Archive of Morphological Data for the *Coregonus artedi* Species Complex of the Great Lakes, Lake Nipigon, and Great Slave Lake

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FRONTISPIECE. Locations of place names mentioned in the text.

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ABSTRACT

This publication is a user guide for an archive of morphological data recorded by various authors from North American ciscoes of the *Coregonus artedi* species complex (subfamily *Coregoninae*). The archive is accessible from the Great Lakes Fishery Commission's (GLFC) server, is open access, and contains data for the Laurentian Great Lakes; Lake Nipigon, Ontario; and Great Slave Lake, Northwest Territories. The archive comprises morphometrics and meristics (together metrics) for 6,700 individual Cisco of which 1,400 are accompanied by images. In addition, the archive contains metrics presented as arrays by W. N. Koelz, Coregonid fishes of the Great Lakes, Bulletin of the U.S. Bureau of Fisheries 43(2):297-643, which were based on 10,000 individuals. Spreadsheets in the Metrics folder of the archive are divided broadly into Contemporary and Historical subfolders and the Contemporary subfolder is further divided into Cisco Monograph and Extra Monograph subfolders to encourage statistical assessment of findings in GLFC Miscellaneous Publication 2023. The Images folder is organized into subfolders by lake. Tables in this user guide allow for quick determination of the availability of data by lake, subspecies, author, and year.

INTRODUCTION

This publication explains how to access archival morphological data for the *Coregonus artedi* species complex collected from the Laurentian Great Lakes; Lake Nipigon, Ontario; and Great Slave Lake, Northwest Territories. Data were recorded historically (1917-1925) by Koelz (1929); contemporaneously (1961-2015) by Nicholas Mandrak (University of Toronto), Andrew Muir (Great Lakes Fishery Commission, GLFC), Chris Olds (USDA Forest Service), Thomas Pratt (Ontario Ministry of Natural Resources and Forestry, OMNRF), Scott Reid (OMNRF), Paul Vecsei (Tlicho Government), and Thomas Todd (U.S. Geological Survey, USGS, retired); and by Thomas Todd from the historical collections of Walter N. Koelz archived at the University of Michigan Museum of Zoology. Here *Coregonus artedi* refers to a species complex encompassing all of the forms (here subspecies) described in Koelz (1929) and several described in Eshenroder et al. (2021a, b; 2023 [revision of 2016 original]). Naming of subspecies is as per Eshenroder and Jacobson (2020), who used Koelz's (1929) specific and subspecific names for historically described forms and common names for those more recently described. This taxonomy differs from that of Page et al. (2023), who assigned species rank to all seven of Koelz's (1929) deepwater species, recognized the previously synonymized *C. nipigon* as a species, and placed all shallow-water forms in *C. artedi*, excepting *C. nipigon*.

Digital images of lateral profiles, where available, are included in the archive and can be cross-referenced by image number to the corresponding morphometric and meristic data (together metrics). Most of the morphological data comprise eight linear measurements and one meristic (gill raker number) used in Eshenroder et al. (2023), i.e., the "Cisco Monograph", but other metrics are provided based on availability and are defined in metadata tabs. Koelz's (1929) data, comprising 9,700 individuals, include summaries in the form of arrays from his Tables 6-11 and his individual "Representative Fish", which were digitized under the supervision of author D. L. Yule. In addition, the archive includes metrics for 650 of Koelz's museum specimens reanalyzed by T. Todd. Contemporary data comprising 2,400 individuals from Eshenroder et al. (2023) have been separated out from other contemporary data to allow for statistical analysis of results presented in the Cisco Monograph. All data are provided as open access spreadsheet files on the GLFC's server. Permission is not required for publication with the proviso that this publication and the contributing author are acknowledged.

ARCHIVAL STRUCTURE

The structure of the archive is shown as a tree diagram (Figure 1) with boxes representing folders/subfolders containing data. Metrics and images are the two major folders in the tree. The roots of the tree (subfolders) are individual authors who provided the data, although morphological spreadsheets may contain data from unnamed multiple authors. Hence, metrics for more than one lake and author are stored in the same subfolder. Subfolders under Metrics go first to the Contemporary and Historical subfolders. The Historical subfolder branches to the W. Koelz and T. Todd subfolders. Subfolders immediately under Contemporary go to the Cisco Monograph and Extra Monograph subfolders. The Extra Monograph subfolder contains collections made available to the GLFC that were not analyzed in the Cisco Monograph.

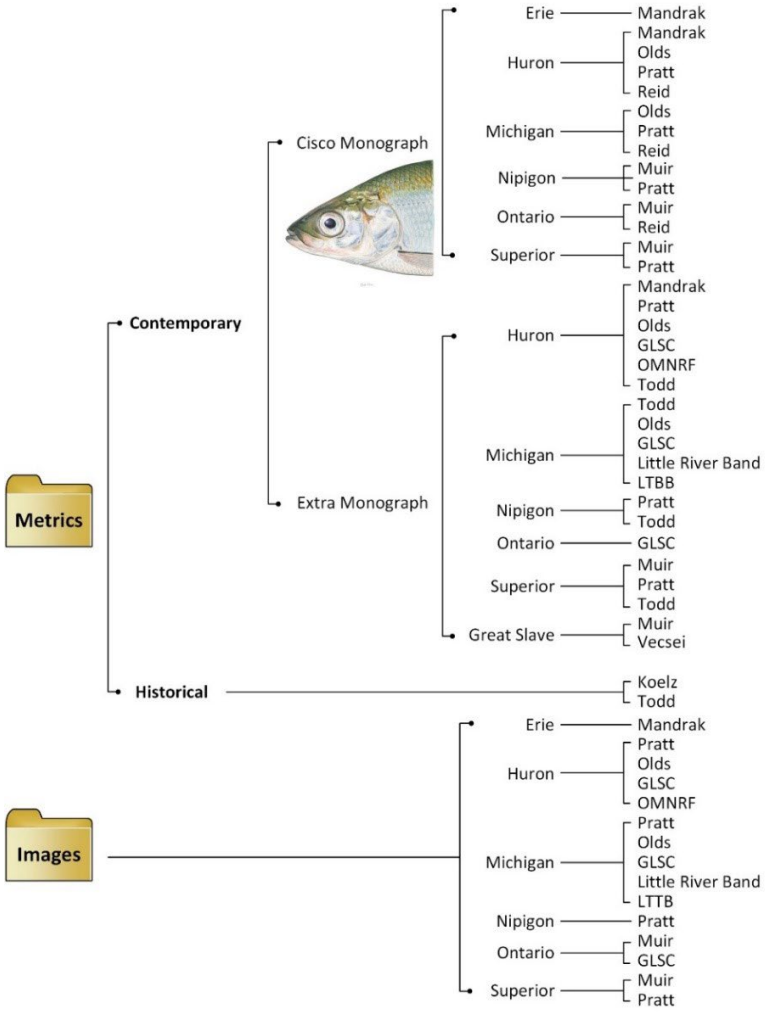

FIGURE 1. Tree diagram showing the hierarchical structure of the Archive of Cisco Metrics and Images (see text for relationships). GLSC = Great Lakes Science Center; OMNRF = Ontario Ministry of Natural Resources and Forestry; GTBI = Grand Traverse Band of Ottawa and Chippewa Indians; LTBB = Little Traverse Bay Bands of Odawa Indians.

An inventory of the metrics available in spreadsheets is provided in the Appendix, Tables A1-A6:

Table A1, Contemporary Cisco Monograph data

Table A2, Contemporary Extra Monograph data
Table A3, Historical data compiled by T. Todd from museum collections
Table A4, W. Koelz's (1929) metrics as displayed in arrays and as representative fish
Table A5, Number of monograph samples with images by lake, subspecies, author, and year
Table A6, Number of extra monograph samples with images by lake, subspecies, author, and year

Using these tables, users can determine if the data they seek are available without having to search spreadsheets. They allow for a quick appraisal of what types of comparisons are possible among these metrics or among other datasets. To access metrics and images go to (https://glfc.box.com/s/dljglh1tzy0gfmjptsq0629kench06ll), which will take you to the archive.

Notes

The form (taxonomic) assignments made by authors are retained. Assignments differ among datasets and may range from visual identification to statistically supported assignments based on metrics. We strongly recommend that where users combine datasets, they apply their own standardized quantitative approach to assigning taxonomy based on the objectives of the study. Predicted assignments, however, have been made for Lake Huron ciscoes collected by N. Mandrak, T. Pratt, and S. Reid. The assignments made by these authors preceded Eshenroder et al. (2023), who hypothesized that five historical subspecies of deepwater Cisco had introgressed into a hybrid swarm, which they named hybrida. Eshenroder et al. (2021a, b), however, determined that all of the shallow-water Cisco likely encountered in Lake Huron by these authors would have been various types of shorthead cisco, as the more-fusiform, historically dominant shallow-water cisco (typical *artedi*) had been extirpated. Therefore, using the taxonomy of Eshenroder et al. (2021a, b), these three authors were likely to have collected only two subspecies of Cisco in Lake Huron—deepwater hybrida and shallow-water shorthead cisco.

We used a linear discriminant analysis (LDA; Johnson and Wichern 1998) to assign the specimens collected from Lake Huron by N. Mandrak (2005-2006), T. Pratt (2005-2007), and S. Reid (2012) into either of two groups: shorthead cisco or hybrida. The LDA model was fitted to data collected in Lake Huron between 2015 and 2019, including 348 hybrida and 580 shorthead cisco that were classified based on morphology. These data were collected by multiple agencies and are maintained in a GLFC database maintained at the Great Lakes Science Center. As several linear measurements (e.g., body depth and maxillary length) were not available for the majority of the collections made by these three authors, only four predictor variables were included in the LDA model. The predictor variables were standard length, standard length to head length ratio, head length to snout length ratio, and total gill rakers. This set comprises a measure of size, two measures of shape, and a meristic all of which have been used by field biologists to distinguish hybrida and shorthead cisco (Eshenroder et al. 2023; Martin et al. 2023). Data for these four variables were available for 97% of the specimens collected by the three authors. The LDA model fitting and prediction were carried out in R (R Core Team 2021) and the package "MASS" (Venables and Ripley 2002).

Referring to the Contemporary subfolder, Cisco Monograph and Extra Monograph spreadsheets, the LDA (predicted) assignments for Lake Huron are in Column Z in the Cisco Monograph and Extra Monograph spreadsheets. Note that predicted assignments could not be made for about 3% of the specimens due to missing data, and these are listed as "None." Because T. Pratt's collection was accompanied by images, a priori (visual) assignments are provided in Column Y for his Cisco Monograph spreadsheet and in Column AB for his Extra Monograph spreadsheet. Out of 125 individuals with a priori assignments in the Cisco Monograph spreadsheet, 10 individuals classified as shorthead cisco in the LDA (column Z) were visually (a priori) determined to be hybrida, and 7 individuals classified as shorthead cisco in the LDA were visually determined to be shorthead cisco. Out of 981 individuals with a priori assignments in the Cisco Monograph spreadsheet, 4 individuals classified as shorthead cisco in the LDA were visually classified as hybrida, and 1 individual classified as a shorthead cisco in the LDA was visually classified as Lake Whitefish *C. clupeaformis* x Cisco. In addition, 2 individuals classified a priori as Lake Whitefish x Cisco were classified in the LDA as shorthead cisco, and 1 individual classified a priori as a Lake Whitefish was classified in the LDA as shorthead cisco. The Extra Monograph spreadsheet LDA had no data for hybrids or Lake Whitefish so these discrepancies are not remarkable and are provided for completeness. The Extra Monograph spreadsheet LDA assignments of shorthead cisco appear to be 100% correct whereas the LDA assignments of hybrida had an error rate of 9%.

As demonstrated above in our comparison of LDA and a priori assignments, lateral profile images allow for a level of quality control, including reassignment, not otherwise possible. Moreover, we encourage field biologists to learn how to make a priori assignments just as they would with fishes that look less alike. Not all samples are statistically processed each year and those that are may be several years old. Recognition of unexpected morphologies in the field also allows for resampling while individuals are more likely to remain available. We note that most of A. Muir and T. Pratt's contemporary samples (Appendix Tables A5 and A6) are cross-referenced to images. As depicted in the Cisco Monograph, the photographic setup used by T. Pratt differs from that used by A. Muir, which can affect comparison of post facto measurements. Images, too, can be helpful in dealing with outliers in morphometric data (Eshenroder et al. 2021a). As a matter of routine, any statistical comparisons of morphology should be preceded by an outlier analysis to minimize measurement error. The data presented here have not been subjected to quality control. We recommend that users undertake outlier identification and treatment before employing these data in an analysis. We assume that elimination of outlier individuals will tend to eliminate misclassifications. See Eshenroder et al. (2021a) for a method of identifying and treating outliers.

Other Data

Stanford Smith's morphological data on Cisco tabulated in Eshenroder et al. (2023) have been digitized and published https://www.sciencebase.gov/catalog/item/5f5a314182cefd9f20863b48 (Pollens-Dempsey et al. 2021). This publication provides data for an important middle period between Koelz (1929) and the contemporary collections in this archive. Likewise, morphological data used in recently completed and ongoing collaborative studies of Cisco involving the GLFC, but not included in Eshenroder et al. 2023, have been compiled into a database maintained at the Great Lakes Science Center. As of April 23, 2024, it comprised 2,283 individuals. Use is by request; contact research@glfc.org.

APPENDIX
Inventory of Data Available in the Archive of Cisco Metrics and Images

Table A1. Contemporary Cisco monograph subfolder: number (*N*) of contemporary samples by lake, subspecies, author (this publication), and year. See Tabular Data in Eshenroder et al. (2023) for additional information.

Lake	Subspecies	Author(s)	Year(s)	*N*
Erie	hybrida	Mandrak	2003–2015	19
Huron	*artedi*-like	Mandrak	2005–2006	10
Huron	*hoyi*-like	Mandrak	2005–2006	418
Huron	*zenithicus*-like	Mandrak	2005–2006	10
Huron	*artedi*-like	Pratt	2006–2007	60
Huron	*hoyi*-like	Pratt	2005–2007	58
Huron	*zenithicus*-like	Pratt	2005–2007	8
Huron	*artedi*-like	Reid	2012	74
Huron	*hoyi*-like	Reid	2012	109
Huron	*zenithicus*-like	Reid	2012	17
Huron	*albus*-like	Olds	2015	24
Michigan	*hoyi*	Pratt	2008	47
Michigan	*hoyi*	Reid	2011	113
Michigan	*albus*-like	Olds	2015	25
Nipigon	*artedi*	Muir	2013	4
Nipigon	*nigripinnis*	Muir	2013	16
Nipigon	*zenithicus*	Muir	2013	9
Nipigon	unknown	Muir	2013	2
Nipigon	*artedi*	Pratt	2008	68
Nipigon	*hoyi*	Pratt	2008	124
Nipigon	*nigripinnis*	Pratt	2008	191
Nipigon	*zenithicus*	Pratt	2008	57
Ontario	*artedi*	Reid	2011	106
Ontario	*artedi*	Muir	2013	41
Superior	*artedi*	Pratt	2004–2008	199
Superior	*hoyi*	Pratt	2004–2008	179
Superior	*kiyi*	Pratt	2004–2008	61
Superior	*zenithicus*	Pratt	2004–2008	167
Superior	*artedi*	Muir	2009–2010	45
Superior	*hoyi*	Muir	2009–2010	81
Superior	*kiyi*	Muir	2009–2010	30
Superior	*zenithicus*	Muir	2009–2010	22

Table A2. Contemporary extra monograph subfolder: number (*N*) of contemporary samples by lake, subspecies, author (this publication), and year. OMNRF = Ontario Ministry of Natural Resources and Forestry; USGS = U.S. Geological Survey; GTBI = Grand Traverse Band of Ottawa and Chippewa Indians; LTBB = Little Traverse Bay Bands of Odawa Indians.

Lake	Subspecies	Author	Year(s)	*N*
Huron	Bloater X Lake herring	Mandrak	2005–2006	10
Huron	Unknown	Mandrak	2005–2006	261
Huron	*hoyi*	Olds	2015	49
Huron	Bloater X Lake herring	Pratt	2006–2007	25
Huron	Bloater X Shortjaw	Pratt	2005–2006	23
Huron	Kiyi X Lake herring	Pratt	2007	2
Huron	Lake herring X Shortjaw	Pratt	2005–2007	7
Huron	*artedi*	Olds	2015–2018	407
Huron	Unknown	Olds	2015	2
Huron	*artedi*	GLSC	2016–2018	58
Huron	*hoyi*	GLSC	2016	349
Huron	Unknown	GLSC	2017	26
Huron	*artedi*	OMNRF	2017–2018	150
Huron	*artedi*	Todd	1974	5
Huron	*artedi*	Todd	1995	20
Huron	*hoyi*	Todd	1974–1979	4
Huron	*zenithicus*	Todd	1979	1
Michigan	*artedi*	Olds	2017–2018	12
Michigan	*hoyi*	Olds	2016–2017	25
Michigan	*hoyi*	GLSC	2018	20
Michigan	*artedi*	Olds	2017–2018	43
Michigan	*artedi*	Olds	2018	22
Michigan	*alpenae*	Todd	1961	1
Michigan	*hoyi*	Todd	1973–1974	173
Michigan	*reighardi*	Todd	1972	2
Michigan	*artedi*	GTBI	2018	22
Michigan	*artedi*	GTBI	2018	23
Nipigon	Blackfin X Bloater	Pratt	2008	6
Nipigon	Blackfin X Lake herring	Pratt	2008	4
Nipigon	Blackfin X Shortjaw	Pratt	2008	7
Nipigon	Bloater X Lake herring	Pratt	2008	3
Nipigon	Bloater X Shortjaw	Pratt	2008	8
Nipigon	Lake herring X Shortjaw	Pratt	2008	8
Nipigon	*artedi*	Todd	1973	9
Nipigon	*hoyi*	Todd	1973	7
Nipigon	*nigripinnis*	Todd	1973	9
Nipigon	*reighardi*	Todd	1973	7
Nipigon	*zenithicus*	Todd	1973	6
Ontario	*artedi*	GLSC	2018	24
Superior	*reighardi*	Pratt	2006	8
Superior	Bloater X Kiyi	Pratt	2006–2007	5
Superior	Bloater X Lake herring	Pratt	2006–2007	8
Superior	Bloater X Shortjaw	Pratt	2006–2007	15

Superior	Kiyi X Lake herring	Pratt	2006–2008	14
Superior	Kiyi X Shortjaw	Pratt	2006	6
Superior	Lake herring X Shortjaw	Pratt	2006–2008	7
Superior	Unknown	Pratt	2006	1
Superior	Bloater X Lake herring	Muir	2009	9
Superior	Bloater X Shortjaw	Muir	2009	3
Superior	*artedi*	Todd	1973–1974	114
Superior	*artedi-zenithicus*	Todd	1974	1
Superior	*hoyi*	Todd	1973–1974	77
Superior	*hoyi-artedi*	Todd	1974	1
Superior	*hoyi-zenithicus*	Todd	1974	1
Superior	*kiyi*	Todd	1973–1974	70
Superior	*kiyi-zenithicus*	Todd	1974	1
Superior	*reighardi*	Todd	1973	24
Superior	*zenithicus*	Todd	1973–1974	257
Superior	*zenithicus-hoyi*	Todd	1974	1
Great Slave	*artedi* - lacustrine	Muir	2008	8
Great Slave	*zenithicus*	Muir	2008	10
Great Slave	*artedi* - lacustrine	Muir	2008–2009	171
Great Slave	*artedi* - riverine	Muir	2008	150
Great Slave	*zenithicus*	Muir	2008–2009	69
Great Slave	*artedi* - lacustrine	Vecsei	2008	53
Great Slave	*artedi* - riverine	Vecsei	2008	82
Great Slave	*zenithicus*	Vecsei	2008	53

Table A3. Historical subfolder compiled by T. Todd from museum collections (number (*N*) of historical samples by lake, subspecies, and years).

Lake	Subspecies	Year(s)	*N*
Erie	*artedi*	1920–1929	5
Huron	*alpenae*	1917–1919	16
Huron	*artedi*	1919	6
Huron	*hoyi*	1919–1923	20
Huron	*johannae*	1917–1923	27
Huron	*kiyi*	1917–1923	14
Huron	*reighardi*	1919	1
Huron	*zenithicus*	1917–1919	30
Huron	*zenithicus*	1931	1
Michigan	*alpenae*	1920–1924	34
Michigan	*artedi*	1921	5
Michigan	*hoyi*	1921	2
Michigan	*johannae*	1906	8
Michigan	*johannae*	1920	10
Michigan	*nigripinnis*	1920	3
Michigan	*reighardi*	1920–1923	24
Michigan	*zenithicus*	1920–1924	30
Nipigon	*artedi*	1922–1923	9
Nipigon	*hoyi*	1922	26
Nipigon	*nipigon*	1922	7
Nipigon	*reighardi dymondi*	1922	32
Nipigon	*zenithicus*	1922	22
Ontario	*artedi*	1921	5
Ontario	*hoyi*	1923	10
Ontario	*kiyi*	1921	7
Ontario	*reighardi*	1921	20
Superior	*artedi*	1923	8
Superior	*hoyi*	1921–1922	13
Superior	*kiyi*	1921–1922	21
Superior	*nigripinnis*	1921	2
Superior	*nigripinnis cyanopterus*	1917	26
Superior	*reighardi dymondi*	1921–1923	57
Superior	*zenithicus*	1921–1923	196

Table A4. W. Koelz's (1929) historical subfolder (displayed in arrays and as representative fish); number (*N*) of samples by lake, subspecies, and years.

Lake	Subspecies	Year(s)	*N*
Erie	*artedi*	1920–1924	750
Huron	*johannae*	1917–1923	441
Huron	*alpenae*	1917–1925	387
Huron	*zenithicus*	1917–1923	162
Huron	*nigripinnis*	1917–1923	130
Huron	*kiyi*	1917–1923	212
Huron	*hoyi*	1917–1923	873
Huron	*artedi*	1917–1924	340
Michigan	*johannae*	1919–1923	122
Michigan	*alpenae*	1919–1924	383
Michigan	*zenithicus*	1919–1923	140
Michigan	*reighardi*	1919–1924	406
Michigan	*nigripinnis*	1919–1923	53
Michigan	*kiyi*	1919–1923	212
Michigan	*hoyi*	1919–1923	1149
Michigan	*artedi*	1919–1923	391
Nipigon	*zenithicus*	1922	160
Nipigon	*reighardi*	1922	97
Nipigon	*nigripinnis*	1922	230
Nipigon	*hoyi*	1922	174
Nipigon	*artedi*	1922	82
Nipigon	*nipigon*	1922	43
Ontario	*reighardi*	1921–1923	76
Ontario	*kiyi*	1921–1923	132
Ontario	*hoyi*	1917–1923	255
Ontario	*artedi*	1917–1923	266
Superior	*zenithicus*	1917–1925	956
Superior	*reighardi*	1921–1923	234
Superior	*nigripinnis*	1917–1923	162
Superior	*kiyi*	1917–1925	79
Superior	*hoyi*	1921–1923	333
Superior	*artedi*	1917–1925	254

Table A5. Number (*N*) of monograph samples with images by lake, subspecies, author (this publication), and year (may include multiple images of same fish and images of anatomical features).

Lake	Subspecies	Author	Year(s)	*N*
Erie	swarm cisco	Mandrak	2003–2015	19
Huron	*artedi*	Olds	2015	93
Michigan	*hoyi*	Pratt	2008	82
Nipigon	*artedi*	Pratt	2008	67[13]
Nipigon	*hoyi*	Pratt	2008	124[1]
Nipigon	*nigripinnis*	Pratt	2008	188[1]
Nipigon	*zenithicus*	Pratt	2008	56[1]
Ontario	*artedi*	Muir	2013	41
Superior	*artedi*	Pratt	2004–2008	190[14]
Superior	*hoyi*	Pratt	2004–2008	177[2]
Superior	*kiyi*	Pratt	2004–2008	60[2]
Superior	*zenithicus*	Pratt	2004–2008	164[2]
Superior	*artedi*	Muir	2009–2010	45[15]
Superior	*hoyi*	Muir	2009–2010	71[3]
Superior	*kiyi*	Muir	2009–2010	29[3]
Superior	*zenithicus*	Muir	2009–2010	19[3]

[13]Individual fish, all images combined = 1,406.
[14]Individual fish, all images combined = 1,255.
[15]Individual fish, all images combined = 342.

Table A6. Number (*N*) of extra monograph samples with images by lake, subspecies, author (this publication), and year (may include multiple images of same fish and images of anatomical features); GLSC = Great Lakes Science Center; OMNRF = Ontario Ministry of Natural Resources and Forestry; GTBI = Grand Traverse Band of Ottawa and Chippewa Indians; LTBB = Little Traverse Bay Bands of Odawa Indians.

Lake	Subspecies	Author	Year(s)	*N*
Huron	Hybrida	Pratt	2005-2006	199
Huron	Hybrida	Pratt	2007	338
Huron	Bloater X Lake herring	Pratt	2006–2007	25
Huron	Bloater X Shortjaw	Pratt	2005–2006	21
Huron	Kiyi X Lake herring	Pratt	2007	2
Huron	Lake herring X Shortjaw	Pratt	2005–2007	7
Huron	*artedi*	Olds	2016	811
Huron	*artedi*	Olds	2018	144
Huron	*artedi*	GLSC	2016	21
Huron	*artedi*	GLSC	2017	32
Huron	*artedi* (21), hybrida (5)	GLSC	2018	26
Huron	*artedi*	OMNRF	2017	144
Huron	*artedi*	OMNRF	2018	219
Michigan	*artedi* (14), hybrida (12)	Olds	2017–2018	26
Michigan	*hoyi*	GLSC	2018	20
Michigan	*hoyi*	GLSC	2018	43
Michigan	*hoyi*	Pratt	2008	141
Michigan	*artedi*	GTBI	2017–2018	43
Michigan	*artedi*	LTBB	2018	51
Nipigon	Blackfin X Bloater	Pratt	2008	6
Nipigon	Blackfin X Lake herring	Pratt	2008	3
Nipigon	Blackfin X Shortjaw	Pratt	2008	7
Nipigon	Bloater X Lake herring	Pratt	2008	3
Nipigon	Bloater X Shortjaw	Pratt	2008	7
Nipigon	Lake herring X Shortjaw	Pratt	2008	8
Ontario	*artedi*	GLSC	2018	24
Superior	*reighardi*	Pratt	2006	8
Superior	Bloater X Kiyi	Pratt	2006–2007	5
Superior	Bloater X Lake herring	Pratt	2006–2007	8
Superior	Bloater X Shortjaw	Pratt	2006–2007	14
Superior	Kiyi X Lake herring	Pratt	2006–2008	14
Superior	Kiyi X Shortjaw	Pratt	2006	5
Superior	Lake herring X Shortjaw	Pratt	2006–2008	7
Superior	Unknown	Pratt	2006	1
Superior	Bloater X Lake herring	Muir	2009	9
Superior	Bloater X Shortjaw	Muir	2009	3

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