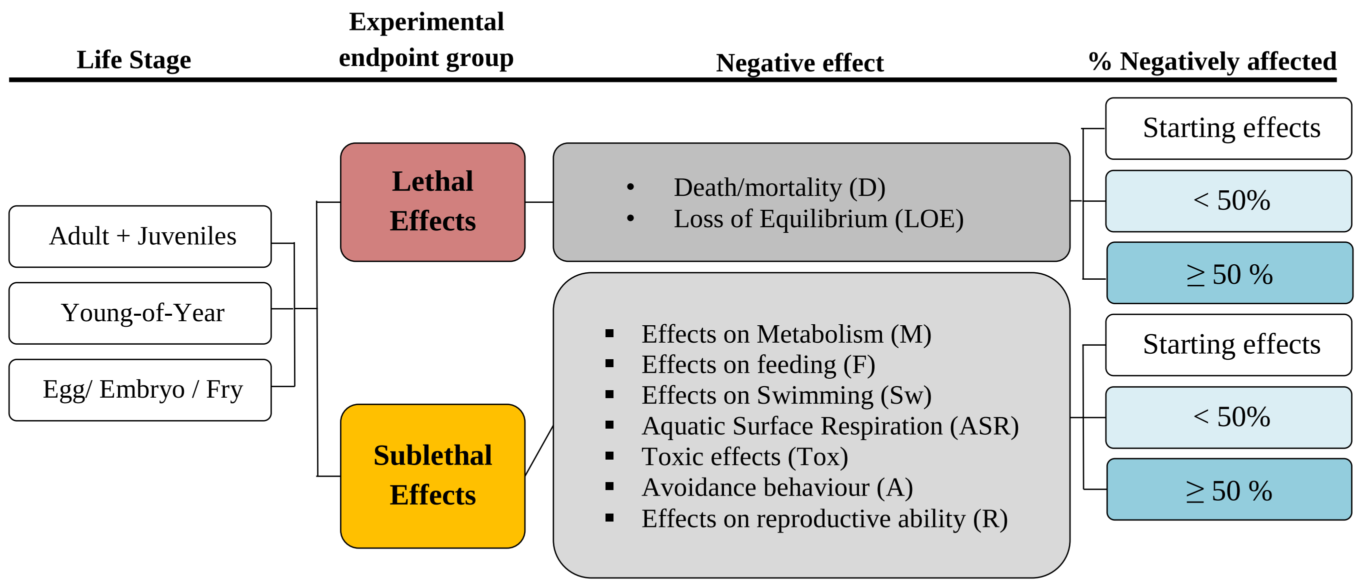

Figure 1. Classification pathway of dissolved oxygen tolerance levels for Great Lakes fish species extracted from literature.

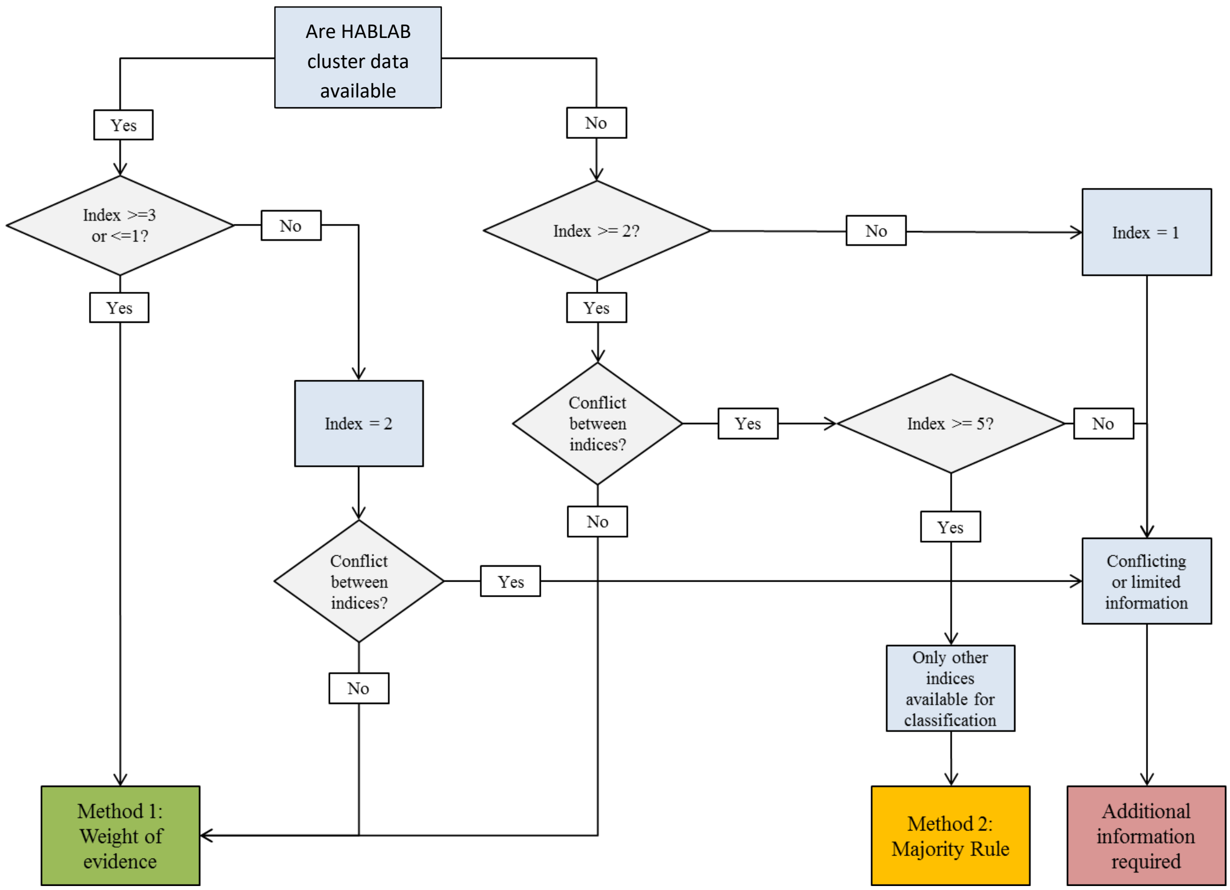

Figure 2. The dissolved oxygen (DO) guild classification decision tree. Index or indices value(s) represent the number of indices available for classification. “Conflict” refers to disagreements in guild classification between indices. Final DO guild classifications combine a weight of evidence approach using Method 1 and Method 2.

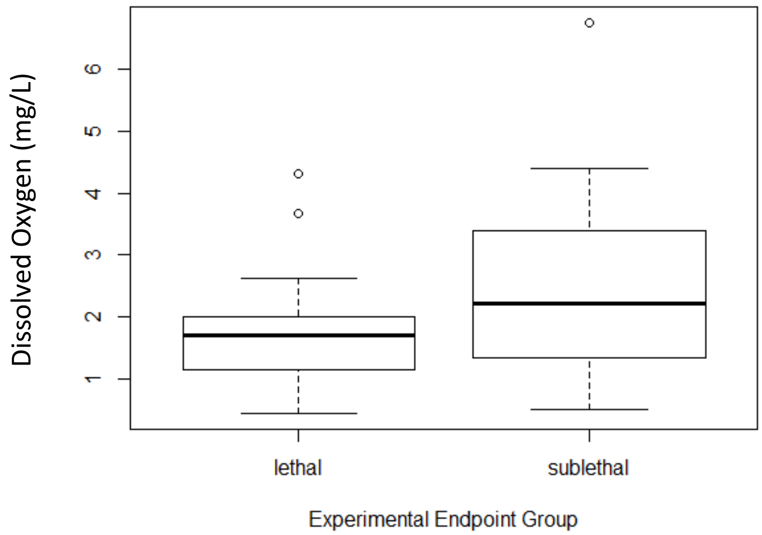

Figure 3. Boxplot of dissolved oxygen tolerance in ≥ 50% negatively affected for adult and juvenile lethal and sublethal experimental endpoint groups for all species combined.

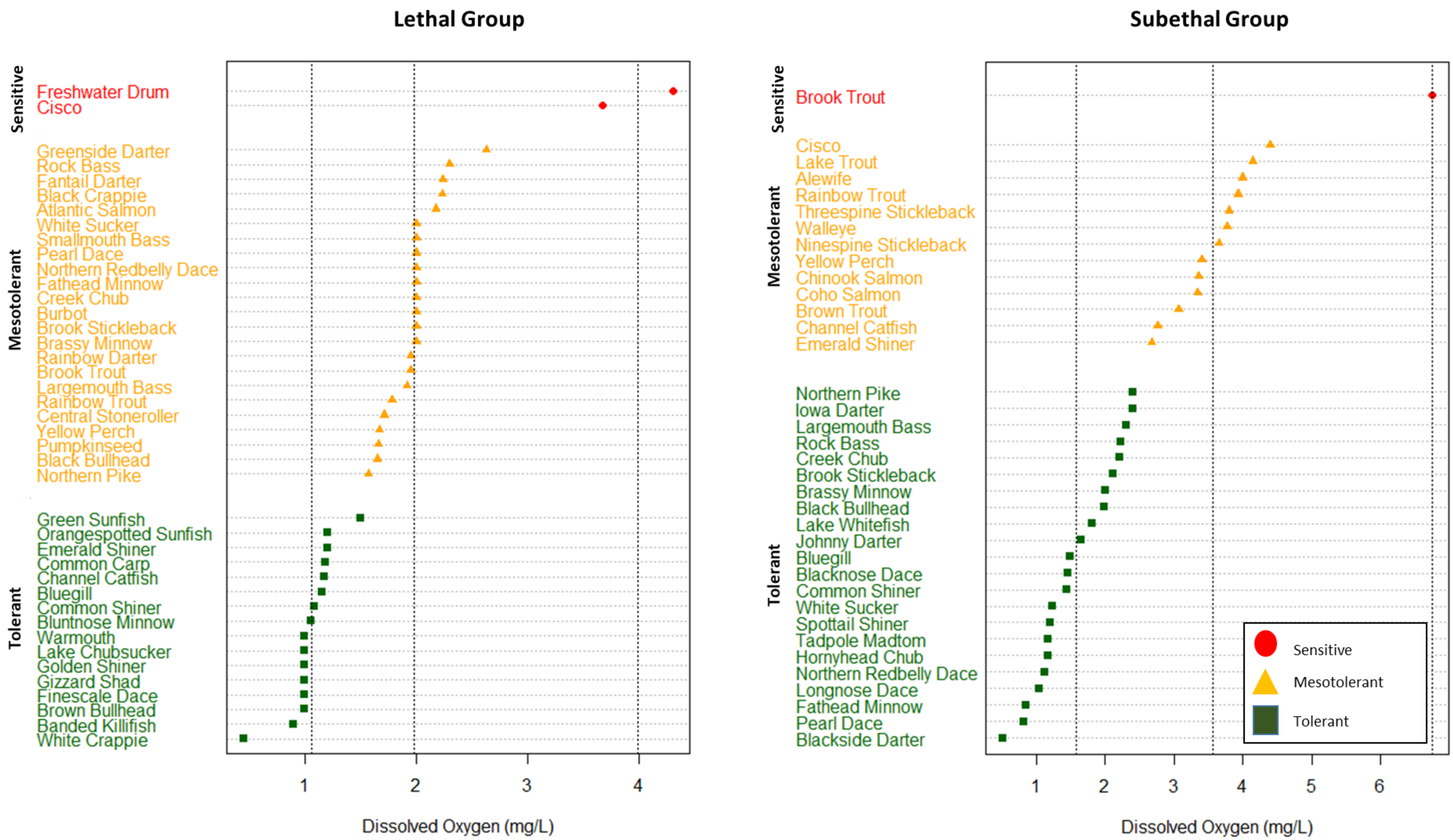

Figure 4. Mean dissolved oxygen tolerance and dissolved oxygen guilds for lethal and sublethal groups of the ≥ 50% negatively affected adults and juveniles using k-means clustering for HABLAB data. The vertical dotted lines represents individual guild mean DO tolerance.

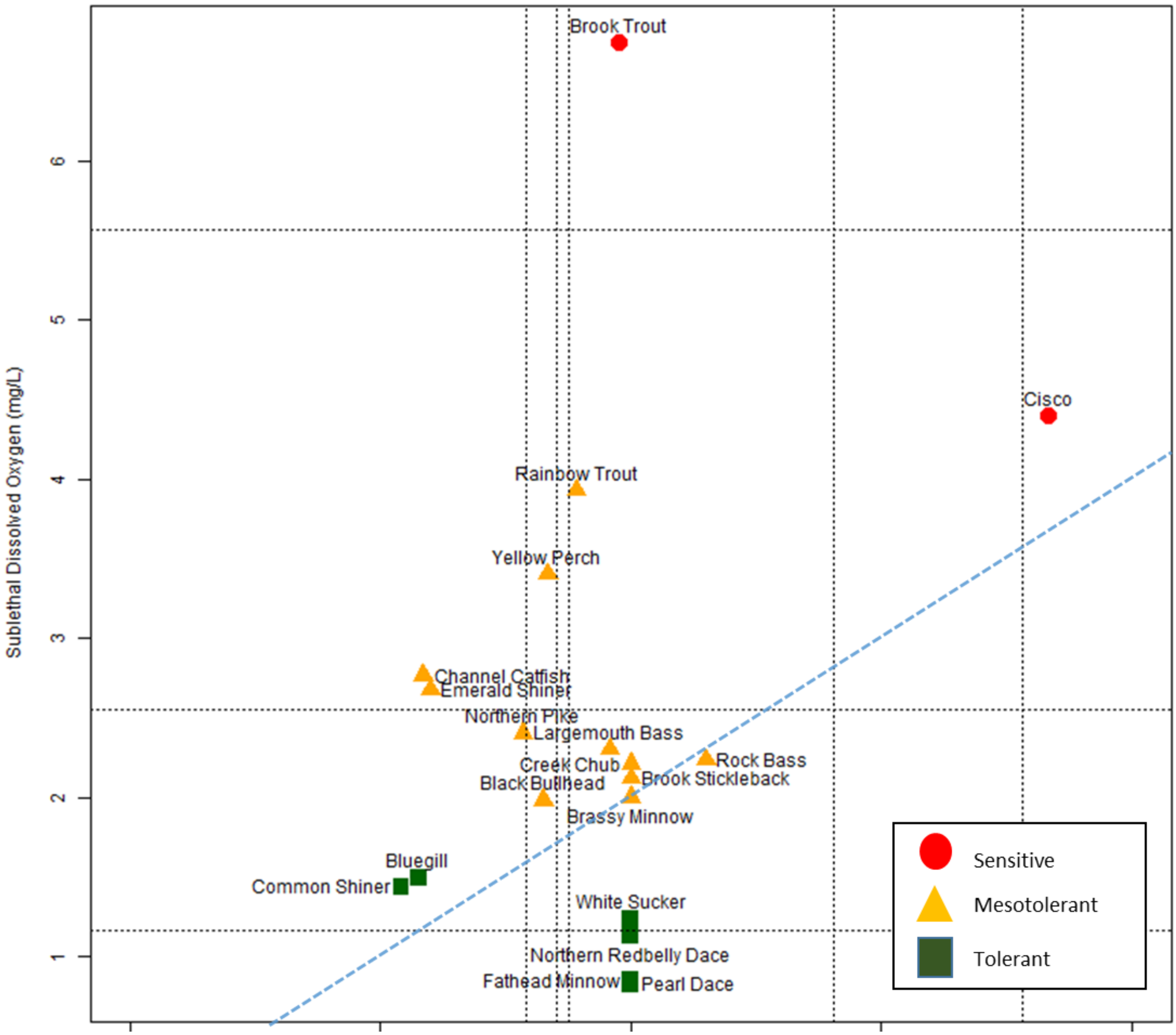

Figure 5. Mean dissolved oxygen tolerance and dissolved oxygen guilds for combined experimental endpoint groups (lethal and sublethal) of the ≥ 50% negatively affected adults and juveniles, using k-means clustering for HABLAB data. The dashed blue line represents a 1:1 relationship between lethal and sublethal tolerance values.

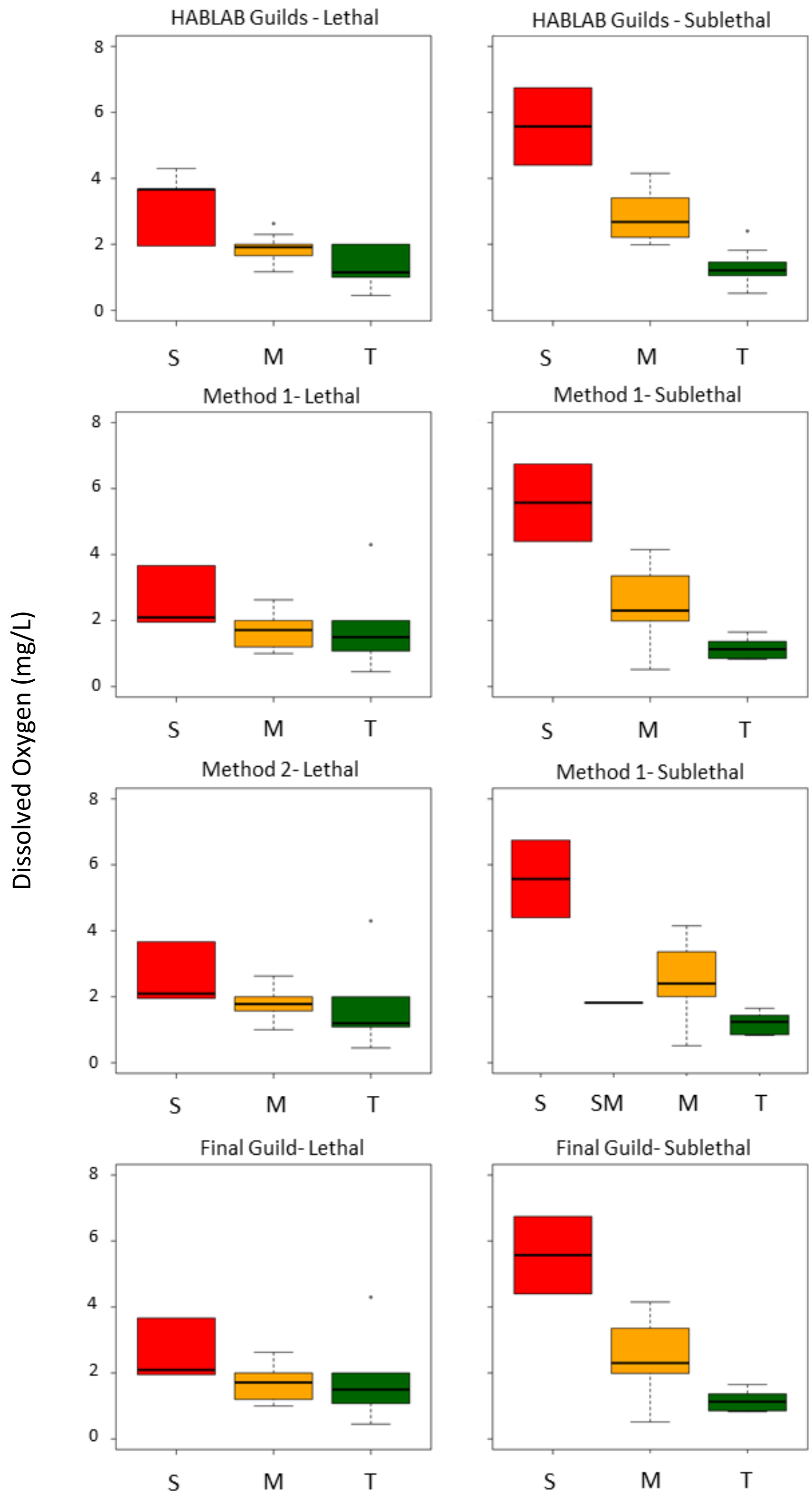

Figure 6. A comparison of the boxplots of different dissolved oxygen (DO; mg/L) fish guild classifications methods using DO means extracted from the lethal and sublethal groups of the HABLAB dataset. “S”, “SM”, “M”, and “T” represent sensitive, sensitive/mesotolerant, mesotolerant, and tolerant guilds, respectively.

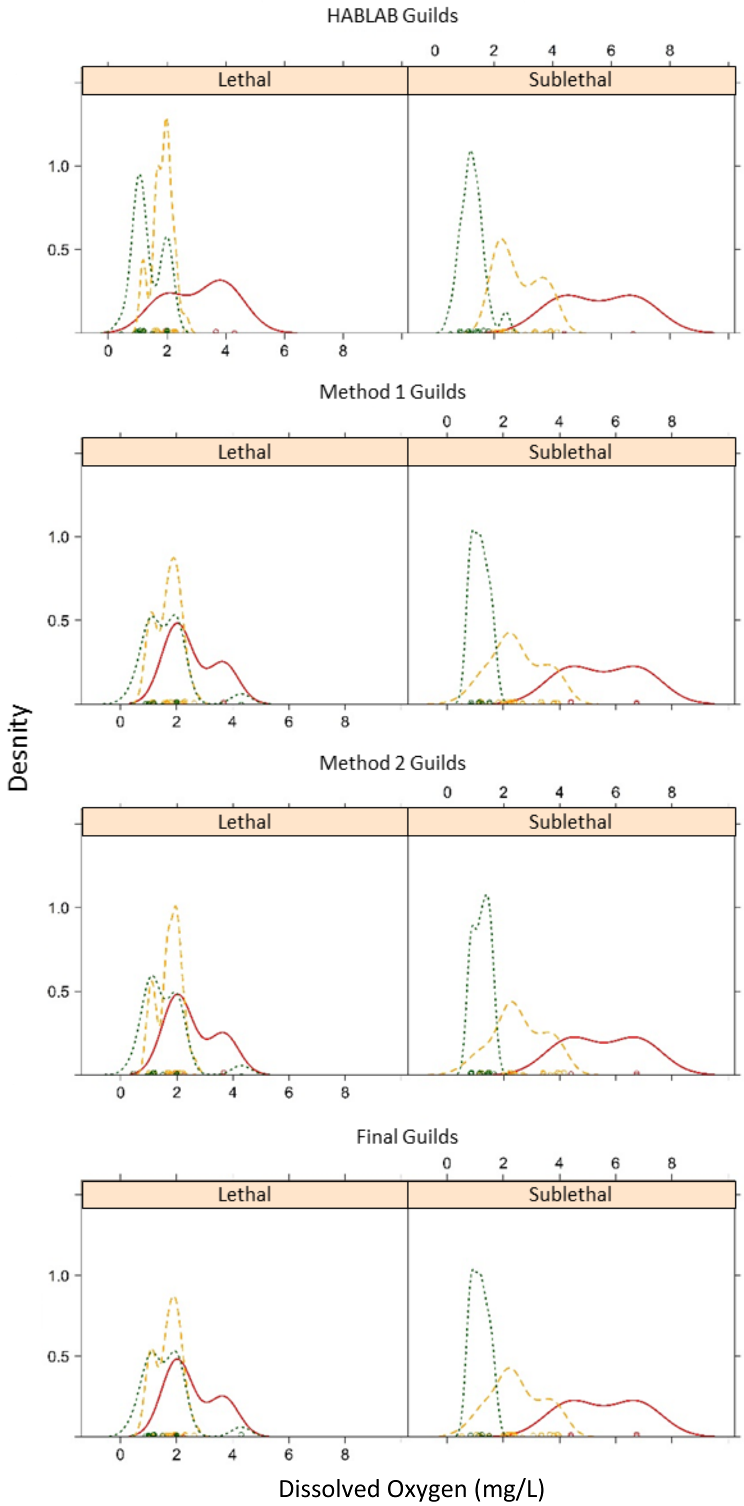

Figure 7. A comparison of the kernel density estimation of different dissolved oxygen (DO; mg/L) fish guild classification methods using DO means extracted from the lethal and sublethal groups of the HABLAB dataset. The solid red, dashed yellow and dotted green lines represent sensitive (S), mesotolerant (M), and tolerant (T) guild classifications, respective

APPENDIX

DISSOLVED OXYGEN THRESHOLD TABLES

Table A1. Adult and juvenile life stage table illustrating the sublethal effects of dissolved oxygen (DO) averaged across studies by species. S stands for starting effects observed in the population. Ontario Freshwater Fishes Life History Database (OFFLHD) information comes from Eakins (2019)(OMNRF = Ontario Ministry of Natural Resources and Forestry). U.S. Fish and Wildlife Service (USFWS, 1982–1989) habitat suitability indices (HSI) for dissolved oxygen were derived from habitat suitability curves in the HSI reports.
Note: "--" indicates no data.

OMNRF species ID	Common name	OFFLHD thermal guild	DO (mg/L) sublethal effects % negatively affected			OFFLHD tolerance class	USFWS DO HSI (mg/L)	
			S	<50%	≥50%		Low	High
61	Alewife	cold	—	—	4.00	intermediate	—	—
73	Coho Salmon	cold	—	5.70	3.35	intolerant	3.75	7.25
75	Chinook Salmon	cold	6.00	2.39	3.37	intolerant	3.8	10.3
76	Rainbow Trout	cold	5.72	6.13	3.93	intolerant	3	7
78	Brown Trout	cold	4.59	—	3.07	intolerant	3	10.5
80	Brook Trout	cold	6.80	—	6.74	intolerant	4	8
81	Lake Trout	cold	7.00	—	4.15	intolerant	6	8
91	Lake whitefish	cold	—	—	1.82	intolerant	—	—
93	Cisco	cold	—	—	4.40	intolerant	—	—
131	Northern Pike	cool	—	4.50	2.41	intermediate	—	—
163	White Sucker	cool	—	—	1.24	tolerant	1.5	6
182	Northern Redbelly Dace	cool	—	—	1.13	intermediate	—	—
186	Common Carp	warm	3.59	—	—	tolerant	1.5	6
189	Brassy Minnow	cool	—	—	2.01	intermediate	—	—
192	Hornyhead Chub	cool	—	—	1.18	intermediate	—	—
196	Emerald Shiner	cool	—	—	2.68	intermediate	—	—
198	Common Shiner	cool	—	—	1.44	intermediate	—	—
201	Spottail Shiner	cool	—	—	1.21	intermediate	—	—
209	Fathead Minnow	warm	—	4.00	0.85	tolerant	—	—
210	Blacknose Dace	cool	—	—	1.46	intermediate	—	—
211	Longnose Dace	cool	—	—	1.05	intermediate	—	—
212	Creek Chub	cool	—	—	2.21	intermediate	1	5
214	Pearl Dace	cool	—	—	0.83	intermediate	—	—
231	Black Bullhead	warm	—	—	1.99	intermediate	2	6
233	Brown Bullhead	warm	6.94	—	—	intermediate	—	—
234	Channel Catfish	warm	—	4.11	2.77	tolerant	—	—
236	Tadpole Madtom	warm	—	—	1.18	intermediate	—	—
281	Brook Stickleback	cool	—	—	2.12	intermediate	—	—
282	Threespine Stickleback	cool	—	—	3.80	intermediate	—	—
283	Ninespine Stickleback	cool	—	—	3.66	intermediate	—	—
311	Rock Bass	warm	—	—	2.24	intermediate	—	—
314	Bluegill	warm	2.25	—	1.50	intermediate	0	5
317	Largemouth Bass	warm	4.67	5.00	2.30	tolerant	0	8
331	Yellow Perch	cool	—	4.23	3.41	intermediate	—	—
334	Walleye	cool	3.88	—	3.77	intermediate	1	4.2
338	Iowa Darter	cool	—	—	2.40	intermediate	—	—
341	Johnny Darter	cool	—	—	1.65	tolerant	—	—
344	Blackside Darter	cool	—	—	0.52	intermediate	—	—

Table A2. Adult and juvenile life stage summary of lethal effects of low dissolved oxygen (DO, levels in mg/L) averaged across studies by species. S stands for starting effects observed in the population. Ontario Freshwater Fishes Life History Database (OFFLHD) information comes from Eakins (2019))(OMNRF = Ontario Ministry of Natural Resources and Forestry). U.S. Fish and Wildlife Service (USFWS, 1982–1989) habitat suitability indices (HSI) for DO were derived from habitat suitability curves in the HSI reports.

OMNRF species ID	Common name	OFFLHD thermal guild	DO (mg/L) lethal effects % of population dead			OFFLHD tolerance class	USFWS DO HSI (mg/L)	
			S	<50%	≥50%		Low	High
77	Atlantic Salmon	cold	—	—	2.17	intolerant	—	—
261	Banded Killifish	cool	—	—	0.90	tolerant	—	—
231	Black Bullhead	warm	—	—	1.65	intermediate	2	6
319	Black Crappie	warm	—	—	2.23	tolerant	1.5	5
314	Bluegill	warm	—	—	1.15	intermediate	0	5
208	Bluntnose Minnow	warm	—	—	1.05	intermediate	—	—
189	Brassy Minnow	cool	—	—	2.00	intermediate	—	—
281	Brook Stickleback	cool	—	—	2.00	intermediate	—	—
80	Brook Trout	cold	—	—	1.95	intolerant	4	8
233	Brown Bullhead	warm	—	—	1.00	intermediate	—	—
78	Brown Trout	cold	2.20	—	—	intolerant	3	10.5
271	Burbot	cold	2.30	—	2.00	intermediate	—	—
216	Central Stoneroller	cool	—	—	1.71	intermediate	—	—
234	Channel Catfish	warm	—	—	1.17	tolerant	—	—
93	Cisco	cold	—	—	3.67	intolerant	—	—
73	Coho Salmon	cold	—	1.71	—	intolerant	3.75	7.25
186	Common Carp	warm	—	—	1.19	tolerant	1.5	6
198	Common Shiner	cool	3.85	—	1.08	intermediate	—	—
212	Creek Chub	cool	—	—	2.00	intermediate	1	5
196	Emerald Shiner	cool	—	—	1.20	intermediate	—	—
339	Fantail Darter	cool	—	—	2.24	intolerant	—	—
209	Fathead Minnow	warm	—	—	2.00	tolerant	—	—
183	Finescale Dace	cool	—	—	1.00	intermediate	—	—
371	Freshwater Drum	warm	—	—	4.30	tolerant	—	—
63	Gizzard Shad	warm	—	—	1.00	tolerant	1	6
194	Golden Shiner	cool	—	1.40	1.00	intermediate	—	—
312	Green Sunfish	warm	—	—	1.50	tolerant	0	5
336	Greenside Darter	warm	—	—	2.63	intermediate	—	—
164	Lake Chubsucker	warm	—	—	1.00	intermediate	—	—
81	Lake Trout	cold	3.00	—	—	intolerant	6	8
317	Largemouth Bass	warm	2.60	—	1.92	tolerant	0	8
162	Longnose Sucker	cold	4.00	—	—	intermediate	4.5	6
131	Northern Pike	cool	0.45	—	1.57	intermediate	—	—
182	Northern Redbelly Dace	cool	—	—	2.00	intermediate	—	—
324	Orangespotted Sunfish	warm	—	—	1.20	tolerant	—	—
214	Pearl Dace	cool	—	—	2.00	intermediate	—	—
313	Pumpkinseed	warm	—	—	1.66	intermediate	—	—
337	Rainbow Darter	cool	—	—	1.95	intolerant	—	—
76	Rainbow Trout	cold	1.00	—	1.78	intolerant	3	7
311	Rock Bass	warm	—	—	2.30	intermediate	—	—
316	Smallmouth Bass	warm	—	—	2.00	intermediate	1	6
323	Warmouth	warm	—	—	1.00	intermediate	—	—
318	White Crappie	warm	—	—	0.45	tolerant	1	5
163	White Sucker	cool	—	—	2.00	tolerant	1.5	6
331	Yellow Perch	cool	—	2.16	1.67	intermediate	—	—

Table A3. Young-of-the-year life stage summary of sublethal effects of low dissolved oxygen (DO) averaged across studies by species. S stands for starting effects observed in the population. Ontario Freshwater Fishes Life History Database (OFFLHD) information comes from Eakins (2019))(OMNRF = Ontario Ministry of Natural Resources and Forestry). Note: "—" indicates no data.

OMNRF species ID	Common name	OFFLHD thermal guild	DO (mg/L) sublethal effects % negatively affected		
			S	< 50%	≥ 50%
73	Coho Salmon	cold	—	5.00	2.50
80	Brook Trout	cold	—	—	6.00
131	Northern Pike	cool	—	—	2.00
234	Channel Catfish	warm	—	3.60	2.25
314	Bluegill	warm	—	—	1.00
317	Largemouth Bass	warm	—	—	2.00
331	Yellow perch	cool	—	7.00	2.67
334	Walleye	cool	—	—	2.00
73	Coho Salmon	cold	—	5.00	2.50

Table A4. Young-of-the-year life stage summary of the lethal effects of low dissolved oxygen (levels in mg/L) averaged across studies by species. S stands for starting effects observed in the population. Ontario Freshwater Fishes Life History Database (OFFLHD) information comes from Eakins (2019))(OMNRF = Ontario Ministry of Natural Resources and Forestry). Note: "—" indicates no data.

OMNRF Species ID	Common Name	OFFLHD Thermal Guild	DO (mg/L) Lethal Effects % of population dead		
			S	<50%	≥50%
71	Pink Salmon	cold	—	—	2.10
73	Coho Salmon	cold	—	—	1.30
75	Chinook Salmon	cold	—	—	1.75
76	Rainbow Trout	cold	3.84	1.55	1.88
78	Brown Trout	cold	2.20	—	2.33
80	Brook Trout	cold	2.70	—	1.81
131	Northern Pike	cool	—	—	0.83
163	White Sucker	cool	—	—	0.98
181	Goldfish	warm	—	—	1.05
192	Hornyhead Chub	cool	—	—	1.06
194	Golden Shiner	cool	—	—	0.70
198	Common Shiner	cool	—	—	0.97
200	Blacknose Shiner	cool	—	—	2.00
202	Rosyface Shiner	warm	—	—	1.49
204	Sand Shiner	warm	—	—	0.93
208	Bluntnose Minnow	warm	—	—	1.04
209	Fathead Minnow	warm	—	1.77	0.73
212	Creek Chub	cool	—	—	0.84
216	Central Stoneroller	cool	—	—	0.95
217	Striped Shiner	cool	—	—	1.03
231	Black Bullhead	warm	—	—	1.13
232	Yellow Bullhead	warm	—	—	0.49
234	Channel Catfish	warm	—	—	0.94
262	Blackstripe Topminnow	warm	—	—	0.88
312	Green Sunfish	warm	—	—	0.63
313	Pumpkinseed	warm	—	—	2.00
314	Bluegill	warm	—	—	0.84
315	Longear Sunfish	warm	—	—	0.68
316	Smallmouth Bass	warm	1.25	—	0.95
317	Largemouth Bass	warm	—	—	0.99
324	Orangespotted Sunfish	warm	—	—	0.62
331	Yellow Perch	cool	—	3.83	1.95
334	Walleye	cool	—	—	1.27
337	Rainbow Darter	cool	—	—	1.10
339	Fantail Darter	cool	—	—	0.98
341	Johnny Darter	cool	—	—	0.70
361	Brook Silverside	warm	—	—	1.59

Table A5. Embryo and fry life stage summary of the sublethal effects of low dissolved oxygen averaged across studies by species. S stands for starting effects observed in the population. Ontario Freshwater Fishes Life History Database (OFFLHD) information comes from Eakins (2019))(OMNRF = Ontario Ministry of Natural Resources and Forestry). Note: "—" indicates no data.

OMNRF species ID	Common name	OFFLHD thermal guild	DO (mg/L) sublethal effects % negatively affected		
			S	<50%	≥50%
73	Coho Salmon	cold	—	5.00	5.70
75	Chinook Salmon	cold	—	5.30	2.33
76	Rainbow Trout	cold	7.18	5.35	5.70
78	Brown Trout	cold	—	—	3.50
80	Brook Trout	cold	—	—	2.30
81	Lake Trout	cold	—	3.46	5.15
131	Northern Pike	cool	3.22	—	—
163	White Sucker	cool	—	—	2.50
186	Common Carp	warm	4.87	—	—
209	Fathead Minnow	warm	—	3.47	2.65
234	Channel Catfish	warm	—	4.15	2.30
316	Smallmouth Bass	warm	—	—	6.15
317	Largemouth Bass	warm	—	—	4.83
334	Walleye	cool	—	—	3.40

Table A6. Embryo and fry life stage table summary of the lethal effects of low dissolved oxygen averaged across studies by species. S stands for starting effects observed in the population. Ontario Freshwater Fishes Life History Database (OFFLHD) information comes from Eakins (2019))(OMNRF = Ontario Ministry of Natural Resources and Forestry). Note: "—" indicates no data.

OMNRF species ID	Common name	OFFLHD thermal guild	DO (mg/L) lethal effects % of population dead		
			S	<50%	≥50%
76	Rainbow Trout	cold	—	6.00	4.74
77	Atlantic Salmon	cold	—	9.02	4.15
78	Brown Trout	cold	8.00	3.00	3.20
93	Cisco	cold	4.00	3.00	1.33
131	Northern Pike	cool	—	—	2.60
163	White Sucker	cool	—	—	4.20
186	Common Carp	warm	—	—	1.20
209	Fathead Minnow	warm	—	5.01	3.04
234	Channel Catfish	warm	5.80	—	2.33
302	White Bass	warm	—	—	5.26
316	Smallmouth Bass	warm	—	—	2.74
317	Largemouth Bass	warm	—	2.60	2.04
334	Walleye	cool	—	5.13	4.13

DISSOLVED OXYGEN REFERENCE TABLES

Table A7. List of references compiled for adult and juvenile Great Lakes fish dissolved oxygen (DO) tolerance. Effect groups are categorized as follows: negative effects that cause fish mortality (or death; D) and the loss of equilibrium (LOE), aquatic surface respiration (ASR), avoidance (A), effects on behaviour (B), metabolism (M), and swimming (Sw). In cases where a DO tolerance level was taken from other literature reviews, the original reference was cross validated and the duplicates were removed.

Common name	Scientific name	Negative effect groups	Reference	Source reference
Alewife	*Alosa pseudoharengus*	A	Klumb et al. 2004	
Atlantic Salmon	*Salmo salar*	D	Hansen et al. 2015	
		LOE	Barnes et al. 2011	
Banded Killifish	*Fundulus diaphanus*	D	Doudoroff and Shumway 1970	Moore 1942
Bass	*Micropterus sp.*	M	Oregon DEQ 1995	
Black Bullhead	*Ameiurus melas*	ASR	Chapman and Mackenzie 2009	Gee et al. 1978
			Gee et al. 1978	
		B	Gee et al. 1978	
		D	Doudoroff and Shumway 1970	Moore 1942
Black Crappie	*Pomoxis nigromaculatus*	D	Doudoroff and Shumway 1970	Hart 1942
			Doudoroff and Shumway 1970	Moore 1942
Blacknose Dace	*Rhinichthys atratulus*	ASR	Chapman and Mackenzie 2009	Gee et al. 1978
			Gee et al. 1978	
		B	Gee et al. 1978	
Blackside Darter	*Percina maculata*	ASR	Chapman and Mackenzie 2009	Gee et al. 1978
			Gee et al. 1978	
		B	Gee et al. 1978	
Blackstripe Topminnow	*Fundulus notatu*	B	Lewis 1970	
		M, ASR	Rutledge and Beitinger 1989	
Bluegill	*Lepomis macrochirus*	A	Davis 1975	Whitmore et al. 1960
			Oregon DEQ 1995	
		ASR	Lewis 1970	
		D	AEP 1997	Petrosky and Magnuson 1973
			Doudoroff and Shumway 1970	Baker 1941
			Doudoroff and Shumway 1970	Hart 1942
			Doudoroff and Shumway 1970	McNeil 1956
			Doudoroff and Shumway 1970	Moore 1942
			Oregon DEQ 1995	
		D, ASR	Doudoroff and Shumway 1970	Baker 1941
		D, LOE	Farwell et al. 2007	
Bluntnose Minnow	*Pimephales notatus*	D	Doudoroff and Shumway 1970	Wilding 1939

Common name	Scientific name	Negative effect groups	Reference	Source reference
Brassy Minnow	*Hybognathus hakinsoni*	ASR	Chapman and Mackenzie 2009	Gee et al. 1978
			Gee et al. 1978	
		B	Gee et al. 1978	
		D	Doudoroff and Shumway 1970	Black et al. 1954
Brook Stickleback	*Culaea inconstans*	ASR	Chapman and Mackenzie 2009	Gee et al. 1978
			Gee et al. 1978	
		B	Gee et al. 1978	
		D	Doudoroff and Shumway 1970	Black et al. 1954
Brook Trout	*Salvelinus fontinalis*	D	Doudoroff and Shumway 1970	Black et al. 1954
			Doudoroff and Shumway 1970	Graham 1949
		M	Davis 1975	Beamish and Mookherjii 1964
			Davis 1975	Graham 1949
			Davis 1975	Irving et al. 1941
		Sw	Davis 1975	Graham 1949
			Oregon DEQ 1995	
Brown Bullhead	*Ameiurus nebulosus*	D	Doudoroff and Shumway 1970	Black et al. 1954
			Doudoroff and Shumway 1970	Hart 1942
		M	Davis 1975	Grigg 1969
			Oregon DEQ 1995	
Brown Trout	*Salmo trutta*	A	Oregon DEQ 1995	
		B	Elliott 2000	
		D	Doudoroff and Shumway 1970	Privolnev 1954
		M	Chapman 1986	
			Davis 1975	Irving et al. 1941
Burbot	*Lota lota*	D	Doudoroff and Shumway 1970	Black et al. 1954
			Doudoroff and Shumway 1970	Privolnev 1954
Central Stoneroller	*Campostoma anomalum*	D	Doudoroff and Shumway 1970	Baker 1941
			Doudoroff and Shumway 1970	Baker 1941
		LOE	AEP 1997	Hlohowskyj and Chagnon 1991
Centrarchid	*Centrarchidae*	A	Oregon DEQ 1995	
		M	Oregon DEQ 1995	
Channel Catfish	*Ictalurus punctatus*	D	Doudoroff and Shumway 1970	Moss and Scott 1961
			Doudoroff and Shumway 1970	Moss and Scott 1961
			Oregon DEQ 1995	
		M	AEP 1997	Carlson et al. 1980
			AEP 1997	Carlson et al. 1980
			Buentello et al. 2000	

Common name	Scientific name	Negative effect groups	Reference	Source reference
			Carlson et al. 1980	
			Chapman 1986	
			Oregon DEQ 1995	
Chinook Salmon	*Oncorhynchus tshawytscha*	A	Oregon DEQ 1995	
		D, ASR	Doudoroff and Shumway 1970	Chapman 1940
		M	Chapman 1986	
		Sw	Katz et al. 1959	
Cisco	*Coregonus artedi*	A	Rudstam and Magnuson 1985	
		D	Jacobson et al. 2008	
			Rudstam and Magnuson 1985	
Coho Salmon	*Oncorhynchus kisutc*	A	Oregon DEQ 1995	
		D	Doudoroff and Shumway 1970	Davison et al. 1959
			Doudoroff and Shumway 1970	McNeil 1956
		M	Chapman 1986	
			Oregon DEQ 1995	
		Sw	Katz et al. 1959	
			Oregon DEQ 1995	
Common Carp	*Cyprinus carpio*	ASR	Chapman and Mackenzie 2009	Gee et al. 1978
			Chapman and Mackenzie 2009	McNeil and Closs 2007
		D	Doudoroff and Shumway 1970	Downing and Merkens 1957
			Doudoroff and Shumway 1970	Privolnev 1954
			Doudoroff and Shumway 1970	Streltsova 1964
		M	Davis 1975	Beamish and Mookherjii 1964
Common Shiner	*Luxilus cornutus*	ASR	Chapman and Mackenzie 2009	Gee et al. 1978
			Gee et al. 1978	
		B	Gee et al. 1978	
		D	Doudoroff and Shumway 1970	Black et al. 1954
		LOE	Doudoroff and Shumway 1970	Cooper 1960
Crappie	*Pomoxis*	D	Oregon DEQ 1995	
Creek Chub	*Semotilus atromaculatus*	ASR	Chapman and Mackenzie 2009	Gee et al. 1978
			Gee et al. 1978	
		B	Gee et al. 1978	
		D	Doudoroff and Shumway 1970	Black et al. 1954
Emerald Shiner	*Notropis atherinoides*	A	Klumb et al. 2004	
		ASR	Chapman and Mackenzie 2009	Gee et al. 1978
			Gee et al. 1978	
		B	Gee et al. 1978	
		D, LOE	Matthews and Maness 1979	
Fantail Darter	*Etheostoma flabellare*	D, LOE	Hlohowskyj and Wissing 1987	

Common name	Scientific name	Negative effect groups	Reference	Source reference
Fathead Minnow	*Pimephales promelas*	ASR	Chapman and Mackenzie 2009	Gee et al. 1978
			Gee et al. 1978	
		B	Gee et al. 1978	
		D	Doudoroff and Shumway 1970	Black et al. 1954
			Doudoroff and Shumway 1970	Whitworth and Irwin 1961
		M	Robb and Abrahams 2003	
Finescale Dace	*Chrosomus neogaeus*	D	Doudoroff and Shumway 1970	Black et al. 1954
Freshwater Drum	*Aplodinotus grunniens*	D	Doudoroff and Shumway 1970	Moore 1942
Gizzard Shad	*Dorosoma cepedianum*	D	Doudoroff and Shumway 1970	Hart 1942
Golden Shiner	*Notemigonus crysoleucas*	ASR	Lewis 1970	
		D	Doudoroff and Shumway 1970	Hart 1942
			Doudoroff and Shumway 1970	Moore 1942
Goldfish	*Carassius auratus*	ASR	Chapman and Mackenzie 2009	McNeil and Closs 2007
			Lewis 1970	
		Sw	Chapman and Mackenzie 2009	
Green Sunfish	*Lepomis cyanellus*	ASR	Lewis 1970	
		D	Doudoroff and Shumway 1970	Moore 1942
Greenside Darter	*Etheostoma blennioides*	D, LOE	Hlohowskyj and Wissing 1987	
Hornyhead Chub	*Nocomis biguttatus*	ASR	Chapman and Mackenzie 2009	Gee et al. 1978
			Gee et al. 1978	
		B	Gee et al. 1978	
Iowa Darter	*Etheostoma exile*	ASR	Chapman and Mackenzie 2009	Gee et al. 1978
			Gee et al. 1978	
		B	Gee et al. 1978	
Johnny Darter	*Etheostoma nigrum*	ASR	Chapman and Mackenzie 2009	Gee et al. 1978
			Gee et al. 1978	
		B	Gee et al. 1978	
Lake Chubsucker	*Erimyzon sucetta*	D	Doudoroff and Shumway 1970	Hart 1942
Lake Trout	*Salvelinus namaycush*	A	Evans 2007	
			Plumb and Blanchfield 2009	
		D	Evans 2007	
		M	Chapman 1986	
			Evans 2007	
Lake Whitefish	*Coregonus clupeaformis*	B	Gee et al. 1978	
Largemouth Bass	*Micropterus salmoides*	A	Burleson et al. 2001	
			Davis 1975	Whitmore et al. 1960
			Hasler et al. 2009	
		ASR	Lewis 1970	
		B	Hasler et al. 2009	
			Oregon DEQ 1995	

Common name	Scientific name	Negative effect groups	Reference	Source reference
		D	Cech et al. 1979	
			Doudoroff and Shumway 1970	Hart 1942
			Doudoroff and Shumway 1970	Moore 1942
			Oregon DEQ 1995	
			Yamanka et al. 2007	
		M	Chapman 1986	
			Oregon DEQ 1995	
		Sw	Davis 1975	Dahlberg et al. 1968
			Katz et al. 1959	
			Oregon DEQ 1995	
Longnose Dace	*Rhinichthys cataractae*	ASR	Chapman and Mackenzie 2009	Gee et al. 1978
			Gee et al. 1978	
		B	Gee et al. 1978	
Longnose Sucker	*Catostomus catostomus*	D	Oregon DEQ 1995	
Ninespine Stickleback	*Pungitius pungitius*	ASR	Chapman and Mackenzie 2009	Gee et al. 1978
			Gee et al. 1978	
		B	Gee et al. 1978	
Northern Pike	*Esox lucius*	ASR	Chapman and Mackenzie 2009	Gee et al. 1978
			Gee et al. 1978	
		B	Gee et al. 1978	
		D	Doudoroff and Shumway 1970	Moore 1942
			Doudoroff and Shumway 1970	Privolnev 1954
			Doudoroff and Shumway 1970	Privolnev and Koroleva 1953
			Doudoroff and Shumway 1970	Shkorbatov 1965
		M	AEP 1997	Adelman and Smith 1970
			Chapman 1986	
			Chapman and Mackenzie 2009	Gee et al. 1978
Northern Redbelly Dace	*Chrosomus eos*	ASR	Gee et al. 1978	
			Gee et al. 1978	
		B	Doudoroff and Shumway 1970	Black et al. 1954
		D	Doudoroff and Shumway 1970	Moore 1942
Orangespotted Sunfish	*Lepomis humilis*	D	Doudoroff and Shumway 1970	Baker 1941
		D, ASR	Doudoroff and Shumway 1970	Baker 1941
	(blank)	D	Chapman and Mackenzie 2009	Gee et al. 1978
Pearl Dace	*Margariscus margarita*	ASR	Gee et al. 1978	
			Gee et al. 1978	
		B	Doudoroff and Shumway 1970	Black et al. 1954

Common name	Scientific name	Negative effect groups	Reference	Source reference
		D	Doudoroff and Shumway 1970	Moore 1942
Pumpkinseed	*Lepomis gibbosus*	D	Farwell et al. 2007	
		D, LOE	Hlohowskyj and Wissing 1987	
Rainbow Darter	*Etheostoma caeruleum*	D, LOE	Peintka and Parrish 2002	
Rainbow Smelt	*Osmerus mordax*	B	Weithman and Haas 1984	
Rainbow Trout	*Oncorhynchus mykiss*	A	Gee et al. 1978	
		B	AEP 1997	Wirosoebroto-Hartadi 1985; as referenced in Truelson 1997
		D	Doudoroff and Shumway 1970	Downing and Merkens 1957
			Doudoroff and Shumway 1970	McNeil 1956
			Doudoroff and Shumway 1970	Privolnev 1954
			Doudoroff and Shumway 1970	Streltsova 1964
			Franklin 2013	Dean and Richardson 1999
			Franklin 2013	Landman et al 2005
			Oregon DEQ 1995	
			Franklin 2013	Dean and Richardson 1999
		D, ASR	AEP 1997	Pedersen 1987
		M	Chapman 1986	
			Davis 1975	Cameron 1970
			Davis 1975	Downing 1954
			Davis 1975	Hughes and Saunders 1970
			Davis 1975	Irving et al. 1941
			Davis 1975	Itazawa 1970
			Davis 1975	Kutty 1968
			Davis 1975	Randall and Smith 1967
			Davis 1975	Randall et al. 1967
			McDaniel et al. 2005	
			Davis 1975	Jones 1971
		Sw	Oregon DEQ 1995	
			Chapman and Mackenzie 2009	Gee et al. 1978
Rock Bass	*Ambloplites rupestris*	ASR	Gee et al. 1978	
			Gee et al. 1978	
		B	Doudoroff and Shumway 1970	Moore 1942
		D	Carter 2005	
Salmonid	*salmonidae*	D	Oregon DEQ 1995	

Common name	Scientific name	Negative effect groups	Reference	Source reference
			Oregon DEQ 1995	
		M	Oregon DEQ 1995	
		Sw	Doudoroff and Shumway 1970	Black et al. 1954
Smallmouth Bass	*Micropterus dolomieu*	D	Chapman 1986	
Sockeye Salmon	*Oncorhynchus nerka*	M	Chapman and Mackenzie 2009	Gee et al. 1978
Spottail Shiner	*Notropis hudsonius*	ASR	Gee et al. 1978	
			Gee et al. 1978	
		B	Chapman and Mackenzie 2009	Gee et al. 1978
Tadpole Madtom	*Noturus gyrinus*	ASR	Gee et al. 1978	
			Gee et al. 1978	
		B	Jones 1952	
Threespine Stickleback	*Gasterosteus aculeatus*	M, Sw	Oregon DEQ 1995	
Trout	*salmonidae*	D	Oregon DEQ 1995	
		M	Oregon DEQ 1995	
Walleye	*Sander vitreus*	A	Davis 1975	Scherer 1971
		B	Gee et al. 1978	
			Doudoroff and Shumway 1970	Baker 1941
Warmouth	*Lepomis gulosus*	D	Doudoroff and Shumway 1970	Baker 1941
		D, ASR	Doudoroff and Shumway 1970	Baker 1941
White Crappie	*Pomoxis annularis*	D	Doudoroff and Shumway 1970	Baker 1941
		D, ASR	Chapman and Mackenzie 2009	Gee et al. 1978
White Sucker	*Catostomus commersonii*	ASR	Gee et al. 1978	
			Gee et al. 1978	
		B	Doudoroff and Shumway 1970	Black et al. 1954
		D	Rudstam and Magnuson 1985	
Yellow Perch	*Perca flavescens*	A	Chapman and Mackenzie 2009	Gee et al. 1978
		ASR	Gee et al. 1978	
			Gee et al. 1978	
		B	Doudoroff and Shumway 1970	Black et al. 1954
		D	Doudoroff and Shumway 1970	Moore 1942
			Doudoroff and Shumway 1970	Wilding 1939
			Rudstam and Magnuson 1985	Petit 1973
			Robb and Abrahams 2003	
		D, LOE	Doudoroff and Shumway 1970	Burdick et al. 1954
		LOE	AEP 1997	Carlson et al. 1980
		M	Carlson et al. 1980	
			Chapman 1986	

Table A8. List of references compiling young of the year (YOY) life stages for Great Lakes fish dissolved oxygen (DO) tolerance. Effect groups are categorized as the following: negative effects that cause fish mortality (or "Death"; D), effects on behaviour (B), metabolism (M), effects on feeding (F) and swimming (Sw). In cases where a DO tolerance level is taken from other literature reviews, the original reference was cross validated and duplicates were removed.

Common name	Scientific name	Negative effect groups	Reference	Source reference
Atlantic Salmon	*Salmo salar*	D	Casas-Mulet et al. 2014	
			Franklin 2013	Cote et al. 2012
Brook Trout	*Salvelinus fontinalis*	M	AEP 1997	Siefert and Spoor 1974
Brown Trout	*Salmo trutta*	D	AEP 1997	Garric et al. 1990
			Doudoroff and Shumway 1970	Bishal 1960
			Franklin 2013	Roussel 2007
			Oregon DEQ 1995	
		M, Sw	Jones 1952	
Channel Catfish	*Ictalurus punctatus*	D	Durborow et al. 1985	
			Oregon DEQ 1995	
		M	Carlson and Siefert 1974	
Chinook Salmon	*Oncorhynchus tshawytscha*	Sw	Davis et al. 1963	
Cisco	*Coregonus artedi*	D	Brooke and Colby 1980	
			Oregon DEQ 1995	
Coho Salmon	*Oncorhynchus kisutc*	M	AEP 1997	Siefert and Spoor 1974
		Sw	Davis et al. 1963	
Common Carp	*Cyprinus carpio*	D	Doudoroff and Shumway 1970	Kuznetsova 1958
		M	Davis 1975	Itazawa 1970
Fathead Minnow	*Pimephales promelas*	D	AEP 1997	Brungs 1971
			Brungs 1971	
		M	AEP 1997	Brungs 1971
			Brungs 1971	
Lake Trout	*Salvelinus namaycush*	M	AEP 1997	Carlson and Siefert 1974
			Garside 1959	
			Oregon DEQ 1995	
Largemouth Bass	*Micropterus salmoides*	B	Oregon DEQ 1995	
		D	Dudley and Eipper 1975	
			Oregon DEQ 1995	
		M	Oregon DEQ 1995	
		M, F	Oregon DEQ 1995	
Northern Pike	*Esox lucius*	D	AEP 1997	Siefert and Spoor 1973
		M	Davis 1975	Siefert and Spoor 1973
Rainbow Trout	*Oncorhynchus mykiss*	D	Coble 1961	
			Doudoroff and Shumway 1970	Streltsova 1964
			Franklin 2013	Landman et al 2005
			Oregon DEQ 1995	

Common name	Scientific name	Negative effect groups	Reference	Source reference
			Rombough 1986	
			Rombough 1988	
		M	Ciuhandu et al. 2005	
			Davis 1975	Holeton 1971
			Miller et al. 2008	
Salmonid	*salmonidae*	D	Carter 2005	
			Oregon DEQ 1995	
Smallmouth Bass	*Micropterus dolomieu*	D	AEP 1997	Siefert and Spoor 1974
			Oregon DEQ 1995	
			Siefert and Spoor 1974	
		M	AEP 1997	Carlson and Siefert 1974
Walleye	*Sander vitreus*	D	AEP 1997	Siefert and Spoor 1974
			Oregon DEQ 1995	
			Oseid and Smith 1971	
		M	AEP 1997	Siefert and Spoor 1974
White Bass	*Morone chrysops*	D	AEP 1997	Siefert and Spoor 1974
			Siefert and Spoor 1974	
White Sucker	*Catostomus commersonii*	D	AEP 1997	Siefert and Spoor 1974
			Oseid and Smith 1971	
		M	AEP 1997	Siefert and Spoor 1974

Table A9. List of references compiling egg, embryo, and fry life stages for Great Lakes fish dissolved oxygen (DO) tolerance. Effect groups are categorized as the following: negative effects that cause fish mortality (or "Death"; D) and the loss of equilibrium (LOE), aquatic surface respiration (ASR), avoidance (A), metabolism (M) and swimming (Sw). In cases where a DO tolerance level is taken from other literature reviews, the original reference was cross validated and duplicates were removed.

Common name	Scientific name	Negative effect groups	Reference	Source reference
Black Bullhead	*Ameiurus melas*	D	Smale and Rabeni 1995	
Blacknose Shiner	*Notropis heterolepis*	D	Doudoroff and Shumway 1970	Black et al. 1954
Blackstripe Topminnow	*Fundulus notatu*	D	Smale and Rabeni 1995	
Bluegill	*Lepomis macrochirus*	ASR	Petit 1973	
		D	Doudoroff and Shumway 1970	Moss and Scott 1961
			Moss and Scott 1961	
			Smale and Rabeni 1995	
		D, LOE	Petit 1973	
		M	Petit 1973	
Bluntnose Minnow	*Pimephales notatus*	D	Smale and Rabeni 1995	
Brook Silverside	*Labidesthes sicculus*	D	Smale and Rabeni 1995	
Brook Trout	*Salvelinus fontinalis*	A	Oregon DEQ 1995	
		D	Doudoroff and Shumway 1970	Graham 1949
			Doudoroff and Shumway 1970	King 1943
		LOE	Doudoroff and Shumway 1970	Burdick et al. 1954
Brown Trout	*Salmo trutta*	D	Doudoroff and Shumway 1970	Bishal 1960
			Doudoroff and Shumway 1970	Burdick et al. 1954
			Doudoroff and Shumway 1970	King 1943
Central Stoneroller	*Campostoma anomalum*	D	Smale and Rabeni 1995	
Channel Catfish	*Ictalurus punctatus*	D	Moss and Scott 1961	
			Torrans 2008	
		M	AEP 1997	Andrews et al. 1973
			Carlson et al. 1980	
			Torrans 2008	
Chinook Salmon	*Oncorhynchus tshawytscha*	D	Doudoroff and Shumway 1970	Katz et al. 1959
Coho Salmon	*Oncorhynchus kisutc*	LOE	Doudoroff and Shumway 1970	Townsend and Earnest 1940
			Doudoroff and Shumway 1970	Townsend et al. 1938
		M	AEP 1997	Brett and Blackburn 1981
			Brett and Blackburn 1981	
		Sw	Davis et al. 1963	
Common Carp	*Cyprinus carpio*	D	Doudoroff and Shumway 1970	Opuszynski 1967
Common Shiner	*Luxilus cornutus*	D	Smale and Rabeni 1995	
Creek Chub	*Semotilus atromaculatus*	D	Smale and Rabeni 1995	

Common name	Scientific name	Negative effect groups	Reference	Source reference
Fantail Darter	*Etheostoma flabellare*	D	Smale and Rabeni 1995	
Fathead Minnow	*Pimephales promelas*	D	Smale and Rabeni 1995	
		D, LOE	Robb and Abrahams 2003	
Golden Shiner	*Notemigonus crysoleucas*	D	Smale and Rabeni 1995	
Goldfish	*Carassius auratus*	D	Doudoroff and Shumway 1970	Basu and Basu 1949
			Doudoroff and Shumway 1970	Fry 1957
Green Sunfish	*Lepomis cyanellus*	D	Smale and Rabeni 1995	
Hornyhead Chub	*Nocomis biguttatus*	D	Smale and Rabeni 1995	
Johnny Darter	*Etheostoma nigrum*	D	Smale and Rabeni 1995	
Largemouth Bass	*Micropterus salmoides*	D	Doudoroff and Shumway 1970	Moss and Scott 1961
			Moss and Scott 1961	
			Smale and Rabeni 1995	
		D, LOE	Petit 1973	
		M	Petit 1973	
Longear Sunfish	*Lepomis megalotis*	D	Smale and Rabeni 1995	
Northern Pike	*Esox lucius*	ASR	Petit 1973	
		D, LOE	Petit 1973	
		M	Petit 1973	
Orangespotted Sunfish	*Lepomis humilis*	D	Smale and Rabeni 1995	
Pink Salmon	*Oncorhynchus gorbuscha*	D	Doudoroff and Shumway 1970	Privolnev and Koroleva 1953
Pumpkinseed	*Lepomis gibbosus*	D	Doudoroff and Shumway 1970	Black et al. 1954
Rainbow Darter	*Etheostoma caeruleum*	D	Smale and Rabeni 1995	
Rainbow Trout	*Oncorhynchus mykiss*	D	AEP 1997	Thurston et al. 1981
			Davis 1975	Lloyd 1961
			Doudoroff and Shumway 1970	Alabaster et al. 1957
			Doudoroff and Shumway 1970	Burdick et al. 1954
			Doudoroff and Shumway 1970	King 1943
		LOE	Doudoroff and Shumway 1970	Burdick et al. 1954
			Doudoroff and Shumway 1970	Townsend et al. 1938
Rosyface Shiner	*Notropis rubellus*	D	Smale and Rabeni 1995	
Sand Shiner	*Notropis stramineus*	D	Smale and Rabeni 1995	
Smallmouth Bass	*Micropterus dolomieu*	D	Doudoroff and Shumway 1970	Burdick et al. 1954
			Smale and Rabeni 1995	
		LOE	Doudoroff and Shumway 1970	Burdick et al. 1954
Sockeye Salmon	*Oncorhynchus nerka*	M	Brett and Blackburn 1981	

Common name	Scientific name	Negative effect groups	Reference	Source reference
Striped Shiner	*Luxilus chrysocephalus*	D	Smale and Rabeni 1995	
Walleye	*Sander vitreus*	D, LOE	Petit 1973	
		M	Middleton and Reeder 2003	
			Petit 1973	
Warmouth	*Lepomis gulosus*	ASR	Chapman and Mackenzie 2009	Schofield et al. 2007
White Sucker	*Catostomus commersonii*	D	Smale and Rabeni 1995	
Yellow Bullhead	*Ameiurus natalis*	D	Smale and Rabeni 1995	
Yellow Perch	*Perca flavescens*	A	Suthers and Gee 1986	
		ASR	Petit 1973	
		D	Suthers and Gee 1986	
		D, LOE	Petit 1973	
			Robb and Abrahams 2003	
		M	Petit 1973	

DATA GAPS TABLE

Table A10. Families of freshwater fishes occurring in Ontario, modified from "Ontario Ministry of Natural Resources Fish Species Codes and Names" (E. Holm, Royal Ontario Museum as derived from Dodge et al. 1984), with notes which species were reviewed and not reviewed in this report. Great Lakes and inland Ontario species not reviewed lacked dissolved oxygen tolerance information in the literature.

Family:	Reviewed in this report:	Not reviewed in this report:
Lampreys (Petromyzontidae)		American Brook Lamprey
		Chestnut Lamprey
		Northern Brook Lamprey
		Sea Lamprey
		Silver Lamprey
Sturgeons (Acipenseridae)		Lake Sturgeon
Gars (Lepisosteidae)		Longnose Gar
		Spotted Gar
Bowfins (Amidae)		Bowfin
Herring (Clupeidae)	Alewife	American Shad
	Gizzard Shad	
Trout and Salmon subfamily (Salmoninae)	Brook Trout	Aurora Trout
	Brown Trout	
	Chinook Salmon	
	Coho Salmon	
	Lake Trout	
	Pink Salmon	
	Rainbow Trout	
	Atlantic Salmon	
Whitefish subfamily (Coregoninae)	Cisco	Bloater
	Lake Whitefish	Nipigon Cisco
		Pygmy Whitefish
		Round Whitefish
		Shortjaw Cisco
Smelt (Osmeridae)	Rainbow Smelt	
Pike (Esocidae)	Northern Pike	Chain Pickerel
		Grass Pickerel
		Muskellunge
Mudminnow (Umbridae)		Central Mudminnow
Mooneyes (Hiodontidae)		Goldeye
		Mooneye

Family:	Reviewed in this report:	Not reviewed in this report:
Suckers (Catostomidae)	Lake Chubsucker	Bigmouth Buffalo
	Longnose Sucker	Black Buffalo
	White Sucker	Black Redhorse
		Golden Redhorse
		Greater Redhorse
		Northern Hob Sucker
		Quillback
		River Redhorse
		Shorthead Redhorse
		Silver Redhorse
		Smallmouth Buffalo
		Spotted Sucker
Carp and Minnow (Cyprinidae)	Blacknose Dace	Blackchin Shiner
	Blacknose Shiner	Bridle Shiner
	Bluntnose Minnow	Cutlip Minnow
	Brassy Minnow	Eastern Silvery Minnow
	Central Stoneroller	Fallfish
	Common Carp	Ghost Shiner
	Common Shiner	Grass Carp
	Creek Chub	Gravel Chub
	Emerald Shiner	Lake Chub
	Fathead Minnow	Mimic Shiner
	Finescale Dace	Pugnose Minnow
	Golden Shiner	Pugnose Shiner
	Goldfish	Redfin Shiner
	Hornyhead Chub	Redside Dace
	Longnose Dace	River Chub
	Northern Pearl Dace	Rudd
	Northern Redbelly Dace	Silver Chub
	Rosyface Shiner	Silver Shiner
	Sand Shiner	Spotfin Shiner
	Spottail Shiner	
	Striped Shiner	
North American Catfishes (Ictaluridae)	Black Bullhead	Brindled Madtom
	Brown Bullhead	Flathead Catfish
	Channel Catfish	Margined Madtom
	Tadpole Madtom	Northern Madtom
	Yellow Bullhead	Stonecat

Family:	Reviewed in this report:	Not reviewed in this report:
Freshwater Eels (Anguillidae)		American Eel
Topminnow (Fundulidae)	Banded Killifish	
	Blackstripe Topminnow	
Cods (Gadidae)	Burbot	
Sticklebacks (Gasterosteidae)	Brook Stickleback	Fourspine Stickleback
	Ninespine Stickleback	
	Threespine Stickleback	
Trout-perches (Percopsidae)		Trout-perch
Temperate Bass (Moronidae)	White Bass	White Perch
Sunfishes (Centrarchidae)	Black Crappie	
	Bluegill	
	Green Sunfish	
	Largemouth Bass	
	Longear Sunfish	
	Orangespotted Sunfish	
	Pumpkinseed	
	Rock Bass	
	Smallmouth Bass	
	Warmouth	
	White Crappie	
Perches (Percidae)	Blackside Darter	Channel Darter
	Fantail Darter	Eastern Sand Darter
	Greenside Darter	Least Darter
	Iowa Darter	Logperch
	Johnny Darter	River Darter
	Rainbow Darter	Ruffe
	Walleye	Sauger
	Yellow Perch	Tessellated Darter
New World Silversides (Atherinopsidae)	Brook Silverside	
Goby (Gobiidae)		Round Goby
		Tubenose Goby
Drums (Sciaenidae)	Freshwater Drum	
Sculpins (Cottidae)		Deepwater Sculpin
		Mottled Sculpin
		Slimy Sculpin
		Spoonhead Sculpin

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