Development of tributary conservation priorities for Great Lakes migratory fishes

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1. Introduction

Migratory river-spawning fish are integral to Great Lakes ecosystems. Many Great Lakes fish populations require tributary spawning habitat to maintain lakes (Mion et al. 1998, Fielder 2002, Hayden et al. 2014), or to maintain a population at all (Auer 1996, Lane et al. 1996). Some tributary spawning populations represent Evolutionary Significant Units that should be conserved (Meffe 1995, Stepien and Faber 1998, McQuown et al. 2003, Wilson et al. 2008). Finally, migratory fish provide important material transport and other services between Great Lake and tributary habitats that we are only beginning to understand in the Great Lakes (Burtner et al. 2011, Childress 2010), but that have been well documented elsewhere (Pringle 1997, Winemiller and Jepsen 1998, Gende et al. 2002, Flecker et al. 2010). Because of these important processes, many Great Lakes conservation plans include migratory fish as a focus for conservation (Great Lakes Interagency Task Force 2014, Pearsall et al. 2013).

The lack of access to spawning habitat, due primarily to dams and road-stream crossings that have become passage barriers, puts migratory fish species at risk (Cooper et al. 2017). On average across the whole Great Lakes basin, 32% of the available stream habitat for Great Lakes migratory fish is actually connected to the lakes, ranging from 54% in the Lake Superior basin to 19% in the Lake Michigan basin (Table 1). When one takes into account the impact of culverts that act as partial or complete barriers, only an estimated 13% of the streams are unblocked (Neeson et al. 2015). In addition to dams and other barriers, migratory fish are threatened by a variety of other stressors, including sedimentation from agricultural or urban land use, altered hydrology, physical habitat alteration, and invasive species (Hay-Chmielewski and Whelan 2007, Reid et al. 2008, Fielder and Baker 2004, Franks-Taylor et al. 2010). The impact of these stressors is particularly evident in species such as lake sturgeon, whose low numbers warranted listing of the species as State Threatened in Michigan and as a conservation concern in other Great Lakes states (Galarowitz 2003). However, all migratory fish are impacted and these impacts are not well understood for the migratory guild as a whole. Distributions of most Great Lakes river-spawning fishes are poorly documented and most conservation assessments for migratory fish are species specific (e.g., Fielder and Baker 2004, Boase 2007). Better distributional information on migratory fishes will allow for more effective conservation of this important guild, which links the Great Lakes to our inland river systems (Dolinsek et al. 2014).

Given the lack of information on native Great Lakes migratory fish, restoration priorities for dams and barriers and awards for grant funding have been based primarily on benefits to only a few native migratory species and the number of river miles that can be reconnected through barrier removal or modification. Most efforts to prioritize tributaries for migratory fish have focused on individual species or a small number of species (Enterline 2000, Coscarelli 2006, Hay-Chmielewski and Whelan 2007, Zheng et al. 2009). There has been no effort to comprehensively evaluate which tributaries are most important across the broad suite of native and desirable non-native migratory fishes.

To address this information gap, our objective was to prioritize tributaries across the Great Lakes basin for their importance to Great Lake migratory fish. To accomplish this, we assembled a large database to map the distribution of Great Lakes migratory fish across the Great Lakes basin and developed an index of each stream reach's value to these species. The index was calculated based on three metrics: how frequent the species has been collected within the reach, how abundant it was in collections, and how frequent it was collected in the Great Lakes near the downstream outlet. We then pooled reach level index scores into larger hydrologic unit scores to identify priority areas separately for above and below lowest dam barriers. Finally, we will discuss how the priorities identified from these analyses can be used to help prioritize conservation for more effective results.

Methods

Migratory fish identification and classification

We define Great Lakes migratory fish as those species that migrate for some aspect of their life history from the Great Lakes into tributary rivers. The species considered for this analysis comprise a broad suite of migratory species that occur across the entire Great Lakes basin. This includes 37 native species as well as five managed non-native species that are socioeconomically valuable (e.g., Pacific salmon) (Table 2). To develop this list, we consulted fish biologists, NatureServe's online species database, Great Lakes FishMap online database (http://fishmap.uoguelph.ca/main), Fishtraits online Database, fish life history books (Becker 1983, Trautman 1981, and Bailey et al. 2004), and other literature (Goodyear 1982, Lane et al. 1996, Leonardi and Gruhn 2001, Zorn and Sendek 2001, McLaughlin et al. 2006, Cwalinski et al. 2006, Schrouder et al. 2009, Roseman et al. 2009, Landsman et al. 2011, Eakins 2012). We also classified migratory behavior for each species based on their known or assumed typical migratory distance from research, expert option, or inferred from species in the same genus or family (Table X). As limited information exists on movement patterns for migratory fishes, we also considered maximum distances observed for other fishes in the same genus or family.

Fish data acquisition and attribution to a binational hydrography

We acquired fish distribution and abundance data (when available) throughout the entire Great Lakes basin (U.S. & Canada) from a total of 40 original sources (Table 3). The final dataset (after processing/checking and omitting records above natural barriers—see below) includes nearly 332,600 records of fish presence sampled between 1823 and 2014 from streams and the Great Lakes. We appended each individual dataset into a master migratory fish dataset, and used ArcMap 10.2 (ESRI 2013) to locate the closest flowline in the hydrography developed for FishWerks, an online decision tool to optimize barrier removal (Moody et al. 2017). The hydrography is based on the Great Lakes Aquatic Habitat Framework's synthetic drainage lines (Forsythe et al. 2016) as well as the National Hydrography Database Plus Version 2 (NHD Plus V2 2012), and the Ontario Integrated Hydrology Dataset (OMNR 2013). To ensure that fish sampling locations were accurately assigned to stream reach lines, we manually checked points that moved 100m or more when automatically "snapped" to the nearest stream reach. Given that more than one source could contain the same sampling event, we identified potential duplicates based on a combination of sample date, species and proximity to potential duplicate sample. Great Lake data were not checked as these data typically offered only location, year and species name.

Relating Great Lake Data to Stream Network

To give greater weight to tributaries having known occurrences of migratory species in close proximity to the mouth of a stream network, we related species data from the Great Lakes to the stream network. We used GIS to create buffers around each lake species data point and adjusted the size of the buffer for species that migrate large or moderate distances. Species samples that occurred close to a stream outlet were scored higher than those that were further away. Species with moderate migratory distances had buffers sized at 5 km (inner), 10 km (middle), and 20 km (outer), while high distance species had buffers sized at 10 km, 20 km, and 50 km, respectively. The buffers were intersected with the terminal point (i.e., the mouth) of tributaries draining directly into the Great Lakes. We assigned a score of three to terminal points intersected by the inner buffer, two for the middle buffer, and one for the outer buffer. Buffers for all Great lakes occurrences of each species that intersected with each terminal point were summed. We then attributed the sum of the buffer scores to every upstream reach from the terminal point.

Accounting for Natural Barriers

Major waterfalls occur throughout the Great Lakes basin and naturally restrict upstream movement of migrating fish species. To assess the status of potential habitat for Great Lakes migratory fish we used the location of dams and waterfalls to distinguish reaches currently connected to the Great Lakes (connected), reaches above dams, but below natural barriers (unconnected), and reaches above natural barriers (naturally disconnected) (Figure 1). No comprehensive waterfalls layer existed previously for the Great Lakes, thus we synthesized the location of major waterfalls across the region (Diebel et al. in prep). These data were acquired by:

1. Soliciting entities that have undergone previous efforts to collect and map natural barriers across the region
2. Gathering coordinates from websites that are aimed at documenting information on waterfalls,
3. Reviewing grey literature, aerial imagery or photos, or consulting with regional experts to determine whether each waterfall was passable (erroring toward excluding waterfalls that we were not confident were full barriers to fish migration), and
4. Consulting with regional experts to determine any major waterfalls not obtained from the previous efforts.

Waterfalls were classed into two categories; waterfalls that block upstream movement of all species, and waterfalls blocking the movement of non-jumping species. As high abundances of fish are often located directly below waterfalls, we retained reaches that contained waterfalls. Data on reaches above all-species waterfalls were not considered in further analyses. We retained data for species with high jumping ability on reaches above non-jumping species waterfalls. Species considered to have high jumping (or climbing) capability included American eel (*Anguilla rostrata*), Atlantic salmon (*Salmo salar*), Brown trout (*Salmo trutta*), Chinook salmon (*Oncorhynchus tshawytscha*), Coho salmon (*Oncorhynchus kisutch*), Pink salmon (*Oncorhynchus gorbuscha*) and Rainbow trout (*Oncorhynchus mykiss*). We did not calculate index scores for reaches above waterfalls thought to block passage for all species. As fish are often found in high abundances directly below waterfalls, we calculated index scores for reaches that contain the lowest waterfall in a river network.

Reach-scale index

We developed a migratory fish index, calculated for each species and specific to each reach containing any fish data described above. This index combines three metrics:

1. Frequency of occurrence (the number of times a species was collected from a reach)
2. Abundance of the species
3. Frequency of occurrence near the mouth of a tributary (buffer counts described above)

We used these three metrics as a means for extracting information that would be indicative of habitat important to migratory fishes from a variety of datasets. The frequency that a fish has been collected from a reach is a general indication of habitat relevant to that fish species. Where a species has been collected in high abundance is also a measure of relevant habitat but may also be indicative of a spawning run. To evaluate this assumption, we compared abundances within and outside the spawning period for each species and found that many species did have higher abundances within the spawning season (Table 4; Figure 2), and only 15 species had lower abundances. This would indicate that abundance is a good indicator of fish migration to spawning habitat. The frequency that the species has been collected near the river outlet with the Great Lakes provided a means for better linking tributary habitat with Great Lakes populations. While some Great Lakes fishes disperse long distances from their tributary spawning habitat, most fish remain relatively near the river outlet (Hayden et al. 2014).

The index score is an average of the rank of each metric. We calculated the rank for the frequency metric by grouping the reaches with collection data for a given species into four classes (1-4) using natural breaks in GIS. Reaches where a species had not been collected were given a value of zero. For reaches where abundance data existed, an average and maximum abundance was calculated. The rank for each reach for abundance was also defined by natural breaks (1-4). Reaches having presence data but no abundance data were then placed into the lowest class (i.e., 1), because the presence of a species implies that at least one individual had been reported, so penalizing these reaches for not having abundance data seemed problematic. Reaches having neither presence or abundance data were assigned a zero for this metric. For a given reach, the higher of the rank based on either average and maximum abundance was used for index calculations. We gave more weight to samples with high abundances, which can be indicative of a spawning run, which could be masked by using only an average abundance. Finally, the same procedure was used for the summed coastal buffer counts; species counts around terminal points were ranked based on natural breaks (0, 1-4) and every upstream reach draining to that point were assigned this value. However, when no stream data (frequency or abundance) existed, the reach did not receive an index score, in order to restrict our prioritization to streams that have documented presence of each species.

Distance filter to distinguish migratory and resident populations

Since we utilized a wide variety of data sources that were not specific to migratory fish, our fish data includes individuals from resident populations. While this is an issue, data specific to Great Lakes migratory only populations is largely unavailable. Moreover, spawning habitat used by resident populations is suitable for the same species migrating inland from the Great Lakes when access is possible (Curry and Spacie 1984, Chapman et al. 2012), so even resident data can be informative for Great Lakes migrants. However, for species that are limited by migratory distance, resident data in habitat that is beyond their migration distance is particularly problematic. Therefore, for species that are known to only move short distances upstream, we restricted the index for reaches located long distances upstream from the Great Lakes. Specifically, we reviewed literature to identify thirteen species to apply a distance filter to reduce the weight of the index for distant upstream reaches (Table 1).

Migration distances are not documented for most species (particularly for minnows and darters), so when necessary, we used surrogate species (e.g., same genus or family) to identify migration limitations. We chose 50 km as the lowest maximum distance we would consider for a distance filter, because our review suggested that most migratory species have the capacity to travel that far. When a study was found documenting a maximum observed distance migrated, then no filter was applied from the tributary mouth up to this value. Upstream of this maximum distance, a sloped filter approach was applied to the calculated index, with the slope intercepting with zero at the point where the maximum distance is doubled. For example, the index for a species having a maximum observed distance of 50 km would have no filter applied to reaches from the mouth upstream to 50 km. From 50-100 km, a multiplier would be applied to each index using the equation $y = -0.02x + 2$, where x = distance upstream. Reaches further than 100 km from the mouth would be assigned an index value of zero.

Watershed-scale priorities

Given that the sampling effort is highly variable among stream reaches with the majority having never been sampled, we also developed species-specific priorities at a broader scale than the individual reach. We used HUC 10 spatial units (USGS 2017) on the U.S. side, while Ontario's Quaternary Watersheds (OMNRF 2015) were used on the Canadian side of the basin, which are comparable in size to the HUC 10 units. Rolling up to this scale reduces the effect of sampling variability while still maintaining enough detail to be meaningful to fisheries managers and the broader conservation community. Throughout the paper we generally use "watersheds" to describe these units, but we acknowledge that the HUCs used on the U.S. side are not "true" watersheds (Omernik et al. 2017).

Our watershed-scale priorities were calculated as an average index of all reaches in a hydrologic unit. We did this using two sets of data. First, we averaged the index score using all reaches regardless of connectivity status. Next, we used the location of dams to calculate an average index of only connected or unconnected reaches separately. Any reach above a waterfall was not used for any watershed-scale calculations. The average index values were mapped in GIS using natural breaks to identify five priority classes.

Multi-species priorities

In addition to species-specific identification of priority areas, we also identified the highest priority areas for the full suite of native and socioeconomically valuable Great Lakes migratory fishes. We calculated a multi-species score for all species based on the average reach index score for each species within the watershed. To calculate the score, we ranked the watersheds within each species by the average index score of the reaches with tie values given the same rank. We then averaged the rank across all species within each watershed to calculate a multi-species priority score specific to each hydrologic unit. Finally, the average rank was relativized to a 0-100 scale and mapped in GIS. Natural breaks were used to identify five multi-species priority classes. We repeated this for just the connected reaches within the watershed as well as for the unconnected reaches.

Results and Discussion

Our results represent the first attempt to comprehensively map the importance of tributaries to Great Lakes migratory river-spawning fishes across the Great Lakes. The products include priority reaches and small watersheds for each of the 42 species, and a ranking of the small watersheds across all species. This allows for flexibility in using the resulting priorities; high priority unconnected reaches could be targeted for barrier removal or fish passage improvements, while high priority connected reaches may be suited for habitat improvement or protection.

Individual species priorities

A species-specific migratory index was calculated for 42 native and managed Great Lakes migratory fishes at the reach scale and for watersheds by averaging the index scores across connected and unconnected reaches. We present two examples – Walleye and Yellow Perch - of these results here, with perch representing a species for which a distance filter was applied (Figure 3 and 4). Maps for the rest of the Great Lakes migratory fish species are available here. Results at the reach level suggest lower latitude tributaries have the highest density of top priority reaches for yellow perch (Figure 3; darkest red). Examples in this class include those draining to southern Lake Michigan (e.g., Kalamazoo River, Grand River), Saginaw Bay (e.g., Pinconning River) and Western and Central Lake Erie (e.g., Portage River, Grand River). However, when one looks at the index scores averaged across whole watersheds for connected and unconnected reaches, the maps show much greater differentiation of priority areas.

Multi-species priorities

All reaches

The top 10 rivers identified from the multi-species analysis using all reaches represents tributaries from each of the five Great Lakes (Figure 5a; Table 5), however 50% of them drain into Lake Michigan with the Fox River in Wisconsin ranking as the top priority across all migratory fish species we prioritized. The Genessee River in New York and the Credit River in Ontario were the two top 10 identified from the Lake Ontario basin. Cattaraugus Creek in New York was the only Lake Erie tributary, while the Bois Brule River in Wisconsin, and the Au Sable River in Michigan represented the only top 10 tributaries from the Lakes Superior and Huron basins respectively.

Connected reaches

Priorities identified across multiple species using only connected reaches were generally similar to the priorities using all reaches (Figure 5b). The Genesee River was the top ranking connected watershed, followed by the Credit River, Fox River, Bois Brule River, Au Sable River, Cattaraugus Creek and Pine River in Michigan; all of which were also identified using all reaches. Three new watersheds were identified as top priorities when considering only connected reaches; the Thames River draining to Lake St. Clair in Ontario, Conneaut Creek draining to

Lake Erie from Ohio and Pennsylvania, and the Lower Maumee River draining to Lake Erie in Ohio were additionally identified as top currently-connected priorities from a multi-species perspective.

Unconnected reaches

Similarly to connected-only priorities, the unconnected priorities included a number of the same tributaries identified by the analysis using all reaches, and included multiple portions of the Fox River, the Upper Muskegon River, and the Menominee River (Figure 5c). New priorities identified includes the Trent River draining to Lake Ontario in Ontario and the Grand River draining to Lake Michigan in Michigan. From the Lake Huron basin, the Pine River that flows into the Au Sable River near its mouth was identified, as well as the Indian River which flows out from Burt Lake and into the Cheboygan River in Michigan. Finally, the Otter River, a tributary to the Sturgeon River draining to Lake Superior in the Upper Peninsula of Michigan was additionally identified as a top priority based on our multi-species analyses.

Addressing data bias

To fully understand fish movement patterns, you need data at high resolution over large spatial and temporal scales (Fausch et al. 2002). While comprehensive data of that quality specific to Great Lakes migratory fishes are not available for the Great Lakes, we are confident that our approach to ranking streams for value to migratory fish make appropriate and best use of the data that are available. We looked at three potential sources of bias or error to make this determination including seasonality of data, the inability to distinguish resident from migratory populations and inconsistent sampling effort. For this region, most stream data are collected in warm weather months that do not necessarily coincide with spawning periods. To assess the effect of seasonal bias, we compared index scores for species within known spawning periods (David, in prep.) to scores for the rest of the year (Table 4) and found that for 26 species the average index score was higher in the spawning period, with 12 of those differences significant at $p>.10$, as shown for walleye in Figure 2. While our results were significant for only about 1/3 of our species, we feel the patterns of the index are informative in terms of relative priority. Certainly, more seasonally dynamic monitoring schedules would help to alleviate this.

We also wanted to test the assumption that our analysis would not be biased by using abundance data that was not standardized by sampling effort. Sampling area and time sampled were available for five data sets that covered parts of the United States and Canada. We log transformed the data to create a linear relationship, then used a scatter plot to determine the correlation. Abundance and relative abundance were strongly correlated (R^2 =0.98; Figure 6). We also calculated the R^2 for abundance and abundance standardized by time at .88. We felt that these results warranted continued use of all abundance data.

While we believe the process of limiting the distance upstream for species that don't travel long distances helps to focus on habitat of greater importance to migratory fish, this is an area that warrants greater study. A recent comprehensive review of fish movement studies in the Great Lakes found that only 11 of the species evaluated here have had movement studies conducted on them, and for five of those species there were three or fewer studies (Landsman et al. 2011). Experts consulted during our review believed that most migratory species were generally not limited by migratory distance up tributaries, since Great Lakes river distances are relatively small in comparison with distances many of these fish migrate within the Mississippi or Ohio River systems. However, some species do tend to migrate in much greater numbers closer to the Great Lakes (e.g., brook trout, yellow perch). In addition, Jones et al. (2003) demonstrated that there are biological limitations with how far upstream walleye can successfully spawn and survive. More research on these distances and which species are limited by them would improve future analyses like this.

Regarding sampling bias, we believe that the watersheds are a better unit for prioritization than reach-level results. Some reaches have never been sampled and others have been heavily sampled. Averaging across each watershed helps to minimize sampling bias, because each hydrologic unit includes a mix of reaches that have and have not had collections. There is also potential for modeling efforts to use these empirical data to more comprehensively predict high quality habitat across all reaches and further minimize any effect of sampling bias.

The approach taken in this study provides critical information on native migratory river-spawning fish that will result in better decisions regarding where to restore connectivity to key riverine habitats in the Great Lakes basin. When combined with other information, the comprehensive, multi-species priority tributaries for migratory fish identified here can play a key role in making better decisions on where to conduct tributary conservation efforts, and how much is needed. To be effective, these results would need to be combined with other data to make quality decisions on resource expenditures. For example, connectivity restoration decisions should also consider locations and types of dams and other barriers, current condition of habitat, feasibility and opportunities for barrier removal, and current and potential distributions of invasive species such as sea lamprey and round goby. And in fact, our data have been incorporated into such a decision tool called FishWerks (Moody et al. 2017). In addition, the individual species maps can also play an important role in decision making. The types of individual species should help to determine key conservation decisions, such as whether fish passage around a barrier is sufficient or whether dam removal would be required to provide access or restore habitat. This information could play an important role in an integrative approach to barrier management.

Tables

Table 1. Connectedness to the Great Lakes

Lake	Total stream length (m)	Total naturally connected stream length (m)	Total naturally disconnected stream length (m)	Total currently connected stream length (m)	% naturally connected of total	% currently connected of potential (excludes streams above waterfalls)
Michigan	44234634	40522704	3711930	7639689	91.61%	18.85%
Huron	62403430	44098593	18304837	13210947	70.67%	29.96%
Erie	38624546	37115419	1509127	12431098	96.09%	33.49%
Ontario	32196615	13883259	18313356	5471405	43.12%	39.41%
Superior	65897699	25022407	40875292	13448476	37.97%	53.75%
Totals	243356924	160642382	82714542	52201615	66.01%	32.50%

Table 2. Great Lakes Migratory Fish species, collection records, and migratory attributes.

Scientific name	Common name	First year recorded	Last year recorded	Distance filter used (km)	Migratory distance category
Acipenser fulvescens	Lake sturgeon	1900	2014	NA	
Anguilla rostrata	American eel	1900	2013	NA	
Aplodinotus grunniens	Freshwater drum	1925	2014	NA	
Carpiodes cyprinus	Quillback	1926	2014	NA	
Catostomus catostomus	Longnose sucker	1904	2013	50	
Catostomus commersonii	White sucker	1901	2014	50	
Coregonus artedi	Lake herring	1906	2013	NA	
Coregonus clupeaformis	Lake whitefish	1906	2013	NA	
Couesius plumbeus	Lake chub	1906	2013	50	
Esox lucius	Northern pike	1900	2014	NA	
Esox masquinongy	Muskellunge	1907	2014	NA	
Hiodon tergisus	Mooneye	1900	2010	NA	
Ichthyomyzon castaneus	Chestnut lamprey	1900	2014	NA	
Ichthyomyzon unicuspis	Silver lamprey	1900	2014	NA	
Ictalurus punctatus	Channel catfish	1923	2014	NA	
Ictiobus cyprinellus	Bigmouth buffalo	1939	2014	NA	
Lepisosteus osseus	Longnose gar	1912	2014	74	
Lota lota	Burbot	1906	2014	NA	
Micropterus dolomieu	Smallmouth bass	1902	2014	87	
Morone chrysops	White bass	1900	2014	NA	
Moxostoma anisurum	Silver redhorse	1902	2014	NA	
Moxostoma macrolepidotum	Shorthead redhorse	1906	2014	NA	
Moxostoma valenciennesi	Greater redhorse	1924	2014	NA	
Notropis atherinoides	Emerald shiner	1906	2014	50	
Notropis hudsonius	Spottail shiner	1900	2014	50	
Oncorhynchus gorbuscha	Pink salmon	1959	2014	NA	
Oncorhynchus kisutch	Coho salmon	1910	2014	NA	
Oncorhynchus mykiss	Rainbow trout	1905	2014	NA	
Oncorhynchus tshawytscha	Chinook salmon	1910	2014	NA	
Perca flavescens	Yellow perch	1900	2014	82	
Percina caprodes	Logperch	1902	2014	50	
Percina copelandi	Channel darter	1926	2013	50	
Percina shumardi	River darter	1960	2012	50	
Percopsis omiscomaycus	Trout-perch	1900	2014	NA	

Prosopium cylindraceum	Round whitefish	1907	2012	NA	
Rhinichthys cataractae	Longnose dace	1902	2014		50
Salmo salar	Atlantic salmon	1947	2013	NA	
Salmo trutta	Brown trout	1910	2014	NA	
Salvelinus fontinalis	Brook trout	1856	2014		50
Salvelinus namaycush	Lake trout	1906	2013	NA	
Sander canadensis	Sauger	1897	2010	NA	
Sander vitreus	Walleye	1901	2014	NA	

Table 3. Data Sources

Location	Source	Name of Data Set	Stream	Coastal
Ontario	Ministry of Natural Resources	Aquatic Resource Area	X	X
	Ministry of Natural Resources	Flowing Water Information System	X	
	Ausable Bayfield Conservation Authority		X	
	Credit Valley Conservation Authority	Watershed Monitoring	X	
	Credit Valley Conservation Authority	Historic Data	X	
	Essex Region Conservation Authority		X	X
	Conservation Halton		X	
	Hamilton Conservation Authority		X	
	Kawartha Conservation Authority	Hoopnet Data	X	
	Kawartha Conservation Authority	Stream Data	X	X
	Lake Simcoe Conservation Authority		X	
	St. Clair Conservation Authority		X	
	Toronto Region Conservation Authority		X	X
	Upper Thames Conservation Authority		X	
	Department of Fisheries and Oceans		X	X
	Royal Ontario Museum	Ichthyology Collection	X	
Illinois	Department of Natural Resources		X	X
Indiana	Department of Natural Resources		X	
	Department of Environmental Management	Biological Community Assessment	X	
Michigan	Department of Environmental Quality	Procedure 51 fish assemblage data 1990-2006	X	

	Department of Natural Resources	Michigan Fish Atlas (http://www.dnr.state.mi.us/spatialdatalibrary /metadata/michigan_fish_atlas.htm8)		
	Department of Natural Resources	Fish Collections Database (managers database)	X	X
	Department of Natural Resources	Michigan Rivers Inventory	X	
	Central Michigan University – Tracy Galarowitz	Saginaw Bay tributary data (unpublished)	X	
Minnesota	Department of Natural Resources	Fish Mapper*	X	X
New York	Department of Environmental Conservation	New York Fish Atlas Database (http://www.nysm.nysed.gov/nysm-fish-atlas-database)	X	X
Ohio	Ohio EPA		X	
	Ohio EPA	Nearshore fish sampling 1970 to present		X
	Ohio State University Museum		X	X
Pennsylvania	Fish & Boat Commission**		X	X
	PA Sea Grant		X	
	Natural History Museum at TREC		X	
Wisconsin	DNR		X	X
	FishMap		X	X
US - Great Lakes	USFWS -Sea Lamprey Control	Larval lamprey surveys	X	
	National Fish Habitat Partnership		X	
	Goodyear Atlas	http://glein.er.usgs.gov/introduction.html		X

	Great Lakes Coastal Wetland Monitoring Program			X
	US Geological Survey	IchthyMaps	X	X

**sources include: MN Department of Natural Resource, Bell Museum, Natural Resource Research Institute, Minnesota Pollution Control Agency, US Geological Survey and US Forest Service*
***sources include: Pennsylvania Fish and Boat Commission, Pennsylvania Sea Grant, Natural History Museum and Pennsylvania State University Museum*

Table 4. Comparison of abundance in the spawning period to non-spawning period. Species with t-test p-values < 0.10 are in bold type.

Species	higher abundance in spawning period	**Spawning period average abundance**	**Non-spawning period average abundance**	**p-value**
Acipenser fulvescens	**n**	**1.6**	**4.7**	**0.010**
Anguilla rostrata	n/a	1.0	1.2	
Aplodinotus grunniens	**n**	**7.5**	**18.1**	**0.074**
Carpiodes cyprinus	y	8.0	6.0	0.101
Catostomus catostomus	**y**	**30.7**	**8.6**	**0.033**
Catostomus commersonii	**n**	**15.9**	**24.1**	**0.027**
Coregonus artedi	**n**	**8.0**	**19.1**	**0.023**
Coregonus clupeaformis	**y**	**7.5**	**5.0**	**0.063**
Couesius plumbeus	y	14.3	13.9	0.482
Esox lucius	**y**	**25.2**	**5.9**	**< 0.001**
Esox masquinongy	**y**	**6.0**	**3.9**	**< 0.001**
Hiodon tergisus	y	5.0	3.5	n/a
Ichthyomyzon castaneus	y	3.9	3.8	0.386
Ichthyomyzon unicuspis	y	16.4	13.4	0.432
Ictalurus punctatus	**y**	**20.4**	**10.0**	**0.005**
Ictiobus cyprinellus	y	2.8	2.6	0.387
Lepisosteus osseus	**y**	**6.8**	**2.4**	**< 0.001**
Lota lota	y	13.0	6.3	
Micropterus dolomieu	n	13.2	13.4	0.417
Morone chrysops	n	5.6	6.5	0.279
Moxostoma anisurum	**y**	**8.5**	**5.1**	**0.005**
Moxostoma macrolepidotum	y	8.9	7.3	0.147
Moxostoma valenciennesi	y	6.0	5.1	0.129
Notropis atherinoides	n	35.3	36.5	0.414
Notropis hudsonius	y	15.9	13.3	0.220
Oncorhynchus gorbuscha	**y**	**20.3**	**8.4**	**0.083**
Oncorhynchus kisutch	**n**	**13.3**	**71.5**	**< 0.001**
Oncorhynchus mykiss	**n**	**9.3**	**38.6**	**< 0.001**
Oncorhynchus tshawytscha	**n**	**12.0**	**16.6**	**0.089**
Perca flavescens	**y**	**91.7**	**23.8**	**< 0.001**
Percina caprodes	y	10.0	7.8	0.240
Percina copelandi	y	13.7	1.0	
Percina shumardi	**n**	**3.3**	**6.4**	**0.092**

Percopsis omiscomaycus	y	11.4	9.2	0.111
Prosopium cylindraceum	n	3.0	8.2	n/a
Rhinichthys cataractae	**n**	**30.6**	**40.0**	**< 0.001**
Salmo salar	n	15.8	16.7	0.362
Salmo trutta	**n**	**33.4**	**63.9**	**< 0.001**
Salvelinus fontinalis	**y**	**135.9**	**50.5**	**< 0.001**
Salvelinus namaycush	**y**	**17.4**	**8.4**	**0.077**
Sander canadensis	y	4.4	2.7	0.226
Sander vitreus	**y**	**37.3**	**16.3**	**< 0.001**

Table 5. Top 10 rivers from the multi-species priority ranking using all reaches.

Basinwide Priority Rank	Tributary Name	State/Province	Lake Basin
1	Fox River	Wisconsin	Michigan
2	Genessee River	New York	Ontario
3	Upper Muskegon River	Michigan	Michigan
4	Credit River	Ontario	Ontario
5	Bois Brule River	Wisconsin	Superior
6	Cattaraugus Creek	New York	Erie
7	St. Joseph River	Michigan	Michigan
8	Au Sable River	Michigan	Huron
9	Pine River	Michigan	Michigan
10	Menominee River	Michigan/Wisconsin	Michigan

Figures

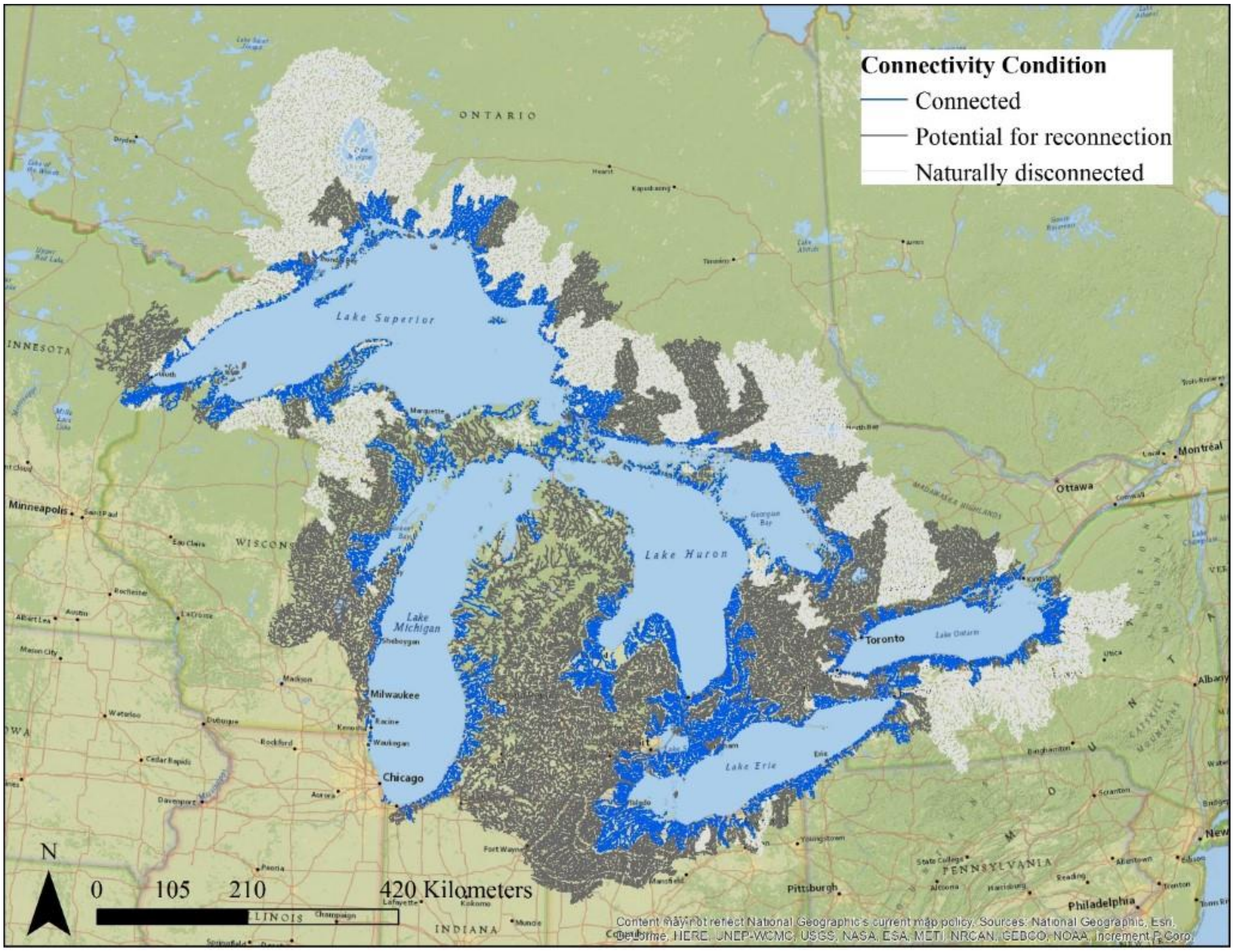

Figure 1. Current connectivity status of stream segments in the Great Lakes Basin that are fully connected to the Great Lakes (below lowest dam; shown in blue), naturally disconnected (above a major waterfall; shown in light grey), and could be reconnected by barrier removal (above lowest dam; shown in dark grey).

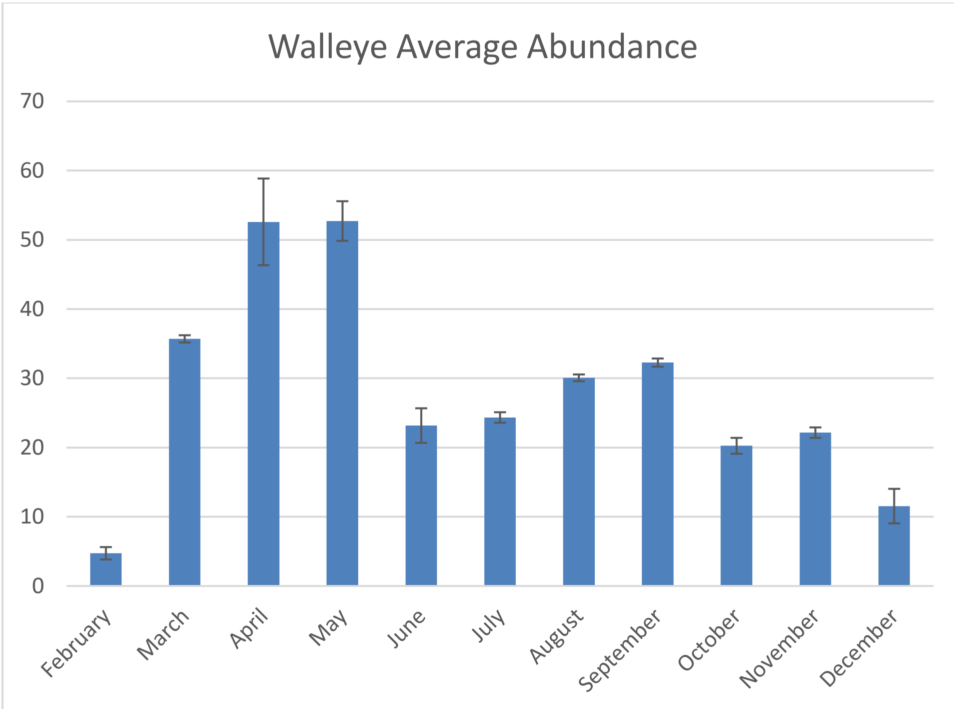

Figure 2. Average walleye abundance by month. The spawning period for walleye is March - May.

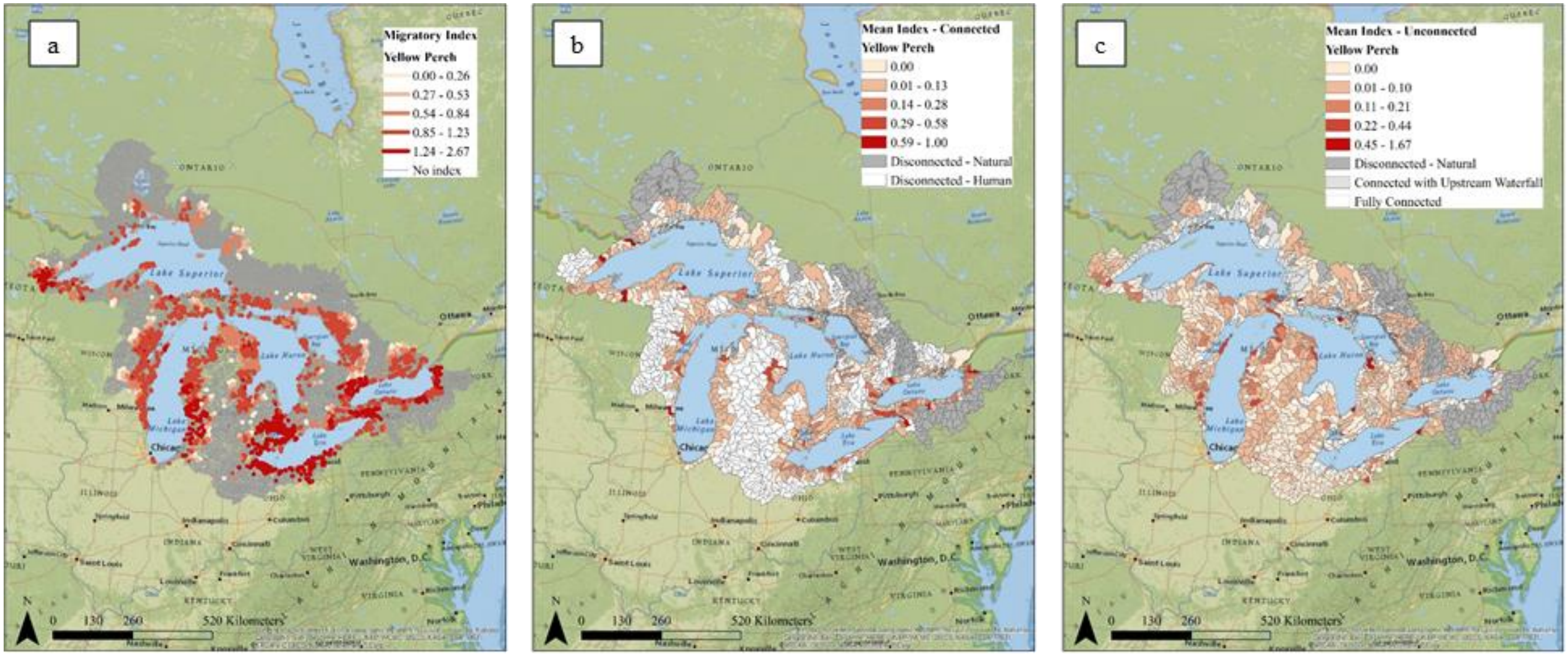

Figure 3a-c. Tributaries that analyses indicate are important to yellow perch for (a) specific stream locations, (b) watersheds using only stream reaches connected to the Great Lakes, and (c) watersheds based only on stream reaches that are unconnected to the Great Lakes.

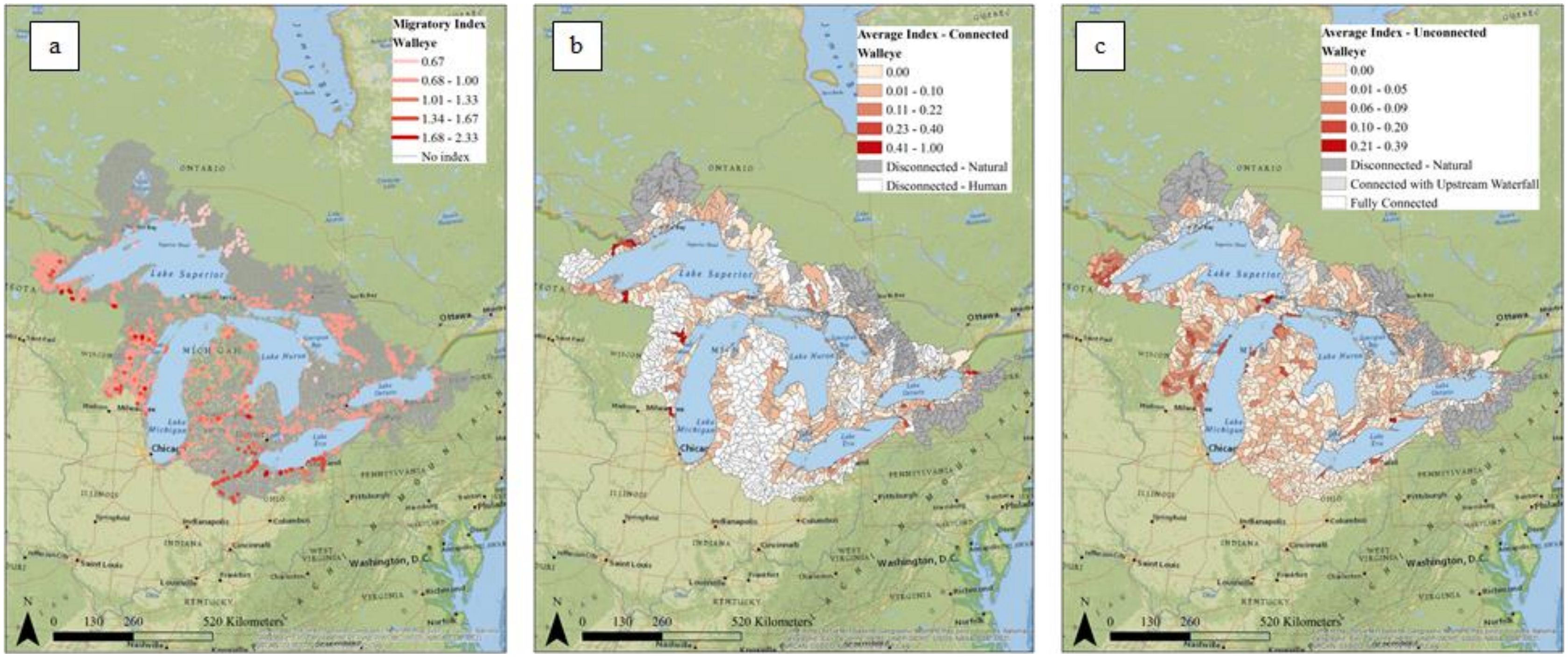

Figure 4a-c. Tributaries that analyses indicate are important to walleye for (a) specific stream locations, (b) watersheds using only stream reaches connected to the Great Lakes, and (c) watersheds based only on stream reaches that are unconnected to the Great Lakes.

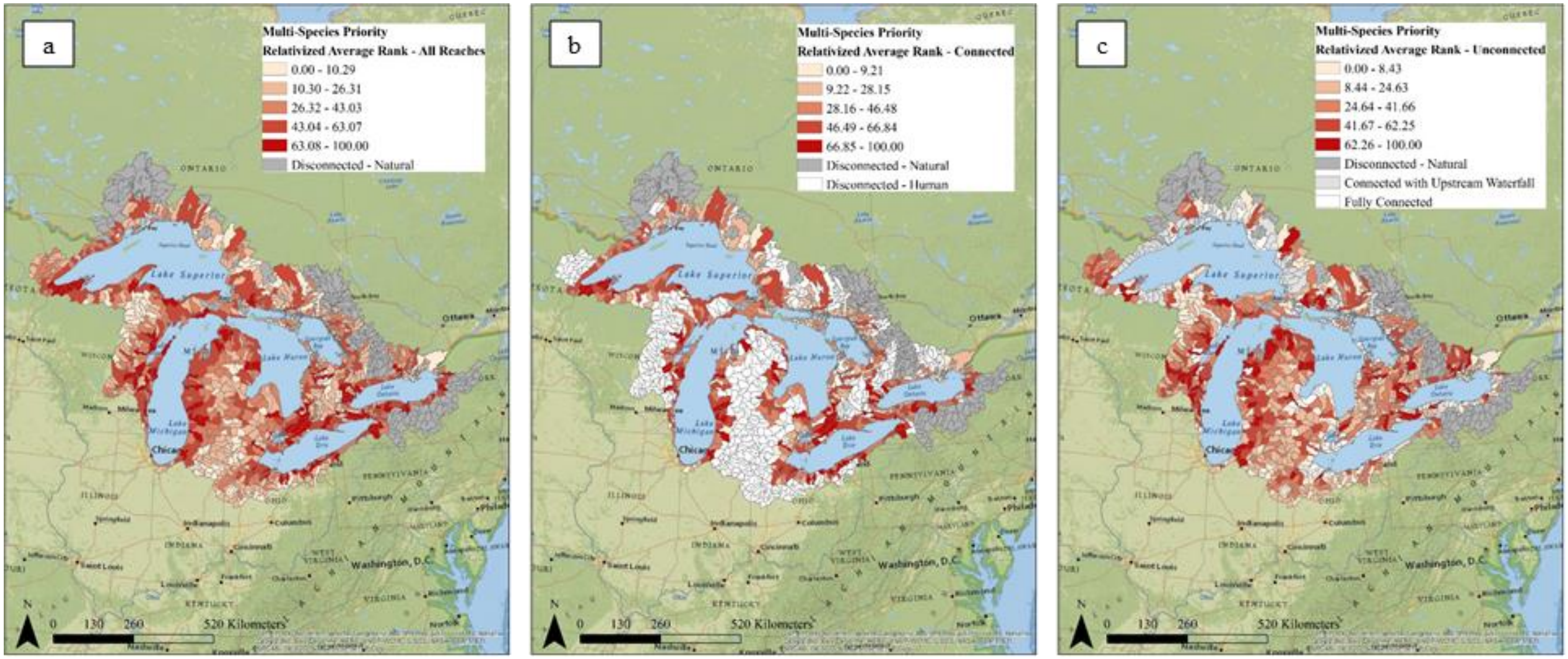

Figure 5a-c. Multi-species priorities determined by average rank of index score for watersheds using data from a) all reaches, (b) only reaches connected to the Great Lakes, and (c) only reaches unconnected to the Great Lakes.

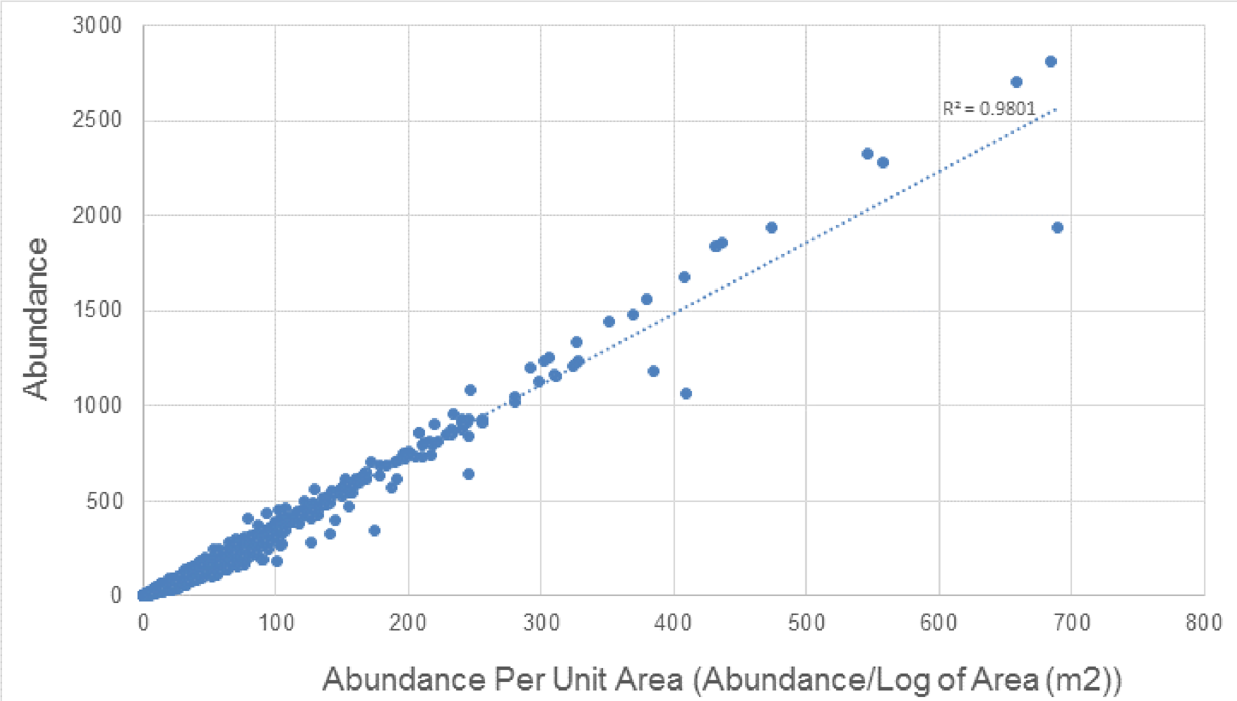

Figure 6. Relationship between abundance and abundance standardized per unit area.

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