Ecography

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Supplementary material

Appendix 1

Analyses of 52 lakes in south-central Ontario, Canada to study the relationship of environmental factors, symmetrical spatial structure, and asymmetrical spatial structure on fish community composition.

Objective

We analysed a subset of the large Ontario Habitat Inventory Index database to quantify the relative role of environmental conditions and spatial patterns that could arise from niche-based processes such as environmental filtering (Keddy 1992) and dispersal limitation (Hubble 2001), such as natural and human-mediated modes of dispersal using a variation partitioning framework and novel spatial statistical methods (Principal Coordinates of Neighbour Matrices (PCNM) and Asymmetrical Eigenvector Maps (AEM)). The analyses of 52 lakes with detailed knowledge on the hydrological connectivity between those lakes was conducted to primarily demonstrate the utility of quantifying directional spatial patterns through the implementation of AEM analysis at a finer spatial scale.

Methods

Fifty-two drainage lakes within the Black and Hollow River watersheds in south-central Ontario were sampled to ascertain environmental conditions and fish community composition. Fish community composition data were collected by intensively sampling lakes continuously over 3–7 d and nights using a variety of sampling gear types (e.g. trap nets, minnow traps, seine nets, plastic traps, and gill nets) and resulted in the sampling of 31 fish species. In conjunction with fish sampling, environmental conditions were assessed for each lake. Lake morphological variables that were collected included: lake area, maximum depth, mean depth, lake elevation, shoreline perimeter, and island perimeter. Water quality variables that were measured included: pH, secchi depth, conductivity, colour, and concentrations of dissolved organic carbon and dissolved inorganic carbon. Furthermore, hydrological connectivity was assessed for each lake by obtaining detailed descriptions of the hydrological connections between each lake. For more details on sampling methodology, please see Jackson (1988), Jackson and Harvey (1989), and Olden et al. (2001).

Data analyses were performed as described in the main text. Environmental variables were log-transformed as necessary to satisfy statistical assumptions. Fish species data were subjected to the Hellinger transformation and rare species (defined as the presence of a species in only one lake) were removed prior to multivariate analyses. We identified the relative importance of environmental conditions (lake morphology, water quality, and climate), symmetric spatial structure (PCNM variables), and asymmetric spatial structure (AEM variables) by partitioning the variation explained by each component using redundancy analyses (Borcard et al. 1992). The shared variation between environmental variables and spatial descriptors are produced by induced spatial dependence generated by the spatial structure of environmental factors acting indirectly on biological communities. The unique fraction explained by PCNM variables was used as a surrogate of human-mediated dispersal, whereas the unique fraction explained by AEM variables was used as a surrogate of natural dispersal. Forward selection procedures were used to select environmental variables that were significantly explaining variation in fish community composition.

Results and discussion

Environmental conditions, symmetric spatial structure, and asymmetric spatial structure explained over 35% of the variation (72% unadjusted variation) in fish community composition for 52 lakes in the Black and Hollow River watersheds. Upon consideration of explained variation as a percentage of the total fitted fraction, ca 60% of the variation in community composition was attributed to environmental conditions (both solely and spatially structured). Approximately 14% of the variation was explained uniquely by AEM variables representing natural dispersal of fishes within the watersheds. Approximately 8% of the variation was explained uniquely by PCNM variables which represents human-mediated dispersal within the watersheds (Fig. A1). When considering the total amount of variation (unique and shared) explained by each factor, AEM variables explained the greatest amount of variation (74.8%), followed by environmental variables (59.2%), and PCNM variables (52.3%). We demonstrate the utility of AEM analysis in this example by showing that AEM variables can explain significant amounts of variation in structuring fish community composition when detailed hydrological connectivity information is available. This suggests that fishes are moving between lakes (Olden et al. 2001), although the dispersal ability differs among species. The size and swimming ability of a fish species may limit its natural dispersal as riffles, waterfalls, or large distances between lakes may impede some species from colonizing other lakes (Jackson et al. 2001).

Four environmental variables were significantly structuring the fish community in the Black and Hollow River watersheds. The most important environmental variable was lake elevation and explained over 9% of the variation in fish community composition. The other significant environmental variables were pH, lake colour, and area (Table A1). These environmental variables reflect the environmental gradient of the lakes in the watersheds. For example, higher order drainage lakes in this area tend to be in areas of higher elevation, and are deeper, clearer, and found on sandy soils.

Conversely, lakes further down in the watershed are turbid and found in areas of lower elevation and wetlands (Jackson 1988). In the Black and Hollow River watersheds, elevation may be reflecting the relative position of each lake on the landscape which subsequently can influence lake morphology, such as lake size and shape, and environmental characteristics, such as conductivity and productivity (Olden et al. 2001). Surface area of lakes tends to be correlated with species diversity with larger lakes expected to contain larger numbers of species (Barbour and Brown 1974), but also influences epilimnion water temperatures, stratification depth, and availability of cold, well oxygenated water in the hypolimnion (Jackson et al. 2001). Lake acidity has been known to decrease species diversity and smaller bodied species that tend to dominate the lakes in south-central Ontario are especially sensitive (Somers and Harvey 1984, Jackson and Harvey 1989). In this example, we have shown that the inclusion of environmental conditions, overland distances (PCNM) and watercourse distances (AEM) are important to further understanding the factors that are structuring ecological communities. This example corroborates previous studies which suggest that a combination of environmental conditions, human-mediated dispersal, and natural dispersal are structuring fish communities in temperate lakes (Jackson and Harvey 1989, Olden et al. 2001, Leprieur et al. 2009).

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Table A1. Percent variation explained by significant environmental variables in structuring fish community composition in the Black and Hollow Rivers watersheds.

Environmental variable	% variation explained (adjusted R^2)	p-value
Elevation	7.4	0.001
pH	3.8	0.001
Lake colour	2.6	0.004
Area	2	0.016

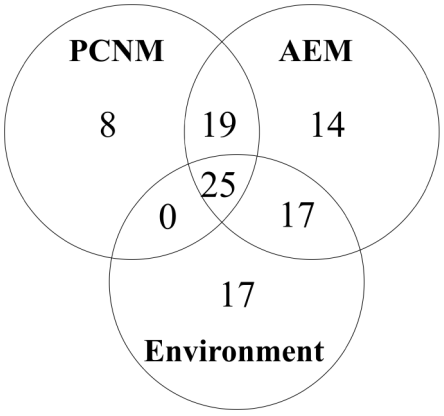

Figure A1. Fractions of adjusted percent variation (R^2_{adj}) explained for fish community composition for the Black and Hollow Rivers watersheds by the set of predictor variables (PCNM = variation explained by pure symmetric spatial structure; AEM = variation explained by pure asymmetric spatial structure; ENV = variation explained by pure environmental conditions) based on variation partitioning analyses.

Appendix 2

Summary of variation partitioning analyses reporting the adjusted percent variation (R^2) explained for the community and each fish assemblage type (Native fishes = Native non-sport fishes) in all drainage basins (Huron = Lake Huron; Nelson = Nelson River; Ont = Lakes Ontario, Erie and St. Clair; StL = St. Lawrence and Ottawa Rivers; Superior = Lake Superior) by the set of predictor variables (Total = variation explained by all variables; PCNM = variation explained by symmetric spatial structure only; AEM = variation explained by asymmetric spatial structure only; ENV = variation explained by environmental conditions only; PCNM + AEM = shared variation explained by PCNM and AEM; AEM + ENV = shared variation explained by environmental variables that are asymmetrically structured; PCNM + ENV = shared variation explained by environmental variables that are symmetrically structured; PCNM + AEM + ENV = shared variation explained by environmental variables that are symmetrically and asymmetrically structured).

Assemblage type	Total	PCNM	AEM	ENV	PCNM+AEM	AEM+ENV	PCNM+ENV	PCNM+AEM+ENV
Community – Huron	20.3	2.9	0.3	4.8	1.3	0	4.8	6.2
Community – Nelson	17.1	3.1	0.6	6.1	0.2	0	3.5	3.5
Community – Ont	16.8	2.6	1	5.9	0.4	1.6	1.6	3.6
Community – StL	17.9	1.4	0.6	7.7	0.5	2.4	1.2	4.2
Community – Superior	23.2	4.2	0	6.6	1.2	0.9	4	6.3
Native fishes – Huron	19.6	–0.3	–0.1	4.1	1.7	0.2	5.4	8.6
Native fishes – Nelson	14.4	2	0.1	4.5	0.8	–0.3	5.1	2.1
Native fishes – Ont	15.2	3.3	1.0	4.2	0.5	1.4	2.0	2.8
Native fishes – StL	17.2	–0.3	0.7	7.7	0.4	3.3	0.3	5.2
Native fishes – Superior	11.7	–0.9	–0.1	6.5	1.3	0.8	2.6	1.6
Sport fishes – Huron	28.4	5.2	0.5	7.8	1.3	0	6.8	6.8
Sport fishes – Nelson	24.8	4.2	1.2	12	–0.4	0.3	4.2	3.4
Sport fishes – Ont	23.5	1.9	1.2	9.8	0.3	2.5	2.2	5.6
Sport fishes – StL	23.7	1.6	0.7	10.9	0.6	2.4	2.2	5.4
Sport fishes – Superior	36.8	6.8	–0.1	10.8	1.6	1.2	6.1	10.5
Bait fishes – Ont	8.1	0.6	0.5	1.5	0.4	0.8	1.2	3.1
Bait fishes – Huron	14.4	5.7	0.2	1.2	0.8	0	2.8	3.8
Bait fishes – Nelson	15.4	4.2	0.2	3.7	0.5	0.2	2.3	4.3
Bait fishes – StL	11.7	2.9	0.3	1.8	0.6	0.4	2.2	3.6
Bait fishes – Superior	21.3	5.8	–0.2	1.9	1.3	0.4	2.7	9.4
Non-native fishes – Huron	13.4	6.7	1.3	2.7	–0.2	0	1.2	1.6
Non-native fishes – Nelson	8.4	8.1	–1.3	0.5	1.2	0	0.1	–0.3
Non-native fishes – Ont	14.6	7.2	–0.4	4.1	0.5	2.1	0.7	0.5
Non-native fishes – StL	–0.5	–3.9	–0.3	1.9	0.2	1	–0.2	0.8
Non-native fishes – Superior	15.4	11.3	0.7	1	1.2	0	1.8	–0.6

Appendix 3

Adjusted percent variation (R^2) explained for each species in the Lakes Ontario, Erie and St. Clair drainage basin by the set of predictor variables (Total = variation explained by all variables; ENV = variation explained by environmental conditions only; PCNM = variation explained by symmetric spatial structure only; AEM = variation explained by asymmetric spatial structure only; PCNM + AEM + ENV = shared variation explained by environmental variables that are symmetrically and asymmetrically structured).

Species	Total	ENV	PCNM	AEM	ENV+PCNM+AEM
American eel, *Anguilla rostrata*	19.9	9.2	–6.0	1.5	4.0
Banded killifish, *Fundulus diaphanus*	47.2	6.1	8.2	7.8	2.5
Black crappie, *Pomoxis nigromaculatus*	37.1	15.2	7.4	0.2	5.6
Blackchin shiner, *Notropis heterodon*	2.1	2.4	–6.8	0.6	0.2
Blacknose dace, *Rhinichhthys atratulus*	59.6	1.3	35.5	12.4	4.2
Blacknose shiner, *Notropis heterolepis*	3.1	1.4	–0.8	0.1	–0.8
Bluegill, *Lepomis macrochirus*	36.8	3.3	9.3	2.2	3.9
Bluntnose minnow, *Pimephales notatus*	14.1	6.4	4.6	–0.8	0.3
Brassy minnow, *Hybognathus hankinsoni*	–7.2	–1.0	–7.2	0.9	–1.0
Brook stickleback, *Culaea inconstans*	13.1	2.3	9.0	3.1	–1.6
Brook trout, *Salvelinus fontinalis timagamiensis*	13.0	8.1	–1.5	–0.4	3.0
Brown bullhead, *Ameiurus nebulosus*	12.9	1.2	4.8	2.1	–0.2
Brown trout, *Salmo trutta*	0.1	1.7	–2.0	0.6	–0.1
Burbot, *Lota lota*	11.5	10.4	–1.7	–1.7	1.4
Central mudminnow, *Umbra limi*	19.2	4.4	13.7	3.9	–2.2
Channel catfish, *Ictalurus punctatus*	37.7	1.4	32.9	0.2	–1.0
Common carp, *Cyprinus carpio*	38.9	12.4	18.0	2.0	0.1
Common shiner, *Luxilus cornutus*	2.1	3.8	–2.5	0.8	1.6
Creek chub, *Semotilus atromaculatus*	15.0	0.7	2.7	–0.2	0.8
Emerald shiner, *Notropis atherinoides*	–7.4	–1.3	–6.2	–0.9	–0.5
Fallfish, *Semotilus corporalis*	–6.7	1.2	–10.2	–1.8	0.8
Fathead minnow, *Pimephales promelas*	16.2	2.0	4.1	0.3	6.8
Finescale dace, *Phoxinus neogaeus*	8.4	5.0	1.0	0.2	0.0
Gizzard shad, *Dorosoma cepedianum*	76.1	32.9	4.6	8.1	22.4
Golden shiner, *Notemigonus crysoleucas*	1.0	0.9	–3.5	0.4	–0.8
Goldfish, *Carassium auratus*	55.5	7.0	50.0	5.0	–4.7
Hornyhead chub, *Nocomis biguttatus*	–8.8	–0.5	–5.5	–2.4	0.4
Iowa darter, *Etheostoma exile*	27.2	8.0	11.4	7.0	–2.0
Johnny darter, *Etheostoma nigrum*	18.9	0.2	–1.3	10.6	0.9
Lake trout, *Salvelinus namaycush*	30.0	24.6	–0.4	–0.8	1.3
Lake herring, *Coregonus artedi*	12.7	11.2	–1.1	–0.6	0.7
Lake whitefish, *Coregonus clupeaformis*	12.0	10.0	1.4	–0.3	–0.9
Largemouth bass, *Micropterus salmoides*	26.0	8.0	5.0	2.5	1.5
Logperch, *Percina caprodes*	25.3	16.0	7.2	3.0	–3.5
Longnose gar, *Lepisosteus osseus*	9.7	6.5	–3.8	–0.5	2.3
Longnose sucker, *Catostomus catostomus*	2.9	–0.5	–2.7	–0.7	1.3
Mimic shiner, *Notropis volucellus*	–13.5	–1.6	–9.9	–2.8	0.8
Mottled sculpin, *Cottus bairdi*	20.9	5.6	12.4	4.0	–0.7
Muskellunge, *Esox masquinongy*	20.5	7.6	–1.6	1.7	0.9
Northern pike, *Esox lucius*	51.4	6.1	10.4	4.3	–1.6
Northern redbelly dace, *Phoxinus eos*	16.7	10.3	1.8	0.4	1.2
Pearl dace, *Margariscus margarita*	–5.6	–0.6	–5.4	–1.3	0.4
Pumpkinseed, *Lepomis gibbosus*	9.9	0.3	3.9	1.3	–1.0

Rainbow smelt, *Osmerus mordax*	5.8	2.6	2.7	–0.7	–0.1
Rainbow trout, *Oncorhynchus mykiss*	5.4	1.0	2.6	–1.6	0.8
Redside dace, *Clinostomus elongatus*	–5.4	–0.6	–7.0	–1.2	1.0
River chub, *Nocomis micropogon*	24.7	5.0	19.6	7.1	–4.7
Rock bass, *Ambloplites rupestris*	17.7	8.0	0.9	–0.3	1.3
Round whitefish, *Prosopium cylindraceum*	–11.7	–1.4	–8.4	–2.7	0.1
Sauger, *Sander canadensis*	–0.6	0.8	1.1	–1.6	–0.3
Shorthead redhorse, *Moxostoma macrolepidotum*	5.5	5.4	–7.6	0.9	0.5
Silver redhorse, *Moxostoma anisurum*	–5.9	–0.5	–6.5	–0.8	0.8
Smallmouth bass, *Micropterus dolomieu*	27.3	9.2	4.5	2.2	–2.4
Spotfin shiner, *Cyprinella spiloptera*	–13.4	0.2	–10.4	–3.2	0.8
Spottail shiner, *Notropis hudsonius*	18.9	10.8	3.3	0.8	–0.5
Trout-perch, *Percopsis omiscomaycus*	10.3	3.1	4.9	–1.2	1.4
Walleye, *Sander vitreus*	17.6	8.6	–3.3	0.3	0.1
White sucker, *Catostomus commersoni*	13.2	5.3	2.0	1.1	–0.9
Yellow perch, *Perca flavescens*	18.5	6.5	–0.4	1.0	0.0
Yellow bullhead, *Ameiurus natalis*	9.1	0.1	8.9	0.2	–1.9

Appendix 4

Adjusted percent variation (R^2) explained for each species in the Lake Huron drainage basin by the set of predictor variables (Total = variation explained by all variables; ENV = variation explained by only environmental conditions; PCNM = variation explained by only symmetric spatial structure; AEM = variation explained by only asymmetric spatial structure; PCNM + AEM + ENV = shared variation explained by environmental variables that are symmetrically and asymmetrically structured).

Species	Total	ENV	PCNM	AEM	ENV+PCNM+AEM
Alewife, *Alosa pseudoharengus*	4.5	4.0	1.4	1.7	–1.5
Banded killifish, *Fundulus diaphanus*	15.2	0.9	4.4	–0.5	4.3
Blackchin shiner, *Notropis heterodon*	–6.4	3.1	–16.7	–0.4	3.7
Black crappie, *Pomoxis nigromaculatus*	7.7	2.2	3.6	1.0	0.1
Blacknose dace, *Rhinichhthys atratulus*	17.8	–0.4	14.7	0.9	–0.6
Blacknose shiner, *Notropis heterolepis*	10.2	1.6	4.6	0.3	1.5
Bluegill, *Lepomis macrochirus*	–5.2	0.3	–8.9	0.5	0.6
Bluntnose minnow, *Pimephales notatus*	20.7	4.3	7.9	0.0	2.3
Bowfin, *Amia calva*	17.0	5.7	11.7	–0.5	0.7
Brassy minnow, *Hybognathus hankinsoni*	–0.4	0.2	–1.5	0.3	–0.2
Brook silverside, *Labidesthes sicculus*	1.2	1.8	–0.3	–0.6	0.4
Brook stickleback, *Culaea inconstans*	10.1	3.0	0.7	2.1	0.8
Brook trout, *Salvelinus fontinalis timagamiensis*	25.4	5.1	4.1	0.5	0.5
Brown bullhead, *Ameiurus nebulosus*	18.4	1.9	–2.2	0.0	1.5
Brown trout, *Salmo trutta*	17.1	1.0	13.3	4.2	–3.2
Burbot, *Lota lota*	15.0	9.7	0.6	0.5	0.8
Central mudminnow, *Umbra limi*	9.6	3.7	–8.1	0.3	4.9
Channel catfish, *Ictalurus punctatus*	5.5	0.2	5.1	–0.1	0.3
Common carp, *Cyprinus carpio*	41.2	4.1	32.4	3.7	–0.9
Common shiner, *Luxilus cornutus*	13.9	2.1	6.9	0.2	0.6
Creek chub, *Semotilus atromaculatus*	21.0	0.5	5.7	0.2	0.9
Emerald shiner, *Notropis atherinoides*	11.9	2.7	10.6	0.5	–0.7
Fathead minnow, *Pimephales promelas*	4.2	3.6	–0.7	0.1	0.0
Finescale dace, *Phoxinus neogaeus*	1.1	3.1	–6.8	0.3	0.7
Golden shiner, *Notemigonus crysoleucas*	11.7	0.6	4.6	–0.4	1.7
Grass pickerel, *Esox americanus vermiculatus*	8.1	0.9	7.5	–0.5	0.5
Hornyhead chub, *Nocomis biguttatus*	3.7	1.0	2.9	2.1	–1.8
Iowa darter, *Etheostoma exile*	14.5	1.0	2.7	1.4	2.9
Johnny darter, *Etheostoma nigrum*	16.0	0.3	7.8	1.6	0.0
Lake herring, *Coregonus artedi*	27.3	9.9	5.8	0.4	1.1
Lake sturgeon, *Acipenser fulvescens*	4.9	–0.1	3.9	0.0	0.9
Lake trout, *Salvelinus namaycush*	34.0	18.8	3.7	0.4	0.4
Lake whitefish, *Coregonus clupeaformis*	34.6	7.2	13.8	1.8	1.1
Largemouth bass, *Micropterus salmoides*	23.8	1.0	1.5	1.6	0.2
Least darter, *Etheostoma microperca*	9.0	0.5	4.7	11.5	–9.4
Logperch, *Percina caprodes*	5.5	3.0	–2.6	–1.0	1.7
Longear sunfish, *Lepomis megalotis*	6.2	–0.5	3.6	4.9	–4.0
Longnose dace, *Rhinichthys cataractae*	–2.5	–0.5	–1.7	0.7	–1.2
Longnose gar, *Lepisosteus osseus*	7.2	2.8	4.3	0.3	–0.3
Longnose sucker, *Catostomus catostomus*	14.4	4.0	1.3	0.6	0.0
Mimic shiner, *Notropis volucellus*	18.8	2.2	10.0	–0.2	2.4
Mottled sculpin, *Cottus bairdi*	–3.5	0.7	–6.2	1.5	–1.8
Muskellunge, *Esox masquinongy*	21.4	2.6	15.3	–0.3	2.0

Ninespine stickleback, *Pungitius pungitius*	7.0	–0.6	5.0	0.1	1.2
Northern hognose sucker, *Hypentelium nigricans*	–1.6	1.8	–2.1	–0.5	0.9
Northern pike, *Esox lucius*	40.3	8.2	10.3	0.9	3.4
Northern redbelly dace, *Phoxinus eos*	17.4	6.6	–1.7	–0.1	2.3
Pearl dace, *Margariscus margarita*	10.7	1.1	4.8	0.8	0.1
Pumpkinseed, *Lepomis gibbosus*	33.2	1.2	2.6	–0.4	1.7
Rainbow smelt, *Osmerus mordax*	18.8	5.6	6.2	0.8	–0.1
Rainbow trout, *Oncorhynchus mykiss*	8.1	1.3	3.6	1.1	0.2
Redside dace, *Clinostomus elongatus*	3.7	1.7	0.4	–0.3	0.6
River chub, *Nocomis micropogon*	23.2	0.9	19.4	2.1	–0.9
Rock bass, *Ambloplites rupestris*	22.4	3.3	–1.8	0.3	0.7
Round whitefish, *Prosopium cylindraceum*	4.9	3.4	–0.8	1.2	–0.2
Sand shiner, *Notropis stramineus*	24.9	0.9	18.4	0.2	5.4
Sauger, *Sander canadensis*	8.6	1.4	8.4	–0.9	0.7
Shorthead redhorse, *Moxostoma macrolepidotum*	10.1	0.9	7.7	0.3	–0.2
Silver redhorse, *Moxostoma anisurum*	1.0	2.1	–0.7	0.6	–0.7
Slimy sculpin, *Cottus cognatus*	12.5	1.1	10.6	–0.9	1.5
Smallmouth bass, *Micropterus dolomieu*	31.9	10.8	6.2	0.0	0.6
Splake, *Salvelinus fontinalis X S. namaycush*	–0.1	1.0	–1.0	0.5	–0.2
Spoonhead sculpin, *Cottus ricei*	–1.3	0.9	–0.7	–0.6	0.1
Spottail shiner, *Notropis hudsonius*	10.8	2.9	6.9	0.2	–0.2
Tadpole madtom, *Noturus gyrinus*	43.9	2.2	21.8	0.4	8.5
Trout-perch, *Percopsis omiscomaycus*	3.3	1.5	1.1	0.3	0.2
Walleye, *Sander vitreus*	31.2	10.3	9.0	0.6	0.7
White bass, *Morone chrysops*	–0.8	3.8	–2.2	1.0	–1.1
White sucker, *Catostomus commersoni*	14.8	5.0	0.2	–0.4	2.5
Yellow bullhead, *Ameiurus natalis*	9.8	8.5	2.9	3.4	–1.0
Yellow perch, *Perca flavescens*	19.2	3.4	0.6	0.0	2.2

Appendix 5

Adjusted percent variation (R^2) explained for each species in the Lake Superior drainage basin by the set of predictor variables (Total = variation explained by all variables; ENV = variation explained by environmental conditions only; PCNM = variation explained by symmetric spatial structure only; AEM = variation explained by asymmetric spatial structure only; PCNM + AEM + ENV = shared variation explained by environmental variables that are symmetrically and asymmetrically structured).

Species	Total	ENV	PCNM	AEM	ENV+PCNM+AEM
Blacknose dace, *Rhinichhthys atratulus*	–13.0	–0.5	–20.3	–1.7	1.9
Blacknose shiner, *Notropis heterolepis*	21.8	0.4	7.5	–0.3	1.8
Bluntnose minnow, *Pimephales notatus*	1.9	0.4	–9.5	–1.8	2.6
Brassy minnow, *Hybognathus hankinsoni*	–20.4	–0.9	–24.8	2.0	–0.5
Brook stickleback, *Culaea inconstans*	2.2	2.7	–7.4	0.5	0.2
Brook trout, *Salvelinus fontinalis timagamiensis*	40.0	16.5	3.5	0.0	1.6
Brown bullhead, *Ameiurus nebulosus*	41.5	2.4	36.9	0.1	1.4
Burbot, *Lota lota*	25.4	8.0	10.8	2.2	–2.0
Common shiner, *Luxilus cornutus*	6.1	–0.3	–6.2	–1.0	1.1
Creek chub, *Semotilus atromaculatus*	29.3	1.1	6.2	–0.2	1.9
Emerald shiner, *Notropis atherinoides*	20.1	0.7	14.0	–0.3	0.6
Fathead minnow, *Pimephales promelas*	5.4	3.0	0.2	0.0	1.0
Finescale dace, *Phoxinus neogaeus*	6.2	1.8	0.1	–0.4	1.1
Golden shiner, *Notemigonus crysoleucas*	0.6	3.1	0.4	–1.2	1.1
Iowa darter, *Etheostoma exile*	12.8	4.3	7.4	0.1	2.4
Johnny darter, *Etheostoma nigrum*	27.1	1.5	14.8	3.6	–3.6
Lake herring, *Coregonus artedi*	33.5	10.2	9.1	–0.4	–0.1
Lake trout, *Salvelinus namaycush*	29.6	12.7	5.7	–0.5	2.2
Lake whitefish, *Coregonus clupeaformis*	34.8	10.5	8.4	0.8	0.8
Largemouth bass, *Micropterus salmoides*	11.0	5.2	7.9	–0.6	1.3
Logperch, *Percina caprodes*	15.8	5.8	9.9	0.0	2.0
Longnose dace, *Rhinichthys cataractae*	15.0	1.7	11.9	0.0	0.8
Longnose sucker, *Catostomus catostomus*	1.7	9.1	–2.3	–0.2	0.2
Mimic shiner, *Notropis volucellus*	48.2	0.7	27.4	–0.5	6.9
Mottled sculpin, *Cottus bairdi*	8.0	0.3	3.6	–0.3	0.2
Ninespine stickleback, *Pungitius pungitius*	22.7	2.9	13.1	–0.5	2.3
Northern pike, *Esox lucius*	44.3	6.9	9.5	–0.4	2.5
Northern redbelly dace, *Phoxinus eos*	10.1	3.5	–6.9	–1.1	4.6
Pearl dace, *Margariscus margarita*	10.3	1.2	6.6	0.8	0.0
Pumpkinseed, *Lepomis gibbosus*	5.0	–2.1	2.8	–1.9	1.7
Rainbow smelt, *Osmerus mordax*	12.5	1.1	8.8	2.0	–2.0
Rainbow trout, *Oncorhynchus mykiss*	19.8	0.0	14.4	–0.6	4.1
Redside dace, *Clinostomus elongatus*	–0.9	0.8	–5.2	1.8	–1.8
Rock bass, *Ambloplites rupestris*	5.8	–1.6	3.6	0.7	0.1
Round whitefish, *Prosopium cylindraceum*	12.9	–1.9	13.0	–1.0	0.6
Sauger, *Sander canadensis*	15.5	4.9	9.1	7.6	–6.0
Shorthead redhorse, *Moxostoma macrolepidotum*	9.9	5.3	6.6	6.8	–6.4
Silver redhorse, *Moxostoma anisurum*	11.5	3.0	8.6	–1.9	1.7
Slimy sculpin, *Cottus cognatus*	14.0	0.5	9.5	–0.4	–0.1
Smallmouth bass, *Micropterus dolomieu*	17.5	7.4	10.8	1.6	–1.9
Splake, *Salvelinus fontinalis X S. namaycush*	7.4	3.3	6.2	2.4	–2.4
Spottail shiner, *Notropis hudsonius*	42.0	5.9	13.7	–0.6	1.8
Trout-perch, *Percopsis omiscomaycus*	23.5	4.6	11.8	1.4	–0.9

Walleye, *Sander vitreus*	34.4	12.4	10.0	0.3	0.0
White sucker, *Catostomus commersoni*	9.3	8.2	–1.7	–0.3	0.3
Yellow perch, *Perca flavescens*	35.3	5.7	4.5	–0.8	3.1

Appendix 6

Adjusted percent variation (R^2) explained for each species in the Nelson River drainage basin by the set of predictor variables (Total = variation explained by all variables; ENV = variation explained by environmental conditions only; PCNM = variation explained by symmetric spatial structure only; AEM = variation explained by asymmetric spatial structure only; PCNM + AEM + ENV = shared variation explained by environmental variables that are symmetrically and asymmetrically structured).

Species	Total	ENV	PCNM	AEM	ENV+PCNM+AEM
Blackchin shiner, *Notropis heterodon*	2.1	1.7	–4.2	–0.7	2.1
Blacknose dace, *Rhinichhthys atratulus*	7.3	1.7	4.8	0.0	–0.2
Blacknose shiner, *Notropis heterolepis*	6.8	3.5	3.5	–0.4	0.5
Bluntnose minnow, *Pimephales notatus*	21.1	1.3	1.6	1.0	1.7
Brassy minnow, *Hybognathus hankinsoni*	2.9	–0.4	3.1	–2.0	1.5
Brook trout, *Salvelinus fontinalis timagamiensis*	15.7	6.4	8.1	–0.3	1.8
Central mudminnow, *Umbra limi*	0.9	0.0	–5.4	3.7	1.6
Chub, *Couesium plumbeus*	–11.2	0.2	–9.6	–1.1	0.1
Common shiner, *Luxilus cornutus*	8.7	0.4	5.5	–0.5	1.2
Creek chub, *Semotilus atromaculatus*	–1.6	1.0	–1.5	0.7	–1.6
Emerald shiner, *Notropis atherinoides*	13.3	2.9	4.4	0.1	0.5
Fathead minnow, *Pimephales promelas*	13.5	0.6	6.4	0.5	0.8
Finescale dace, *Phoxinus neogaeus*	6.4	2.9	1.7	–0.3	0.3
Golden shiner, *Notemigonus crysoleucas*	10.3	3.1	1.9	0.4	–1.0
Lake herring, *Coregonus artedi*	18.7	13.1	4.6	1.1	–0.1
Lake sturgeon, *Acipenser fulvescens*	2.5	–0.3	–0.1	–1.8	1.1
Lake trout, *Salvelinus namaycush*	44.8	27.6	0.1	0.9	–0.9
Lake whitefish, *Coregonus clupeaformis*	26.1	16.4	2.4	1.0	–0.2
Longjaw cisco, *Coregonus alpenae*	22.8	–0.9	–0.3	22.8	0.0
Longnose dace, *Rhinichthys cataractae*	11.9	2.3	3.6	–0.2	0.1
Longnose sucker, *Catostomus catostomus*	3.3	1.6	3.6	–0.9	0.0
Mimic shiner, *Notropis volucellus*	14.9	3.5	2.1	–0.5	0.9
Mooneye, *Hiodon tergisus*	8.7	4.5	–1.4	0.4	1.4
Muskellunge, *Esox masquinongy*	15.5	5.1	6.3	0.8	–0.1
Nipigon cisco, *Coregonus nipigon*	14.5	–0.2	15.5	–1.3	0.6
Northern pike, *Esox lucius*	23.3	3.7	6.9	0.9	–0.5
Northern redbelly dace, *Phoxinus eos*	5.2	6.8	–3.1	–1.1	1.7
Quillback, *Carpiodes cyprinus*	–0.5	–1.2	0.4	–2.3	1.7
Rainbow smelt, *Osmerus mordax*	17.9	0.1	17.1	–1.0	1.4
Rainbow trout, *Oncorhynchus mykiss*	0.3	0.7	0.4	–1.5	1.0
Redside dace, *Clinostomus elongatus*	5.4	1.3	–2.1	–0.3	1.2
Shorthead redhorse, *Moxostoma macrolepidotum*	10.8	7.4	0.5	–0.6	1.3
Silver lamprey, *Ichthyomyzon unicuspis*	1.7	2.2	0.9	–0.6	0.1
Silver redhorse, *Moxostoma anisurum*	7.1	1.3	5.0	–0.4	0.3
Spottail shiner, *Notropis hudsonius*	22.0	2.9	4.8	1.2	0.4
White sucker, *Catostomus commersoni*	5.6	2.2	–0.1	–0.1	0.8

Appendix 7

Adjusted percent variation (R^2) explained for each species in the St. Lawrence and Ottawa Rivers drainage basin by the set of predictor variables (Total = variation explained by all variables; ENV = variation explained by environmental conditions only; PCNM = variation explained by symmetric spatial structure only; AEM = variation explained by asymmetric spatial structure only; PCNM + AEM + ENV = shared variation explained by environmental variables that are symmetrically and asymmetrically structured).

Species	Total	ENV	PCNM	AEM	ENV+PCNM+AEM
Alewife, *Alosa pseudoharengus*	21.2	3.9	2.8	0.8	1.3
American eel, *Anguilla rostrata*	12.2	2.8	–4.7	1.0	1.8
Banded killifish, *Fundulus diaphanus*	3.8	3.4	–12.7	0.9	0.4
Blackchin shiner, *Notropis heterodon*	10.3	2.5	–4.9	0.1	1.3
Black crappie, *Pomoxis nigromaculatus*	34.4	1.7	–2.2	5.4	3.4
Blacknose dace, *Rhinichhthys atratulus*	–18.6	1.5	–19.2	–0.6	0.5
Blacknose shiner, *Notropis heterolepis*	2.5	–0.1	1.2	–0.3	0.9
Bluegill, *Lepomis macrochirus*	40.2	2.9	–7.2	4.5	1.7
Bluntnose minnow, *Pimephales notatus*	8.6	4.1	–3.6	1.5	0.0
Brassy minnow, *Hybognathus hankinsoni*	–6.6	1.1	–7.5	–0.4	0.4
Bridle shiner, *Notropis bifrenatus*	7.3	–0.6	4.8	0.8	0.5
Brook silverside, *Labidesthes sicculus*	27.6	0.9	20.5	0.1	1.2
Brook stickleback, *Culaea inconstans*	15.1	4.5	8.8	0.3	0.6
Brook trout, *Salvelinus fontinalis timagamiensis*	19.8	8.7	2.7	0.0	0.3
Brown bullhead, *Ameiurus nebulosus*	14.2	3.3	–5.3	0.2	–0.1
Burbot, *Lota lota*	23.2	9.1	4.3	0.5	1.7
Central mudminnow, *Umbra limi*	–3.7	2.0	–8.4	0.5	0.4
Channel catfish, *Ictalurus punctatus*	4.4	2.5	1.2	1.2	0.4
Common shiner, *Luxilus cornutus*	17.4	3.7	6.7	0.4	2.0
Creek chub, *Semotilus atromaculatus*	19.2	0.2	3.0	–0.2	0.2
Emerald shiner, *Notropis atherinoides*	7.0	0.2	6.2	0.7	–0.4
Fallfish, *Semotilus corporalis*	6.5	5.9	–3.8	1.6	1.4
Fathead minnow, *Pimephales promelas*	16.9	9.0	3.2	0.9	–0.2
Finescale dace, *Phoxinus neogaeus*	13.3	10.2	–1.4	0.4	1.0
Golden shiner, *Notemigonus crysoleucas*	5.0	2.6	–2.9	0.7	0.0
Iowa darter, *Etheostoma exile*	14.0	4.0	8.7	0.6	–0.3
Johnny darter, *Etheostoma nigrum*	12.7	3.9	6.9	–0.2	0.1
Lake herring, *Coregonus artedi*	32.1	11.5	11.8	0.7	0.1
Lake sturgeon, *Acipenser fulvescens*	–6.4	5.4	–12.9	0.9	1.7
Lake trout, *Salvelinus namaycush*	33.9	20.8	5.2	0.5	–0.2
Lake whitefish, *Coregonus clupeaformis*	30.1	8.8	11.6	–0.4	0.5
Largemouth bass, *Micropterus salmoides*	18.7	6.3	–10.7	2.6	0.4
Logperch, *Percina caprodes*	19.3	5.9	9.9	1.7	–0.2
Longnose dace, *Rhinichthys cataractae*	1.6	–0.5	0.9	0.7	0.2
Longnose gar, *Lepisosteus osseus*	–16.5	2.9	–19.5	–0.2	0.2
Longnose sucker, *Catostomus catostomus*	19.0	1.6	14.7	0.2	–0.1
Mimic shiner, *Notropis volucellus*	3.5	2.3	0.7	0.3	0.7
Mottled sculpin, *Cottus bairdi*	24.0	0.4	22.4	0.1	–0.4
Muskellunge, *Esox masquinongy*	4.4	3.6	–1.0	1.0	0.9
Ninespine stickleback, *Pungitius pungitius*	6.9	1.3	4.4	2.6	–1.4
Northern pike, *Esox lucius*	32.3	7.2	–1.9	1.5	0.7
Northern redbelly dace, *Phoxinus eos*	16.6	12.7	–0.8	–0.3	0.8
Pearl dace, *Margariscus margarita*	13.6	1.6	8.5	0.5	0.0

Pumpkinseed, *Lepomis gibbosus*	21.9	6.5	0.0	1.5	0.2
Rainbow smelt, *Osmerus mordax*	7.8	4.7	2.8	0.0	–0.2
Rainbow trout, *Oncorhynchus mykiss*	–5.6	1.7	–7.5	–0.5	0.1
Redside dace, *Clinostomus elongatus*	20.6	1.2	15.8	0.6	0.5
Rock bass, *Ambloplites rupestris*	25.1	13.5	2.5	1.4	1.0
Rosyface shiner, *Notropis rubellus*	37.7	3.3	30.6	0.7	1.0
Round whitefish, *Prosopium cylindraceum*	5.2	0.4	2.8	0.0	0.4
Sauger, *Sander canadensis*	11.2	1.1	10.4	0.1	–0.4
Shorthead redhorse, *Moxostoma macrolepidotum*	–15.0	1.9	–18.2	1.0	0.4
Silver redhorse, *Moxostoma anisurum*	–20.4	0.2	–20.9	0.0	0.2
Slimy sculpin, *Cottus cognatus*	27.2	0.9	27.0	0.6	–0.7
Smallmouth bass, *Micropterus dolomieu*	17.5	16.0	–4.7	0.9	0.9
Splake, *Salvelinus fontinalis X S. namaycush*	16.1	1.2	13.1	0.4	–0.2
Spottail shiner, *Notropis hudsonius*	2.2	0.9	–2.2	–0.3	0.5
Trout-perch, *Percopsis omiscomaycus*	26.4	0.5	21.8	0.4	0.1
Walleye, *Sander vitreus*	20.9	11.0	–1.3	1.3	0.1
White sucker, *Catostomus commersoni*	9.9	5.7	0.5	0.4	–0.1
Yellow bullhead, *Ameiurus natalis*	–11.4	1.3	–16.0	–0.2	0.3
Yellow perch, *Perca flavescens*	18.1	10.4	3.9	0.2	1.2