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Fish community structure in the Bay of Quinte, Lake Ontario: The influence of nutrient levels and invasive species

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Intensive, long-term sampling in the Bay of Quinte with multiple gears (i.e. gill nets, bottom trawls, trap nets and boat electrofishing) allowed examination of the fish community and major fish populations in the context of key stressors up to 2009. Excessive nutrient input and hyper-abundant non-native fish species, White Perch and Alewife, shaped the depreciated fish community of the 1970s. After implementation of phosphorus input control measures and simultaneous winter-kills of the hyper-abundant non-native fish in the late 1970s, Walleye recovered and served to restore a predator-prey balance to the fish community by the late 1980s. However, in the absence of a significant recovery of submerged aquatic vegetation (SAV) in littoral areas, off-shore species (e.g. Alewife and White Perch) still tended to dominate; even in littoral areas. Following establishment of Dreissenid Mussels in the mid-1990s, water transparency increased and SAV increased significantly in littoral areas. This pivotal event led to a shift in the fish community that included an overall decline in Walleye, an increase followed by a decrease in Yellow Perch, and dominance by centrarchids (i.e. Bluegill, Pumpkinseed, Black Crappie and Largemouth Bass) in the nearshore. Round Goby invaded in 1999, proliferated and became important in the diet of piscivores by 2003. The current species assemblage, including the piscivores, is diverse and indicative of a healthy fish community.

Keywords: Yellow Perch, White Perch, Walleye, piscivores, centrarchids, fish populations, ecosystem change, Dreissenid Mussels

Introduction

The Bay of Quinte is a very productive system for fish, including species that support important recreational and commercial fisheries both in the bay and eastern Lake Ontario. The Bay of Quinte fish community has experienced significant ecological stress associated with excessive anthropogenic nutrient input and invasion of non-native species. Hurley and Christie (1977) documented the depreciation of the fish community from the 1930s through the mid-1970s, recognizing cultural eutrophication as a major driver of observed fish community change. Excessive nutrient input from municipal sewage led to increased algae production, and decreased oxygen and water clarity; growth of aquatic vegetation was impaired over broad expanses of the bay. These factors suppressed top predators such as Walleye (*Sander vitreus*), Longnose Gar (*Lepisosteus osseus*), Bowfin (*Amia*

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calva), Northern Pike (*Esox lucius*), and Largemouth Bass (*Micropterus salmoides*), as well as Centrarchid species such as Pumpkinseed (*Lepomis gibbosus*), Bluegill (*L. macrochirus*) and Black Crappie (*Pomoxis nigromaculatus*). With piscivore levels low, the abundance of small-bodied species tolerant of hyper-eutrophic water quality conditions, Alewife (*Alosa pseudoharengus*), White Perch (*Morone americana*), and Gizzard Shad (*Dorosoma cepedianum*) exploded. Hurley (1986a) updated trends in fish abundance in the context of reduced nutrient loading (phosphorus control) that occurred in 1977–1978. Hurley (1986a) found that partial recovery of the fish community was related to over-winter mortality of the abundant Alewife and White Perch, and improved water quality following reduced nutrient loading. Predator-prey interactions were identified as critical to restore healthy ecosystem function. In the early 1990s, Dreissenid Mussels invaded the Quinte area (Dermott et al., 2012). Immediately following their establishment, water clarity increased and submerged aquatic vegetation (SAV) re-appeared over vast areas of the Bay (Leisti et al., 2006, 2012). Round Goby (*Neogobius melanostomus*) invaded the Bay of Quinte in 1999 (Dietrich et al., 2006) and was first captured in our surveys in 2001; their abundance increased rapidly over the next two years.

Fish community sampling programs have existed in the Bay of Quinte since the 1950s, initially using gill nets and later adding trap nets, bottom trawls, and boat electrofishing. While each gear has unique bias with respect to habitat and species selectivity, collectively, these programs provide a very comprehensive data set within which long-term trends in the Bay of Quinte fish community can be examined. The first objective of this article was to report on the long-term dynamics of fishes in the Bay of Quinte fish community through 2009 and relate major changes in species dominance and abundance to large-scale ecological events associated with nutrient levels and invasive species. Specifically, results were interpreted relative to four major ecological time-stanzas: (1) phosphorus: prior to implementation of phosphorus control in municipal sewage treatment plants during the winter of 1977–1978; (2) post-phosphorus: after point-source phosphorus control (1978–1994); (3) dreissenid: after Dreissenid Mussel invasion and proliferation (1995–2002); and (4) goby: after Round Goby invasion and proliferation. Our second objective, complementary to and focusing our first objective, was to repeat an analysis presented by Hurley and Christie (1977) and thereby compare and contrast the proportion of piscivores (Minns et al., 1994) in the fish community in both offshore and nearshore habitats and among time-stanzas.

Methods

Study area

The Bay of Quinte is a long (64 km), narrow and productive embayment extending from Trenton in the west and to Kingston and eastern Lake Ontario in the east (see map in Bowlby and Hoyle, 2011). The Trent, Moira, Salmon and Napanee Rivers and numerous warm-water tributaries enter the bay. Physical and biological gradients span shallow and eutrophic conditions in the upper bay and deep and mesotrophic conditions in the lower bay near Lake Ontario. Fish movements are unrestricted in and out of the bay and include annual spawning migrations of Walleye, Alewife, and Lake Whitefish (*Coregonus clupeaformis*).

Sampling programs

Long-term and intensive fish community sampling programs were first initiated on the Bay of Quinte in the late 1950s (Hurley 1986a). Our analysis draws upon trend-through-time catch data from four fishing gears (gill nets, trap nets, bottom trawls, electrofishing) that collectively span five decades of sampling and provide intensive geographic coverage from the mouth of the Trent River in the upper bay to Lake Ontario in the lower bay. Gill nets and bottom trawls sampled offshore habitats while trap nets and boat electrofishing were used nearshore. The nearshore is distinguished from the offshore at approximately 5 m depth. Bottom trawls and electrofishing sampled all sizes of fish, particularly smaller ones, whereas gill nets and trap nets more effectively sampled large-bodied fish. Our analysis only included summer (June-September) data, and therefore makes no attempt to address seasonal variation in species abundance. Detailed sampling methods have been reported elsewhere (Hurley, 1986a, 1992; Bowlby et al., 1991; Casselman and Scott, 2003; Hoyle et al., 2008) but brief summaries are provided here.

Gill net sampling began in 1958, but only one site (at Hay Bay in the middle bay of Quinte) was sampled until 1972, when more sites (along with a second gear type, bottom trawl, see below) were added to extend coverage to the entire Bay of Quinte. We report annual gill net catches from 1972–2009; earlier catches are summarized by Hurley (1986a). All gill net samples come from bottom sets at fixed offshore locations. Seasonal gill net sets were conducted in some years but here only summer catches were included. Generally, gill nets consisted of a graded series of mesh sizes from 38–127 mm stretched mesh in 13 mm increments for a total of eight panels in a single gill net gang. The range of mesh sizes facilitated capture of a wide variety of fish species and sizes but was not effective at capturing very small species (e.g. cyprinids) or the young-of-the-year (YOY) of large species. Gill net mesh was made from multifilament material prior to 1992 and with monofilament thereafter. Paired gill net sets in 1991 using both materials, allowed conversion factors to be calculated (simple linear regression) for major species. Also, prior to 1992 individual mesh panels were 22.9 m (small mesh sizes) or 45.8 m (large mesh sizes) in length but all panels were shortened to 15.2 m thereafter. Catches were adjusted to standardize catch to 15.2 m of each mesh size for the entire time-series. Since 1992, 140 and 152 mm mesh sizes were added to the gill net gang but catches in these mesh sizes were not reported here. Catches for each gill net gang were summed across mesh sizes.

Bottom trawling was conducted every year since 1972 (except 1989) using a $\frac{3}{4}$ Western bottom trawl at several fixed offshore site locations, generally corresponding to the gill net sites. The trawl has a 13 mm mesh cod-end and most effectively samples small fish species and the young of larger species. As for gill nets, only summer bottom trawl catches were reported here. Catches were standardized for the entire time series as total number of individuals per 6 min trawl duration, covering approximately 400 m linear distance and 0.2453 ha in area (Hurley, 1992).

Beginning in 1969, standard 6-ft (1.83-m) trap nets were used to sample fish in the nearshore at two fixed site locations: Trenton (44° 06.0′ N, 77° 31.8′ W) in the upper bay and Hay Bay (44° 05.4′ N, 77° 03.6′ W) in the middle bay. Sampling occurred, primarily in July, in 13 of 20 years between 1969 and 1988; thereafter the program was discontinued. From 2001–2009, excluding 2006, a trap net program that employed a provincially standardized sampling protocol (Nearshore Fish Community Index Netting; Stirling, 1999) was conducted. This program used gear similar to that of the earlier years but sampling sites were chosen at random throughout the Bay of Quinte, in the month of September.

Boat electrofishing was conducted following a standardized protocol (Brousseau et al., 2005). Catch data were collected from 100 m transects at 1.5 m depth at several fixed locations representing a variety of coastal habitat types. Sampling was conducted periodically (1989–1990, 1992, 1999, 2001, 2007 and 2009), depending on Remedial Action Plan (RAP) needs (Brousseau et al., 2011).

Data analysis

For each catch, fish were identified to species and counted. Often fish were weighed in aggregate by species; if not, the weight of the catch was estimated based on either a sub-sample of individual fish weights or a sub-sample of individual fish lengths in combination with a length-weight regression. This resulted in a species-specific description of catch by numbers and biomass. In a few cases, in the recent bottom trawl data, YOY Pumpkinseed and Bluegill were recorded collectively as "Sunfish." Random or length-stratified sub-samples of fish were processed for biological attributes such as weight, sex, state of maturity, and diet. All species-specific catch results were initially summarized (arithmetic means) by year, gear type and geographic areas of the bay: upper, middle and lower as described in detail by Hurley (1986a).

The index of relative importance (IRI; Pinkas et al., 1971; Cortes, 1998) was used to quantify the relative dominance status of each fish species in the Bay of Quinte fish community (IRI = (% by number +% by weight) x (% frequency of occurrence)). This index was developed for diet studies to compare the contribution of different components but has also been adopted more recently in fish community studies (Karpov et al., 1995; Jutagate et al., 2001; Zhu et al., 2008). IRI was calculated for each species, time-stanza and sampling gear combination to examine differences and patterns among time-stanzas and gear types, and averaged across all time-stanzas and gear types to yield an overall fish species importance index.

For selected dominant species, mean catches by number was examined between adjacent time-stanzas with a two-way analysis of variance (ANOVA; STATISTICA 8.0), by gear type, with geographic region and time-stanzas as factors. All test statistics were considered significant at $p < 0.05$.

Table 1. Number of samples taken (total = 3,227) by ecological time-stanza and gear type in the Bay of Quinte, Lake Ontario.

Time-stanza	Years	Gill net	Bottom trawl	Trap net	Electrofishing
Phosphorus	1969–1977	102	95	59	–
Post-phosphorus	1978–1994	376	314	107	136
Dreissenid	1995–2002	300	417	108	138
Goby	2003–2009	236	364	360	115
Totals	41 years	1,014	1,190	634	389

The community biomass consisting of piscivores (PPB) was determined for offshore (gill net) and nearshore (trap nets) habitats. PPB values reported by Hurley and Christie (1977) were re-calculated to include Smallmouth Bass and exclude Channel Catfish. Only data from upper and middle Bay of Quinte were used. A PPB greater than 0.20 was considered indicative of a balanced fish community trophic structure following Hurley et al. (1986), Brousseau et al. (2004) and Brousseau and Randall (2008).

Results and Discussion

A detailed account of fish community trends spanning four decades, utilising four gear types, and covering a diverse geographic area (at both nearshore and offshore habitats) is not possible within the confines of the present article. We instead focus on major highlights, re-examining those first described by Hurley and Christie (1977) and Hurley (1986b) and, particularly, describing responses of the community associated with the return of SAV to vast expanses of the Bay of Quinte fish after Dreissenid Mussel invasion. Preliminary responses of this system to Round Goby invasion are also considered.

Over a 41-year period, 3,227 samples from four gear types (Table 1) caught 65 species (53 native and 12 non-native) of fish representing 27 families (Table 2). Yellow perch (native invertivore), White perch (non-native invertivore) and Alewife (non-native planktivore) were the dominant species. The most important piscivore was Walleye followed distantly by Largemouth Bass. Species dominance and composition varied across the four major time-stanzas and gear types (Table 3).

Chronology of fish community changes among time-stanzas

The phosphorus time-stanza was dominated by White perch, Alewife and Gizzard Shad (herbivore) (Table 3). The Bay of Quinte ecosystem was affected during this stanza by excessive point-source nutrient input that degraded water quality to the point where SAV was severely limited due to light-limitation associated with excessive algal production (Hurley and Christie, 1977; Leisti et al., 2006). In the absence of controlling interactions by top predators and competitors, these small-bodied, tolerant species thrived in the hyper-eutrophic conditions. Reproduction of top predators, especially Walleye, may have been impaired by the poor water quality conditions. Also, the hyper-abundant intermediate predators may have contributed to poor top predator survival through predation on their larval stages (Hurley and Christie, 1977). Nearshore centrarchid species, such as Pumpkinseed, Bluegill, Black Crappie and Largemouth Bass, which depend on abundant SAV for reproduction, feeding and protection, had relatively low IRI values during the phosphorus time-stanza (Table 3).

The post-phosphorus time-stanza was dominated by Yellow Perch, White Perch, and Alewife. Yellow Perch increased in importance but White Perch, Alewife and Gizzard Shad declined compared to the phosphorus time-stanza. Walleye, the key top predator in the system, increased in importance by 2–3 orders of magnitude in three gear types (Table 3). Immediate improvement in water quality, following a 50% reduction in phosphorus loading at local sewage treatment plants in the winter of 1977–1978 (Robinson, 1986), along with massive over-winter die-offs of Alewife in 1977 and White Perch in 1978 set the stage for exceptionally strong percid (Yellow Perch and Walleye) year-classes in 1978 (Hurley, 1986a). The Walleye population subsequently recovered to very high levels (Bowlby et al., 1991) and

Table 2. Index of relative importance (IRI) for fish species (n = 65) caught in the Bay of Quinte, Lake Ontario and pooled for four sampling gears (gill net 44 species; bottom trawl 44 species; trap net 34 species and electrofishing 44 species) from 1969–2009. Origin, thermal regime, trophic class and environment inhabited are indicated. Species are ranked by IRI and those with an IRI less than 0.01 are denoted with "+".

Common name	Scientific name	Origin	Thermal regime	Trophic class	Environment	IRI
Yellow Perch	*Perca flavescens*	Native	Cool	Invertivore	Benthopelagic	3428.10
White Perch	*Morone americana*	Non-native	Warm	Invertivore	Benthopelagic	2639.65
Alewife	*Alosa pseudoharengus*	Non-native	Cool	Planktivore	Pelagic	2082.51
Brown Bullhead	*Ameiurus nebulosus*	Native	Warm	Invertivore	Benthic	1159.24
Pumpkinseed	*Lepomis gibbosus*	Native	Warm	Invertivore	Benthopelagic	863.39
Walleye	*Sander vitreus*	Native	Cool	Piscivore	Benthopelagic	760.18
Bluegill	*Lepomis macrochirus*	Native	Warm	Invertivore	Benthopelagic	617.30
White Sucker	*Catostomus commersoni*	Native	Cool	Invertivore/Detritivore	Benthic	559.84
Gizzard Shad	*Dorosoma cepedianum*	Native	Warm	Herbivore	Pelagic	471.72
Largemouth Bass	*Micropterus salmoides*	Native	Warm	Piscivore	Benthopelagic	318.79
Freshwater Drum	*Aplodinotus grunniens*	Native	Warm	Invertivore	Benthic	308.67
Rainbow Smelt	*Osmerus mordax*	Non-native	Cold	Invertivore	Pelagic	276.80
Trout-perch	*Percopsis omiscomaycus*	Native	Cool	Invertivore	Benthopelagic	135.00
Rock Bass	*Ambloplites rupestris*	Native	Warm	Invertivore	Benthopelagic	111.90
Black Crappie	*Pomoxis nigromaculatus*	Native	Cool	Invertivore	Benthopelagic	107.62
Spottail Shiner	*Notropis hudsonius*	Native	Cool	Invertivore/Planktivore	Benthopelagic	104.29
Channel Catfish	*Ictalurus punctatus*	Native	Warm	Invertivore/Piscivore	Benthic	101.45
Smallmouth Bass	*Micropterus dolomieu*	Native	Warm	Invertivore/Piscivore	Benthopelagic	96.78
Northern Pike	*Esox lucius*	Native	Cool	Piscivore	Benthopelagic	90.65
Common Carp	*Cyprinus carpio*	Non-native	Warm	Invertivore/Detritivore	Benthopelagic	76.09
American Eel	*Anguilla rostrata*	Native	Cool	Invertivore/Piscivore	Benthic	57.49
Round Goby	*Neogobius melanostomus*	Non-native	Cool	Invertivore	Benthic	51.53
Bowfin	*Amia calva*	Native	Warm	Piscivore	Benthopelagic	43.44
Golden Shiner	*Notemigonus crysoleucas*	Native	Cool	Invertivore/Herbivore	Benthopelagic	36.86
Lake Trout	*Salvelinus namaycush*	Native	Cold	Piscivore	Benthopelagic	36.81
Logperch	*Percina caprodes*	Native	Warm	Invertivore	Benthic	21.05
Brown Trout	*Salmo trutta*	Non-native	Cold	Piscivore	Benthopelagic	15.39
Longnose Gar	*Lepisosteus osseus*	Native	Warm	Piscivore	Benthopelagic	13.81
Brook Silverside	*Labidesthes sicculus*	Native	Warm	Planktivore/Invertivore	Pelagic	11.30
Lake Whitefish	*Coregonus clupeaformis*	Native	Cold	Invertivore	Benthic	3.84
Silver Redhorse	*Moxostoma anisurum*	Native	Cool	Invertivore	Benthic	3.33

Emerald Shiner	*Notropis atherinoides*	Native	Cool	Planktivore	Benthopelagic	3.22
Lake Herring	*Coregonus artedi*	Native	Cold	Planktivore/Invertivore	Pelagic	2.99
Bluntnose Minnow	*Pimephales notatus*	Native	Warm	Detritivore	Benthopelagic	1.46
White Bass	*Morone chrysops*	Native	Warm	Invertivore/Piscivore	Benthopelagic	1.36
Johnny Darter	*Etheostoma nigrum*	Native	Cool	Invertivore	Benthic	1.30
Shorthead Redhorse	*Moxostoma macrolepidotum*	Native	Warm	Invertivore	Benthic	0.58
Fathead Minnow	*Pimephales promelas*	Native	Warm	Detritivore/Invertivore	Benthopelagic	0.42
Banded Killifish	*Fundulus diaphanus*	Native	Warm	Invertivore/Planktivore	Benthopelagic	0.40
River Redhorse	*Moxostoma carinatum*	Native	Cool	Invertivore	Benthic	0.36
Blackchin Shiner	*Notropis heterodon*	Native	Cool	Invertivore	Benthopelagic	0.15
Golden Redhorse	*Moxostoma erythrurum*	Native	Warm	Invertivore	Benthic	0.06
Greater Redhorse	*Moxostoma valenciennesi*	Native	Warm	Invertivore	Benthic	0.04
Burbot	*Lota lota*	Native	Cold	Piscivore	Benthic	0.02
Chinook Salmon	*Oncorhynchus tshawytscha*	Non-native	Cold	Piscivore	Pelagic	0.02
Common Shiner	*Luxilus cornutus*	Native	Cool	Invertivore	Benthopelagic	0.02
Mottled Sculpin	*Cottus bairdi*	Native	Cold	Invertivore	Benthic	0.02
Slimy Sculpin	*Cottus cognatus*	Native	Cold	Invertivore	Benthic	0.01
Mooneye	*Hiodon tergisus*	Native	Warm	Invertivore	Pelagic	0.01
Grass Pickerel	*Esox americanus vermiculatus*	Native	Warm	Piscivore	Benthopelagic	0.01
Sea Lamprey	*Petromyzon marinus*	Non-native	Cold	Parasite	Benthopelagic	+
Splake	*Salvelinus fontinalis x S. namaycush*	Non-native	Cold	Piscivore	Benthopelagic	+
Black Bullhead	*Ameiurus melas*	Native	Warm	Invertivore	Benthic	+
Blacknose Shiner	*Notropis heterolepis*	Native	Cool	Invertivore/Herbivore	Benthopelagic	+
Central Mudminnow	*Umbra limi*	Native	Cool	Invertivore	Benthic	+
Goldfish	*Carassius auratus*	Non-native	Warm	Invertivore/Herbivore	Benthopelagic	+
Rainbow Trout	*Oncorhynchus mykiss*	Non-native	Cold	Piscivore	Benthopelagic	+
Lake Sturgeon	*Acipenser fulvescens*	Native	Cool	Invertivore	Benthic	+
Brook Stickleback	*Culaea inconstans*	Native	Cool	Planktivore/Invertivore	Benthopelagic	+
Rudd	*Scardinius erythrophthalmus*	Non-native	Cool	Invertivore/Herbivore	Benthopelagic	+
Atlantic Salmon	*Salmo salar*	Native	Cold	Piscivore	Benthopelagic	+
Quillback	*Carpiodes cyprinus*	Native	Cool	Invertivore	Benthic	+
Stonecat	*Noturus flavus*	Native	Warm	Invertivore	Benthic	+
Threespine Stickleback	*Gasterosteus aculeatus*	Native	Cool	Invertivore	Benthopelagic	+
Silver Lamprey	*Ichthyomyzon unicuspis*	Native	Cool	Parasite	Benthopelagic	+

Note: Lake Trout and Atlantic Salmon are native but extirpated and re-introduced; Golden Redhorse and Black Bullhead are not verified (would represent range expansion); Splake is an introduced artificial hybrid.

Table 3. IRI for fish species caught in the Bay of Quinte separated by sampling gear and ecological time-stanza. Only those species with an IRI greater than 1, in Table 2, are listed. The total number of species caught in each gear and time-stanza (including those species not listed) is indicated. "np" indicates a species was not sampled by that gear in that time-stanza. "+" denotes species with an IRI < 0.01.

	Phosphorus			Post-phosphorus				Dreissenid				Goby			
Species	Gill net	Trawl	Trap net	Gill net	Trawl	Trap net	Electro -fishing	Gill net	Trawl	Trap net	Electro -fishing	Gill net	Trawl	Trap net	Electro -fishing
Yellow Perch	2001.08	453.14	336.86	4138.49	1356.10	706.12	5166.24	8935.15	5478.01	86.95	6431.35	5683.76	4904.10	134.44	5609.76
White Perch	5039.05	6368.02	9792.26	1831.43	1340.43	6069.93	102.75	630.28	1725.05	26.99	1.33	2812.53	3539.41	268.11	47.23
Alewife	6221.33	5975.89	5590.88	3465.30	4974.13	906.84	355.14	452.15	1114.13	np	2.71	627.82	1495.18	np	56.15
Brown Bullhead	115.50	353.40	328.80	48.41	461.29	1938.96	284.59	62.67	1263.40	6897.92	960.72	31.04	883.54	3109.52	648.90
Pumpkinseed	7.78	3.52	665.36	1.48	23.14	1353.01	432.26	45.58	436.52	4006.33	3014.38	14.63	268.34	1582.04	1096.52
Walleye	36.82	0.25	11.87	1642.78	775.41	2115.14	1715.17	1392.51	288.81	658.69	45.49	986.49	414.38	924.74	394.21
Bluegill	+	np	4.28	np	+	5.90	3.36	4.02	15.37	3491.51	399.13	11.05	13.35	3880.17	1431.28
White Sucker	239.10	8.89	46.18	1858.33	861.21	217.36	163.36	1165.14	1899.30	316.27	47.51	551.02	535.74	459.68	28.50
Gizzard Shad	4828.00	55.93	2.79	702.22	546.37	20.60	58.84	24.01	442.85	44.86	42.19	26.41	187.98	83.89	8.91
Lgmouth Bass	0.02	0.08	0.01	0.00	np	0.49	59.21	+	1.07	243.06	1148.09	0.01	1.66	362.85	2965.24
Freshwater Drum	5.27	0.02	0.02	168.20	85.87	26.19	229.76	404.51	395.93	524.51	30.61	506.67	1174.92	841.26	236.30
Rainbow Smelt	5.87	2890.69	np	0.55	1141.13	np	0.04	0.19	104.24	np	np	0.28	9.01	np	np
Trout-Perch	0.03	327.04	np	+	879.67	np	np	np	565.36	np	np	np	252.89	np	np
Rock Bass	10.39	3.17	49.91	34.68	0.86	748.73	260.77	8.44	0.20	19.66	153.85	4.42	0.11	146.51	236.87
Black Crappie	0.02	0.73	231.22	0.04	5.93	65.18	1.23	0.07	2.27	442.66	2.79	1.13	3.03	856.67	1.38
Spottail Shiner	+	140.88	np	np	418.76	np	116.07	0.00	318.86	np	92.85	+	440.38	+	36.59
Channel Catfish	5.78	0.02	95.15	4.21	0.42	658.67	0.13	0.38	0.09	409.51	np	1.36	0.16	345.92	np
Smallmouth Bass	65.94	0.21	107.76	92.29	0.45	980.94	46.46	12.57	1.28	37.32	6.05	0.65	1.15	34.34	64.26
Northern Pike	30.17	0.01	3.10	23.62	2.04	40.66	379.69	50.53	0.87	136.93	398.80	40.21	0.38	160.02	92.66
Common Carp	6.03	65.86	1.38	0.31	242.69	1.81	537.61	0.09	12.40	8.79	49.28	1.28	66.47	54.79	92.50
American Eel	+	414.04	75.83	0.00	144.23	164.22	53.26	np	7.89	2.39	np	np	np	0.44	np
Round Goby	np	np	np	np	np	np	np	0.08	0.21	np	np	38.55	728.75	0.00	5.36
Bowfin	57.06	0.01	92.64	0.37	np	109.68	35.34	np	np	82.87	121.55	np	np	144.62	7.43
Golden Shiner	0.09	+	0.98	0.05	np	0.57	37.82	np	np	0.08	168.63	np	+	0.38	344.30
Lake Trout	0.03	np	np	346.42	0.14	np	np	113.86	+	np	np	91.61	0.02	+	np
Logperch	np	np	np	np	0.30	np	188.56	np	1.16	np	34.69	np	10.69	np	80.38
Brown Trout	0.04	np	np	223.34	0.02	np	np	0.81	+	np	np	6.54	0.03	np	np
Longnose Gar	2.20	0.02	1.42	6.24	1.63	5.18	0.66	25.19	+	8.12	0.17	84.59	0.01	53.03	18.73
Brook Silverside	np	np	np	np	np	np	0.23	np	0.01	np	124.72	np	0.01	np	44.46
Lake Whitefish	0.01	np	np	7.63	33.80	np	0.00	5.10	3.90	np	np	3.32	3.88	+	np
Silver Redhorse	np	np	np	+	np	0.05	0.03	np	np	np	0.93	np	np	26.89	22.05
Emerald Shiner	np	np	np	np	np	np	6.24	np	+	np	1.21	np	np	np	40.81
Lake Herring	0.03	np	np	0.47	0.96	np	np	41.43	0.25	np	np	0.21	1.49	np	np
Bluntnose Minnow	np	np	np	np	np	np	np	np	0.00	np	20.16	np	np	np	1.75
White Bass	1.81	np	0.61	2.56	3.21	1.52	1.11	0.02	1.22	0.32	0.10	0.02	5.40	2.42	0.14
Johnny Darter	+	5.16	np	np	6.56	np	0.10	np	7.10	np	0.46	np	0.10	np	np
No. of species	32	24	23	34	33	27	32	33	37	25	34	30	36	29	39

effectively controlled the formerly hyper-abundant prey fish species (e.g. Alewife) through predation (Hurley, 1986b; Ridgeway et al., 1990). Abundant Walleye may also have prevented Yellow Perch from continuing to increase in the upper bay following production of its own large 1978 year-class. Thus, by the late 1980s to early 1990s a predator-prey balance had been re-established in the offshore portion of the fish community. However, water transparency had not improved to the extent required to promote expansion of SAV (Leisti et al., 2006). As a result, the nearshore fish community (e.g. as shown by trap nets) resembled that of the offshore (gill nets and bottom trawls), where Alewife, White Perch, Yellow Perch and Walleye dominated (Table 3).

Large changes in the fish community occurred in the dreissenid time-stanza (Table 3). Yellow Perch IRI more than doubled in the offshore gill nets and bottom trawls. Walleye, White Perch and Alewife declined in importance in most gears. Brown Bullhead, Pumpkinseed, Bluegill, Black Crappie and Largemouth Bass increased in importance in both nearshore and offshore sampling gear. A key consequence of the Dreissenid Mussel invasion to the Bay of Quinte in the early to mid-1990s was an increase in water transparency (Leisti et al., 2012). As water clarity improved, both SAV cover and extent significantly increased in the upper bay, vegetation bed extent expanded in the middle bay, and there was little response in the lower bay likely due to basin morphometry (Leisti et al., 2006). The re-emergence of aquatic macrophytes in the nearshore allowed for a dramatic increase in the abundance of fish species associated with vegetation such as Pumpkinseed, Bluegill, Black Crappie and Largemouth Bass. Concurrently, White Perch and Alewife declined to low levels in nearshore habitats. Bowlby et al. (2010) suggested that Walleye abundance likely declined due to the habitat and associated fish assemblage changes in the nearshore areas. Yellow Perch abundance increased immediately and dramatically in the upper bay following Dreissenid Mussel invasion but their abundance then declined somewhat as the nearshore centrarchid species became more abundant.

Round Goby were first reported in the Bay of Quinte in 1999 (Dietrich et al., 2006) and first captured in our sampling gear in 2001. Their abundance was high in offshore areas of the bay by 2003, declined rapidly after 2004 in gill net catches but stabilized at relatively high levels in the bottom trawls. This observation suggests that while large Round Goby, vulnerable to gill net gear, were included in the goby size structure soon after goby invasion, after 2004 the goby size structure included primarily smaller individuals. Goby abundance may have been high in nearshore areas prior to 2003 but the nearshore trap nets did not catch them and nearshore electrofishing was not conducted between 2001 and 2007. Round Goby were absent in the electrofishing gear in 2001 and present in 2007. Goby also appeared in the diet of many piscivores in the Bay of Quinte in 2003 (Taraborelli et al., 2010), and were a significant component of the Walleye diet in the Bay of Quinte during 2004–2006 (Bowlby et al., 2010). Walleye growth increased during the goby time-stanza (Bowlby et al., 2010) but whether or not this is due to the diet change is not known. Yellow Perch remained the most important species in the bay during the goby time-stanza (Table 3). White Perch increased in offshore sampling gear compared to the dreissenid time-stanza. Bluegill, Largemouth Bass and Black Crappie continued to increase while Brown Bullhead and Pumpkinseed declined.

Fish community changes during the goby time-stanza did not appear to be as extensive as for the earlier time-stanzas. On the other hand, more time may be required for Round Goby impacts to fully materialize. Fish recruitment responses (e.g. increased fecundity or fitness due to increased growth) may take several generations to become evident. Certainly, Round Goby invasion has potential to dramatically alter the Bay of Quinte foodweb. The species, by being one of the few benthivores that exploit Dreissenid Mussels as prey, provides a new energy vector from dreissenids to higher levels (i.e. piscivores) in the foodweb (Johnson et al., 2005; Dietrich et al., 2006; Campbell et al., 2009).

Trends in dominant species

Yellow Perch was the dominant species in the Bay of Quinte fish community, except during the pre-phosphorus control time-stanza (Table 3). Yellow Perch were prominent in all gears except trap nets which did not effectively capture this species. Yellow Perch abundance trends through time varied with gear type and geographic area of the bay (Figure 1; Appendix). In gill nets, abundance generally increased to a peak in the middle and lower bays during the post-phosphorus time-stanza, and then gradually declined to the present. In contrast, Yellow Perch abundance in the upper bay remained suppressed through the post-phosphorus period, despite production of a very large year-class in 1978,

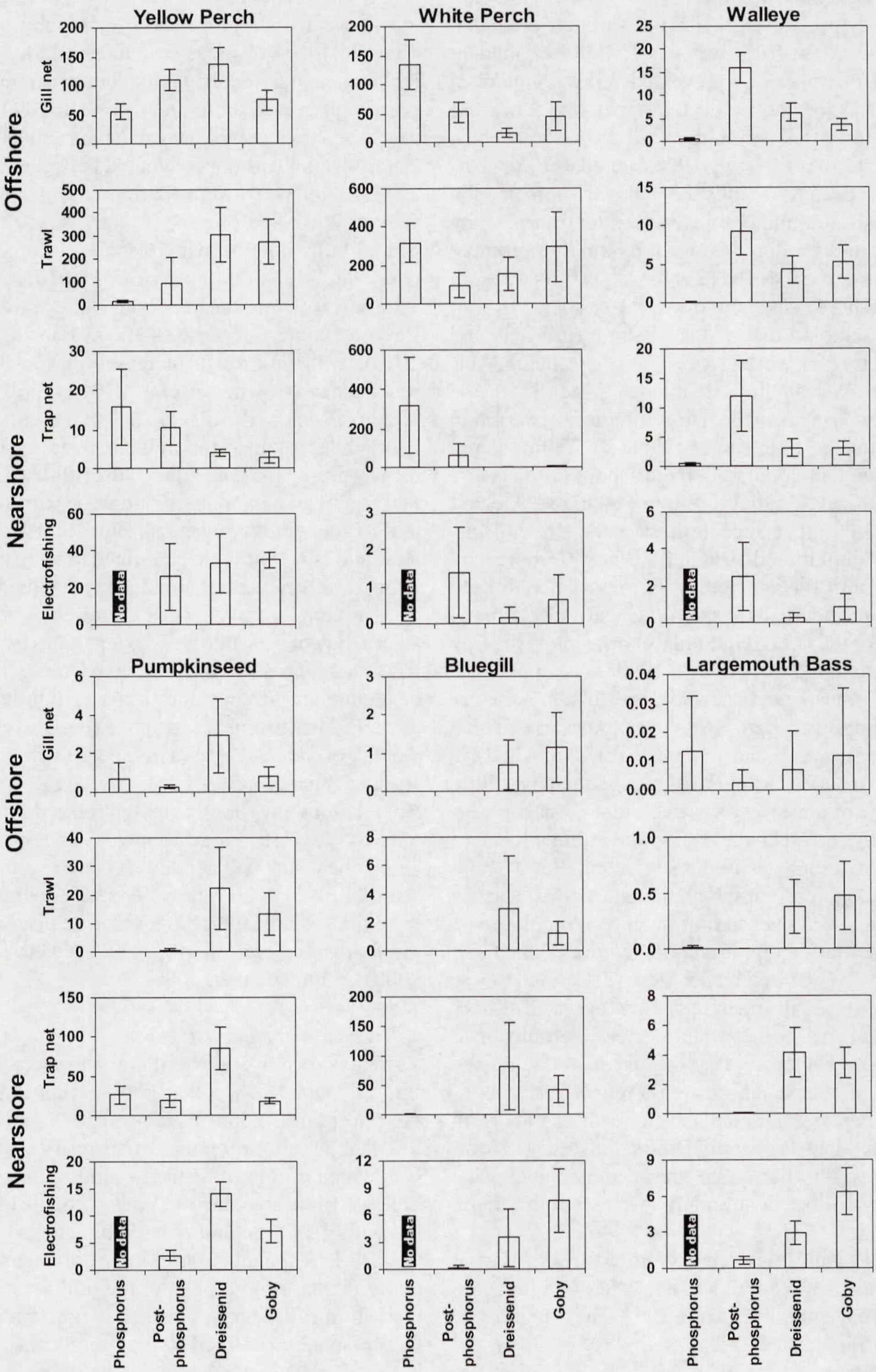

Figure 1. Mean abundance (by number) of selected key species during four ecological time stanzas (phosphorus, post-phosphorus, dreissenid and goby) in two offshore (gill net and trawls) and two nearshore (trap net and electrofishing) gear types. Error bars depict ±2 standard errors.

increased dramatically to very high numbers following Dreissenid Mussel invasion, then declined somewhat. Presumably, predation by the resurging Walleye and/or interactions with Alewife (Hoyle, 1993) inhibited Yellow Perch production in the upper bay after 1978. But after the Dreissenid Mussel invasion in the early 1990s, Yellow Perch abundance increased rapidly in the upper bay. Yellow Perch were scarce in bottom trawl catches, except for the large YOY catch in 1978, in all geographic areas until after Dreissenid Mussel invasion when catches increased in the upper and middle bays. We suggest that the apparent increased survival of young Yellow Perch after dreissenid establishment was associated with expanded SAV (Leisti et al., 2006) at that time. Yellow Perch catches in trap nets were lower in recent time-stanzas compared to past while electrofishing catches remained consistently high through time (Figure 1).

White Perch were important in all gear types; especially offshore gill nets and trawls but also, prior to Dreissenid Mussel invasion, in the nearshore trap nets and electrofishing surveys (Table 3; Appendix). White Perch invaded the Bay of Quinte in the 1950s (Scott and Christie, 1963), quickly rose to prominence in the fish community due to much reduced populations of potential predators and competitors, and were the dominant species in the post-phosphorus time-stanza. The hyper-abundant White Perch were implicated as one of the accumulating factors suppressing Walleye by preying upon Walleye fry (Hurley and Christie, 1977). A catastrophic die-off of the White Perch occurred in 1978 associated with a severely cold winter that year (Minns and Hurley, 1986). In the years following, White Perch recovered but not to increased levels of abundance (Figure 1). Predation by the recovering Walleye population was presumably sufficient to limit the White Perch recovery. Overall, White Perch importance in the fish community reached a low point during the post-Dreissenid Mussel years, but YOY catches in bottom trawls increased in the post-dreissenid and goby time-stanzas. Increased abundance in gill nets lagged that of the bottom trawls and it now appears that the species has regained a high level of prominence in the Bay of Quinte fish community. By way of contrast, White Perch have remained low in nearshore areas (Figure 1; Appendix) suggesting the return of SAV and the associated changes in the nearshore fish community are not conducive to high White Perch abundance.

Walleye was the most important large-bodied, piscivore in the Bay of Quinte fish community. Walleye was important in all gear types, habitats, and time-stanzas except during pre-phosphorus control (Table 3; Figure 1). At that time (late 1960s and 1970s) the population was reduced to remnant levels in the face of degraded water quality conditions and fry predation from the hyper-abundant White Perch population (Hurley and Christie, 1977). The 1978 Walleye year-class was the largest in recent times and was coincident with improved water quality and the White Perch "winter-kill." Although water clarity had improved, even by the early 1990s it had not improved to the extent required to promote significant expansion of SAV (Leisti et al., 2006). Therefore, the nearshore fish community remained depressed. Under these conditions, the Walleye population returned to historically high levels of abundance. Dreissenid Mussel invasion changed these conditions quickly and dramatically, and Walleye populations declined precipitously (Figure 1). A 75% decline in abundance of YOY Walleye occurred at this time (Bowlby et al., 2010) contributing to population levels about 25% of their peak abundance. Potential hypotheses explaining the decline in YOY abundance include reduced food supply/availability linked to dreissenid-induced increases in macrophytes and increased levels of predation and/or competition linked to dreissenid-induced clearing of the water column (Hoyle et al., 2008; Bowlby et al., 2010). Most recently, bottom trawl catches indicate that Walleye year-class strength was similar or somewhat higher in the goby era compared to the dreissenid time-stanza (Table 3; Figure 1). Walleye growth increased and remained higher in the goby time-stanza (Bowlby et al., 2010).

Centrachid species underwent dynamic changes in their contribution to the catch for all gears and time-stanzas (Table 3; Figure 1; Appendix). Centrarchid species dependent on SAV, such as Pumpkinseed, Bluegill, Black Crappie and Largemouth Bass, were depressed greatly during phosphorus and post-phosphorus time-stanzas. Smallmouth Bass and Rock Bass prefer hard substrate devoid of vegetation, and therefore increased in abundance during the post-phosphorus time-stanza and declined after Dreissenid Mussel invasion. Vegetation-dependent species abundance increased significantly after the return of SAV during the Dreissenid Mussel time-stanza (Table 3; Figure 1; Appendix).

Piscivore biomass (PPB)

PPB increased from 0.04 to 0.30 in the offshore and from 0.08 to 0.35 in the nearshore between the phosphorus and post-phosphorus control time-stanzas concomitant with the resurgence of Walleye (Figure 2). For the dreissenid time-stanza, PPB declined to 0.21 in the offshore, due to a decline in Walleye, and to 0.15 in the nearshore, due primarily to declines in Walleye and Smallmouth Bass. PPB remained steady in the offshore but increased to 0.26 in the nearshore for the goby time-stanza. PPB was generally higher in the nearshore. Piscivore species richness was much greater in the nearshore habitat than in the offshore zone. In the nearshore, six piscivores are now relatively common (Figure 2), while in the offshore, Walleye dominated the piscivore assemblage in all time-stanzas. Overall, in the Bay of Quinte, Walleye remain the most important piscivore. Unlike other piscivores, their life history includes annual migrations of adult fish to feed on the abundant Alewife prey in eastern Lake Ontario (Bowlby and Hoyle, 2011); therefore a significant component of the population's production may come from feeding and growth in the lake.

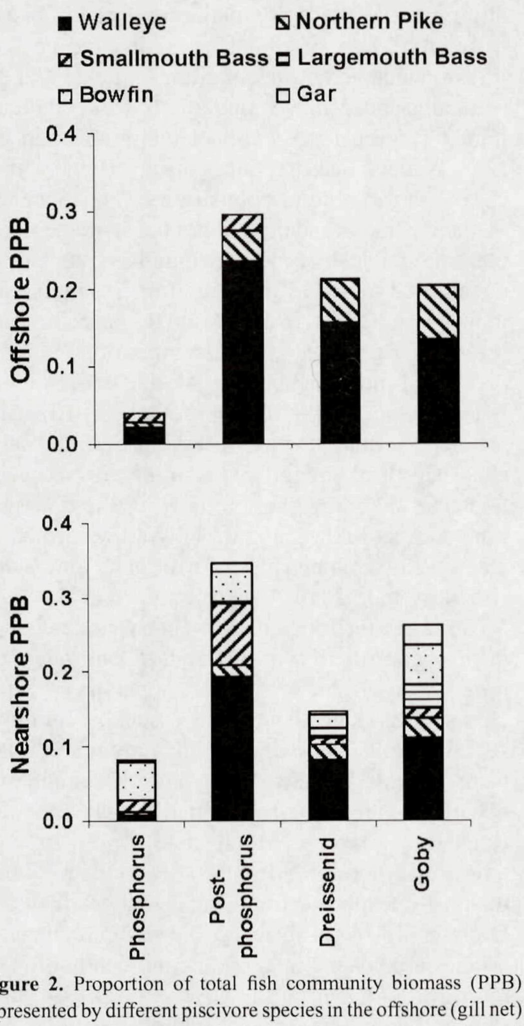

Figure 2. Proportion of total fish community biomass (PPB) represented by different piscivore species in the offshore (gill net) and nearshore (trap net) of the Bay of Quinte in four ecological time-stanzas.

PPB in the Bay of Quinte nearshore (0.26) is now considerably greater than that reported for the 1969–1976 time-period by Hurley and Christie (1977). These authors argued that PPB in the Bay of Quinte should be more like that of West Lake (0.25), a Lake Ontario embayment with similar morphometry and limnology, but not the same level of eutrophication stress. By way of comparison, the PPB in Hamilton Harbour, a degraded embayment habitat, averaged 0.08 during 1988–2008 (Brousseau and Randall, 2008). Similar to the Bay of Quinte, the PPB in Penetang Bay (Severn Sound) increased from 0.12 in 1990 to 0.34 in 2002, as degraded habitat was restored, and this PPB closely matched nearby Hog Bay which averaged 0.35 during this period (Brousseau et al., 2004).

Management implications

Management of aquatic resources in the Bay of Quinte has been challenging because of dynamic ecosystem change caused by the chronological sequence of large-scale ecological stressors: eutrophication, phosphorus control, dreissenid colonization and most recently, the establishment of Round Goby. The Bay of Quinte was designated a Great Lakes Area of Concern (AOC) in 1986 largely due to issues associated with excessive nutrient loadings. One of the impaired beneficial uses was degradation of fish populations. The Bay of Quinte fish community was highly impaired during the pre-phosphorus control period (Hurley and Christie, 1977). By 1985 and post-phosphorus control, the fish community had partially recovered. Walleye, the key top predator in the system, increased in abundance, effectively controlling the formerly hyper-abundant small fish species and restoring a predator-prey balance in the offshore fish community (Hurley, 1986a). But, because SAV remained low in nearshore areas, fish species dependent on this habitat remained suppressed. Continued efforts to control nutrient input along with the Dreissenid Mussel-induced increases in water clarity in the mid 1990s led to recovery of SAV and the fish community associated with that habitat. The Bay of Quinte's fish community trophic structure, measured here as PPB, is now similar to other, non-impaired, Lake Ontario embayments. PPB is also greater than 0.20, in nearshore and offshore habitats, a benchmark value identified by Hurley et al. (1986) below which severe depreciation of the Bay of Quinte fish community occurred. Consistent with Brousseau et al. (2011), the Bay of Quinte fish community currently appears to be indicative of a healthy ecosystem. Looking forward, nutrient input issues and new invasions, in addition to and in the context of broad-scale environmental stressors such as climate change, will mean continued management challenges for the Bay of Quinte ecosystem.

Conclusions

Long-term fish monitoring using a variety of gears was invaluable for tracking the changes in the fish community, in both nearshore and offshore habitats, in different areas of the Bay of Quinte. Fish populations responded to the different environmental and ecological conditions in each of these time-stanzas in a unique manner, as documented in this study. The proportion and diversity of piscivore species was a good indicator of ecosystem health, both spatially and temporally throughout the monitoring period.

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Appendix

Table A1. Mean catches by number for selected prominent Bay of Quinte fish species by gear and ecological time-stanza.

			Ecological time-stanza			
Species	Gear	Region	Phosphorus	Post-phosphorus	Dreissenid	Goby
Yellow Perch	Gill netδ	Upper Bay	36.5 ± 47.3	57.0 ± 29.0	192.0 ± 41.0**	93.7 ± 43.8**
		Middle Bay	51.0 ± 34.4	117.6 ± 20.4**	147.3 ± 29.8	98.0 ± 31.8*
		Lower Bay	79.5 ± 33.4	156.2 ± 20.5**	70.1 ± 29.0**	31.9 ± 31.0
	Trap net		15.9 ± 6.3	10.4 ± 4.3	3.8 ± 8.9	2.8 ± 4.8
	Trawlδ	Upper Bay	13.7 ± 387.0	215.4 ± 237.0	254.3 ± 335.1	352.3 ± 358.3
		Middle Bay	18.3 ± 155.5	39.7 ± 95.2	607.8 ± 134.6**	388.7 ± 143.9*
		Lower Bay	15.5 ± 36.9	17.7 ± 22.6	50.1 ± 32.0	82.0 ± 34.2
	Electrofishing		–	26.1 ± 19.6	33.3 ± 22.7	34.9 ± 22.7
White Perch	Gill netδ	Upper Bay	229.2 ± 47.4	117.6 ± 29.0**	41.6 ± 41.0**	119.4 ± 43.9*
		Middle Bay	97.1 ± 28.9	30.0 ± 17.2**	8.2 ± 25.0	14.2 ± 26.7
		Lower Bay	78.0 ± 15.4	12.6 ± 9.4**	0.5 ± 13.4	1.0 ± 14.3
	Trap net		318.1 ± 126.4	62.2 ± 86.7**	1.6 ± 178.7	4.5 ± 95.5
	Trawl		318.3 ± 106.4	95.3 ± 65.1**	155.9 ± 92.1	294.0 ± 98.5*
	Electrofishing		–	1.4 ± 1.2	0.2 ± 1.4	0.6 ± 1.4
Alewife	Gill netδ	Upper Bay	336.5 ± 69.1	73.6 ± 42.3**	0.9 ± 59.9	1.3 ± 64.0
		Middle Bay	184.0 ± 61.7	102.4 ± 36.7*	8.7 ± 53.4**	3.2 ± 57.1
		Lower Bay	147.2 ± 146.6	250.5 ± 89.8	27.6 ± 127.0**	38.4 ± 135.7
	Trap net		420.1 ± 174.8	28.1 ± 119.9**	0 ± 247.3	0.0 ± 132.2
	Trawl		388.9 ± 233.3	443.2 ± 142.9	136.0 ± 202.0*	176.0 ± 216.0
	Electrofishing		–	np	np	np
Walleye	Gill net		0.7 ± 5.6	23.0 ± 3.4**	10.9 ± 4.9**	7.6 ± 5.2
	Trap net		0.4 ± 5.9	12.0 ± 4.1**	3.1 ± 8.4	3.0 ± 4.5
	Trawl		0.1 ± 3.6	9.3 ± 2.2**	4.3 ± 3.2*	5.2 ± 3.4
	Electrofishing		–	2.5 ± 1.7	0.3 ± 2.0	0.8 ± 2.0
Pumpkinseed	Gill netδ	Upper Bay	0.1 ± 2.4	0.4 ± 1.5	7.5 ± 2.1**	1.6 ± 2.2**
		Middle Bay	0.1 ± 0.7	0.2 ± 0.4	1.2 ± 0.6**	0.9 ± 0.7
		Lower Bay	1.9 ± 0.9	0.3 ± 0.6**	0.0 ± 0.8	0.0 ± 0.9
	Trap net		26.9 ± 11.8	18.8 ± 8.1	86.2 ± 16.6**	18.4 ± 8.9**
	Trawlδ	Upper Bay	0.2 ± 19.8	1.5 ± 12.1	51.5 ± 17.1**	29.4 ± 18.3
		Middle Bay	0.0 ± 8.6	0.3 ± 5.2	15.0 ± 7.4**	10.2 ± 7.9

(Continued on next page)

Table A1. Mean catches by number for selected prominent Bay of Quinte fish species by gear and ecological time-stanza. *(Continued)*

			Ecological time-stanza			
Species	Gear	Region	Phosphorus	Post-phosphorus	Dreissenid	Goby
		Lower Bay	np	np	np	np
	Electrofishing		–	2.6 ± 2.3	14.1 ± 2.7**	7.1 ± 2.7**
Bluegill	Gill netδ	Upper Bay	0.0 ± 1.3	0.0 ± 0.8	2.0 ± 1.1**	3.4 ± 1.2
		Middle Bay	np	np	np	np
		Lower Bay	np	np	np	np
	Trap netδ	Upper Bay	0.8 ± 23.5	0.6 ± 15.7	156.1 ± 33.2**	80.1 ± 19.2**
		Middle Bay	0.4 ± 15.7	0.1 ± 11.1	14.5 ± 31.4	23.5 ± 15.7
		Lower Bay	np	np	4.7 ± 12.4	4.4 ± 6.2
	Trawlδ	Upper Bay	0.0 ± 5.7	0.0 ± 3.5	9.0 ± 4.9**	3.1 ± 5.3
		Middle Bay	0.0 ± 0.5	0.0 ± 0.3	0.0 ± 0.4	0.6 ± 0.4
		Lower Bay	np	np	np	np
	Electrofishing		–	0.2 ± 3.2	3.5 ± 3.7	7.6 ± 3.7
Black Crappie	Gill netδ	Upper Bay	0.0 ± 0.3	0.1 ± 0.2	0.1 ± 0.3	0.6 ± 0.3*
		Middle Bay	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
		Lower Bay	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	Trap net		6.5 ± 3.1	1.3 ± 2.1**	8.1 ± 4.4**	7.2 ± 2.3
	Trawl		0.0 ± 0.3	0.1 ± 0.2	0.4 ± 0.3	0.3 ± 0.3
	Electrofishing		–	0.1 ± 0.1	0.1 ± 0.2	0.1 ± 0.2
Largemouth Bass	Gill net		0.0 ± 0.0	0.0 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
	Trap netδ	Upper Bay	0.0 ± 1.2	0.1 ± 0.8	4.3 ± 1.7**	5.2 ± 1.0
		Middle Bay	0.0 ± 0.5	0.0 ± 0.4	5.6 ± 1.0**	2.5 ± 0.5**
		Lower Bay	np	np	2.6 ± 0.8	1.6 ± 0.4*
	Trawlδ	Upper Bay	0.0 ± 0.3	0.0 ± 0.2	0.9 ± 0.3**	1.2 ± 0.3
		Middle Bay	0.0 ± 0.3	0.0 ± 0.2	0.3 ± 0.3	0.3 ± 0.3
		Lower Bay	np	np	np	np
	Electrofishing		–	0.7 ± 1.5	3.0 ± 1.7*	6.3 ± 1.7*

Note: Values are means ± 95% CI. Asterisks indicate a significant difference between the current and previous ecological time-stanzas (*$p < 0.05$; **$p < 0.01$). Analysis is by geographic region (upper, middle and lower Bay of Quinte) unless the gear x region interaction was not significant (indicated with a "δ" after the gear; $p < 0.05$) in which case data from all regions were pooled. "np" indicates a species was not present in that gear in that time stanza. Boat electrofishing gear was not used in the phosphorus time-stanza.