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Variation in the catchability of yellow perch (*Perca flavescens*) in the fisheries of Lake Erie using a Bayesian error-in-variable approach

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Catch per unit effort (cpue) from fisheries, and abundance or biomass indices from fishery-independent surveys are often used to infer the dynamics of exploited populations. To do this, cpues and survey indices are usually assumed to be proportional to population size or biomass. Four sources of data on the cpue of yellow perch (*Perca flavescens*) in Lake Erie were available to evaluate this assumption: commercial gillnet and trapnet fisheries, an angling fishery, and a fishery-independent gillnet survey. The relationships between fisheries cpue and population biomass (estimated from an age-structured model), and between fisheries and survey cpues were analysed by error-in-variable (EIV) models because of the absence of independent estimates of population size. Cpues were not proportional to population size, estimated by biomass. Catchabilities varied widely among fisheries (gear types), time period, and areas (management units) within Lake Erie. A spatial EIV model showed that the migrations among management units were considerable. The whole-lake spatial EIV model showed that cpues were not proportional to population size.

Keywords: Bayesian, catchability, error-in-variable, Lake Erie, yellow perch.

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Introduction

The relationship between catch per unit effort (cpue) and population size is commonly assumed to be proportional (Quinn and Deriso, 1999), so catchability, the proportion of a population captured per unit of effort, is independent of population size under this assumption. Several studies have demonstrated non-linear relationships between cpue and population size, implying that catchability is a function of population size. Many factors may influence catchability, in fisheries and in fishery-independent surveys, including spatial and temporal aggregation of fish, non-random search behaviour of fishers, changes in fishing power, gear selectivity, and gear saturation (Paloheimo and Dickie, 1964; Pope and Garrod, 1975; MacCall, 1976; Crecco and Savoy, 1985; Crecco and Overholtz, 1990; Rose and Leggett, 1991). Assuming that catchability is independent of population size, when in fact it is not, may result in a bias in estimates of population size and incorrect inferences regarding population dynamics, which increase the potential for mismanagement of a fishery (Crecco and Overholtz, 1990; Walters and Maguire, 1996; Harley *et al.*, 2001).

Lake Erie is the shallowest and most productive of the Great Lakes, and its fisheries input into local economies amounts to several billion dollars (Leach, 1999). Yellow perch (*Perca flavescens*) is one of the main fisheries in Lake Erie (Ohio Department of Natural Resources, 2005). From west to east, Lake Erie is divided into four management units (MU1–MU4) for yellow perch (Figure 1). All data on the cpue of three yellow perch fisheries (commercial gillnet, commercial trapnet, and sport angling), and partnership indices for fishery-independent gillnet surveys, are collected on the basis of these management units (Figure 2). Here, we refer to the partnership indices for fishery-independent gillnet surveys as survey cpue. The discrepancies in the cpues of the three fisheries and survey

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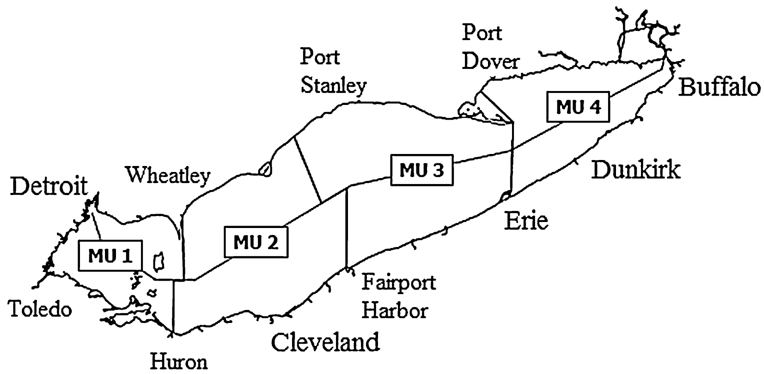

Figure 1. Lake Erie, and the management units for yellow perch fisheries.

cpue over time suggest that some of these series may not be directly proportional to abundance, as assumed in the current statistical catch-at-age model (Myers and Bence, 2001).

When analysing the catchability or the relationship between cpue and population size, one key question is how the form of the relationship between cpue and population size in the absence of independent estimates of population size can be identified. Many stock assessment biologists are well aware that indices based on cpue may not be proportional to population size (or biomass), but in the absence of a method to quantify the bias, assessment biologists fall back on starting with the simplest plausible relationship, i.e. proportionality. The biomass estimates from the age-structured model are not independent of the various cpue indices, because every index was used in fitting the model (which assumes a proportional relationship). Because both cpue and population size were estimated with substantial error, an error-in-variable (EIV) method can be used to analyse the form of the relationship between the two (Richards and Schnute, 1986).

In this study, we use a Bayesian approach to solve the EIV model in analysing the relationship between cpue and population biomass. WinBUGS (Spiegelhalter *et al.*, 2004) was used for the purpose. The idea of the EIV model is to estimate a latent or "true" biomass, then to fit the parameters and all observation errors simultaneously when estimating the relationship between cpue and biomass. The EIV approach helps to answer the question of how to identify the form of the relationship between cpue and

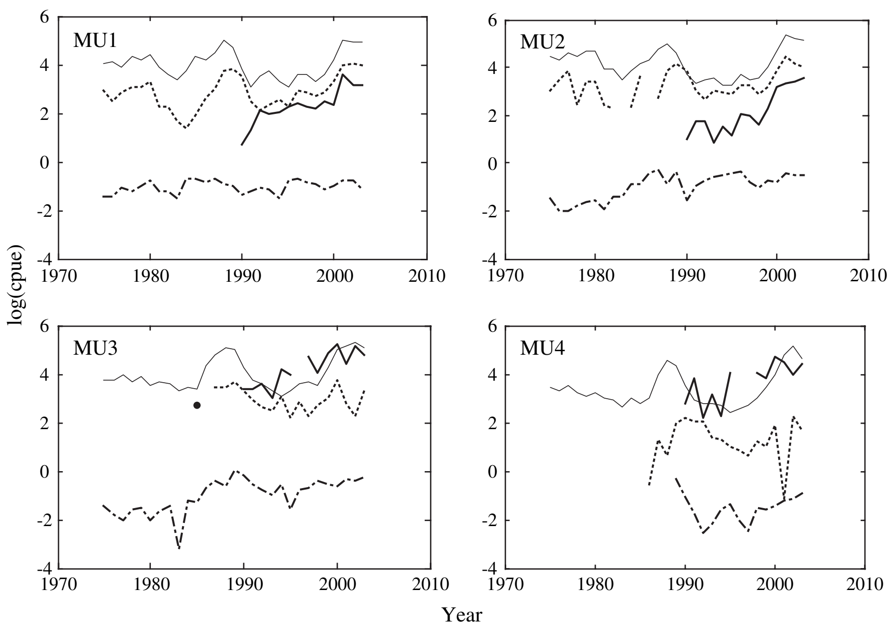

Figure 2. Yellow perch catch rates for age 2+ over time from three fisheries and the survey gillnet fishery cpue (kg km^{-1}; line), the trapnet fishery cpue (kg lift^{-1}; dotted line); the angling fishery cpue (kg h^{-1}; dash–dot line), and survey cpue (thick black line).

population size in the absence of independent estimates of population size. The EIV model was fitted separately to each management area and to each fishing method.

There is mixing of yellow perch among the four management units. A spatial correlation model with error-in-variable was therefore used to analyse the lake-wide relationship between cpue and population biomass. Errors in biomass estimates were correlated across areas, and movement of fish from one area to another produced positive errors in one and negative errors in the other, so making a case that the "stocks" were not well separated. Such correlations were also examined in a Bayesian manner, with biomass estimates from the age-structured model being used as observations, with spatial correlation errors.

Material and methods

Gillnetting is used by the commercial fishing industry in Ontario waters of Lake Erie. Gillnet cpue data extend from 1975 to 2003 in all four management units (Figure 2). Trapnetting gear was employed to a lesser degree. The Ohio trapnet cpue data in MU1 and MU2 extend from 1975 to 2003, in MU3 from 1985 to 2003 (except for 1986), and in MU4 from 1986 to 2003 (Figure 2). The cpue data for the angling fishery extend from 1975 to 2003 in MU1, MU2, and MU3; and from 1989 to 2003 in MU4 (Figure 2). Since 1989, a fishery-independent gillnet survey has been conducted in Ontario waters, with the exception of 1989 in MU1 and MU2, 1996 in MU3, and 1996 and 1997 in MU4 (Figure 2). The survey indices of relative abundance are the fishery-independent Ontario Partnership Index Fishing Survey catch data (Ontario Ministry of Natural Resources, 2000), which we refer to as survey cpue in this article. They were estimated in units of kg set^{-1}, i.e. the total weight (kg) of fish caught divided by the total number of gillnet sets during the survey. The yellow perch stock biomass of the four MUs are from the most recent assessment done by the Lake Erie Committee (LEC), using an age-structured model (Yellow Perch Task Group, 2004). The gillnet and trapnet fisheries and angling fisheries cpues, and the survey cpue were used to tune the population abundance in the age-structured model using a proportional relationship, but with blocked catchabilities based on regulation changes of the yellow perch fisheries and ecosystem changes in Lake Erie (Table 1; Yellow Perch Task Group, 2004).

Several models have been proposed to describe the non-proportional relationship between cpue and biomass (Peterman and Steer, 1981; Bannerot and Austin, 1983; Richards and Schnute, 1986; Arreguín-Sánchez, 1996). Commonly used models include the power model, the logistic model, and the polynomial model. Use of the power model has a long history in modelling the relationship between cpue and biomass (Ultang, 1976; Arreguín-Sánchez, 1996), and is now used widely because of its parsimony (Harley *et al.*, 2001). We chose the power model in this study for that reason. An EIV with a Bayesian approach was used to estimate the parameters of the power model (Gustafson, 2003).

Cpue and catchability

The power model of the relationship between cpue (I) and biomass (B) was

$$I_{g,i,t} = \alpha_{g,i} B_{i,t}^{\beta_{g,i}}, \qquad (1)$$

where g denotes gear type ($g = 1$, 2, 3, and 4, referring to gillnet, trapnet, angling fisheries, and surveys, respectively),

Table 1. Yellow perch time blocks for catchability analysis.

Fishery	MU1	MU2	MU3	MU4
Gillnet fishery	1975–1983	1975–1983	1975–1983	1975–1987
	1984–2005*	1984–2005*	1984–2005*	1988–2005†
Trapnet fishery	1975–1983	1975–1992	1987–1995	1986–1989
	1984–1992‡			
	1993–2005§	1993–2005§	1996–2005§	1990–2005‖
Angling fishery	1975–1983	1975–1983	1975–1983	
	1984–1995¶	1984–1995¶	1984–1995¶	1989–1995
	1996–2005**	1996–2005**	1996–2005**	1996–2005††

*ITQs and minimum mesh size of 57 mm introduced.
†July to August (1988), then to September (1989), 1 km extension of 1 Mile Line to protect smallmouth bass.
‡Spring trapnet restrictions with a 20-cm minimum size limit.
§Spring trapnet restrictions – spring fishery closed until May and minimum size limit for trapnet harvest changed to 22 cm.
‖Water clarity.
¶Bag limit changed from no limit to 50 fish per bag.
**Bag limit changed from 50 to 30 fish per bag.
††New York bag limit changed from no limit to 50 fish per bag.

i indexes the management units, t the years, and α and β are parameters used to model the relationship between I and B. Catchability (q) is the proportion of the population captured per unit of effort, i.e.

$$q_{g,i} = I_{g,i}/B_i = \alpha_{g,i}B_i^{\beta_{g,i}}/B_i = \alpha_{g,i}B_i^{\beta_{g,i}-1}, \tag{2}$$

for gillnet, trapnet, and angling fisheries, and the fishery-independent survey, respectively.

We also explored the catchability of fisheries by analysing the relationship between fisheries cpues and survey cpue. The survey cpue from the fishery-independent survey is expected to be free of many of the biases caused by changes in catchability that affect the commercial fishery (Swain *et al.*, 1994). Yellow perch gillnet surveys were made by the same methods each year; there were no obvious changes in fishing power or efficiency. The relationship between fisheries cpue and survey cpue can be written as

$$I_{g,i,t} = \alpha_{g,i}I_{4,i,t}^{\beta_{g,i}}, \quad g = 1, 2, 3, \tag{3}$$

where α and β are the parameters used to model the relationship between fisheries cpue and survey cpue.

The significance of the relationship between cpue or survey cpue and biomass was assessed. A β value not significantly different from 0 implied a non-significant relationship between cpue or survey cpue and biomass (Equations (1) and (3)). We also investigated evidence for apparent changes in catchability in the gillnet fishery, the trapnet fishery, the angling fishery, and the survey. A β value not significantly different from 1 implied a constant catchability of the fishery relative to the biomass or survey cpue (Equation (2)). A Bayesian error-in-variable approach was used to estimate parameters in the power calibration model in this study.

Error-in-variable (EIV) model

We used EIV models (Gustafson, 2003) to estimate the parameter values of α and β in Equations (1) and (3) because of the absence of an independent estimate of population biomass and measurement error of the biomass and survey cpues.

Lognormal error structure is used for both B and I; Equation (1) can be rewritten as

$$\log_e(I_{g,i,t}) = \log_e(\alpha_{g,i}) + \beta_{g,i}\log_e(\widehat{B}_{i,t}) + \varepsilon_1, \quad g = 1,2,3,4, \; i = 1,2,3,4 \tag{4}$$
$$\log_e(B_{i,t}) = \log_e(\widehat{B}_{i,t}) + \varepsilon_2,$$

where $\log_e(I)$ is the observed cpue, the dependent variable, $\widehat{B}$ in Equation (4) is the true value of biomass, ε_1 is independent of B, has mean 0 and variance $\sigma^2_{\varepsilon_1}$, and B in Equation (4) is the observed value of biomass, ε_2 is independent of B, with mean 0 and variance $\sigma^2_{\varepsilon_2}$. The same modelling approach is used to analyse the relationship between fishery cpue and survey cpue. The Bayesian method was used to estimate $\alpha_{g,i}$, $\beta_{g,i}$, σ_{ε_1}, and σ_{ε_2}. A WinBUGS code for the Bayesian EIV model described above is available upon request.

Error-in-variable with spatial consideration in terms of catchability in the whole lake

In this part of the study, we also analyse the lake-wide cpue and population biomass relationship using a spatially correlated EIV model.

$$\log_e(I_{g,i,t}) = \log_e(\alpha_g) + \beta_g\log_e(\widehat{B}_{i,t}) + \varepsilon_1, \quad g = 1,2,3,4, \; i = 1,2,3,4 \tag{5}$$
$$\log_e(B_{i,t}) = W\log_e(\widehat{B}_{i,t}) + \varepsilon_2,$$

where W is a correlation matrix to show the spatial correlation of biomass among management units. For each time t,

$$W = \begin{bmatrix} b_1 & b_2 & 0 & 0 \\ b_3 & b_4 & b_5 & 0 \\ 0 & b_6 & b_7 & b_8 \\ 0 & 0 & b_9 & b_{10} \end{bmatrix},$$

$$\log_e\left(B_{i=1,2,3,4} = \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \end{bmatrix}\right) = W\log_e\left(\widehat{B}_{i=1,2,3,4} = \begin{bmatrix} \widehat{B}_1 \\ \widehat{B}_2 \\ \widehat{B}_3 \\ \widehat{B}_4 \end{bmatrix}\right) + \varepsilon_2.$$

Correlations between management units that are not connected are assumed to be 0, i.e. there is migration only among units that are connected. The data from the four management units for a specific fishing method were analysed together, i.e. assume α_g and β_g are the same in the whole lake for a specific fishing method. The Bayesian method was used to estimate α_g, β_g, σ_{ε_1}, σ_{ε_2}, and the spatial correlation matrix W. A WinBUGS code for the spatial EIV model described above is available upon request.

Bayesian method and priors

A Bayesian method was used to estimate the parameters in the EIV models. WinBUGS software was used. WinBUGS is a numerically intensive software package that implements general Bayesian models using "Metropolis-Hasting within Gibbs sampling" (Gilks, 1996). Bayesian implementation of these models requires specification of prior distributions on all unobserved quantities. Priors for the models above are listed in Table 2. In general, non-informative priors (here, wide uniform distribution) were used for parameters α_g and β_g; uniform distributions were used for variances $\sigma^2_{\varepsilon_1}$ and $\sigma^2_{\varepsilon_2}$. Uniform prior distributions work better as non-informative priors than inverse-gamma distributions for variance parameters when dealing with multi-level

Table 2. Priors in the error-in-variable and the spatial error-in-variable models.

Model	Parameters	Prior
Error-in-variable	α	Uniform distribution between −8 and 8
	β	Uniform distribution between −1 and 2
	$\sigma^2_{\varepsilon_1}$	Uniform distribution between 0.01 and 20
	$\sigma^2_{\varepsilon_2}$	Uniform distribution between 0.01 and 20
	True B	Based on the normal distribution, and the mean and variance from the observed B
Spatial error-in-variable	α	Uniform distribution between −8 and 8
	β	Uniform distribution between −1 and 2
	$\sigma^2_{\varepsilon_1}$	Uniform distribution between 0.01 and 20
	$\sigma^2_{\varepsilon_2}$	Uniform distribution between 0.01 and 20
	True B	Based on the normal distribution, and the mean and variance from the observed B
	b_s in W	b_1, b_4, b_7, and b_{10} follow uniform distribution between 0.5 and 1; b_2, b_3, b_5, b_6, b_8, and b_9 follow uniform distribution between −0.5 and 0.5

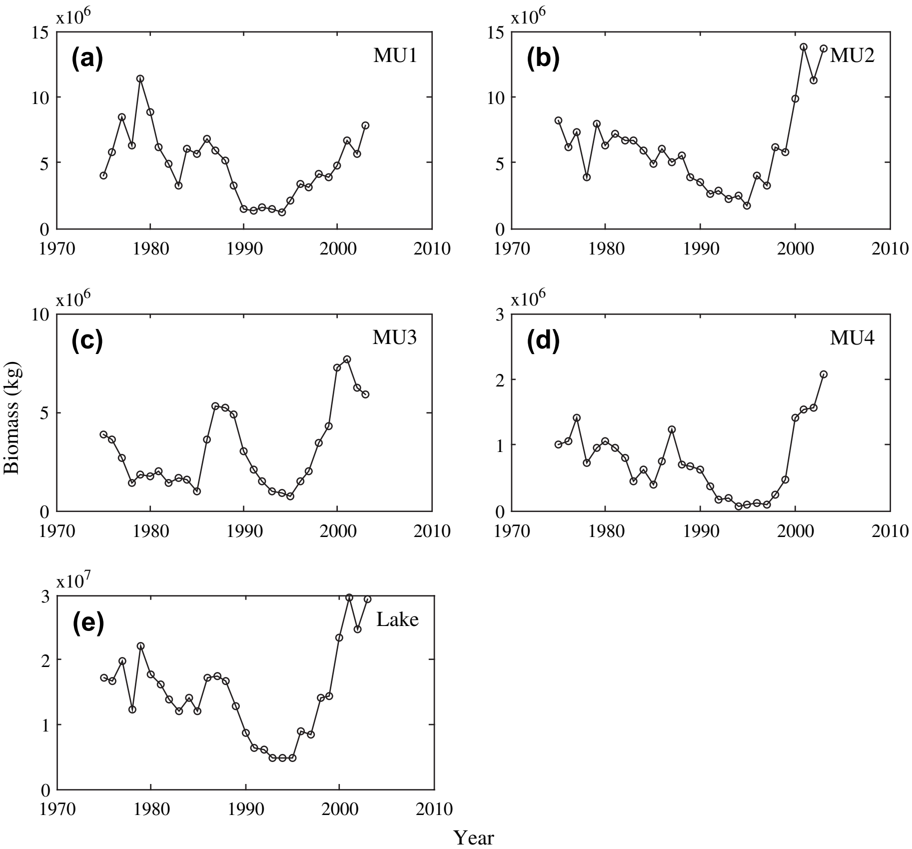

Figure 3. Biomass estimates of the yellow perch fishery for ages 2+ (from Yellow Perch Task Group, 2004). (a) Management unit 1 (MU1); (b) MU2; (c) MU3; (d) MU4; and (e) whole lake.

models (Gelman, 2005). Here, we also chose uniform distribution instead of inverse-gamma. However, we did use inverse-gamma to investigate the sensitivity of the results to inverse-gamma priors. Informative distribution was used for the true biomass, and was based on the observed biomass. Correlations between observed biomass and true biomass from the same unit were set to be between 0.5 and 1, and correlations between observed biomass and true biomass from the neighbouring units to be between −0.5 and 0.5.

To test whether the results are sensitive to the priors, we also did analysis using inverse-gamma IG(0.001,0.001) for variances of $\sigma^2_{\varepsilon_1}$ and $\sigma^2_{\varepsilon_2}$ in the Bayesian EIV model, which is often used as a non-informative prior (Spiegelhalter *et al.*, 2004; Gelman, 2005). For the spatial EIV model, another two sets of priors were used to test the sensitivity to priors. Correlations between observed biomass and true biomass from the same unit were set to be between 0.6 and 1 (or 0.4 and 1), and correlations between observed biomass and true biomass from the neighbouring units to be between −0.5 and 0.6 (or −0.5 and 0.4).

Convergence diagnostics

A critical issue in using MCMC methods is how to determine when random draws have converged to the posterior distribution. Here, three methods were considered: monitor the trace, diagnose autocorrelation plot, and Gelman and Rubin statistics (Spiegelhalter *et al.*, 2004). In this study, three chains were used. After several sets of analysis, for each chain, the first 20 000 iterations with a thinning interval of 10 were discarded, and another 10 000−50 000 iterations were used in the Bayesian EIV model. In the Bayesian spatial EIV model, for each chain, the first 40 000 iterations with a thinning interval of 10 were discarded, and another 20 000−60 000 iterations were used. The final number of the iterations that was used depended on the three diagnostic results.

Results

The gillnet, trapnet, and survey cpues showed similar trends over time in MU1 and MU2; trends diverged in MU3 and MU4 (Figure 2). The angling fishery cpue differed from the other three cpues across all four management units.

Biomass of age 2+ yellow perch as estimated by the Yellow Perch Task Group (2004) in the four management units showed different trends before 1988, but similar trends thereafter (Figure 3). Biomass decreased to a low level in

Table 3. Estimates of the power parameter (β) (posterior median and 95% credible interval) for the relationship of catch per unit effort and biomass (B). β is the value in Equation (1). Median and 95% confidence interval of β estimates are shown.

		MU1			MU2			MU3			MU4		
Cpue	Time blocks*	β	2.5%	97.5%	β	2.5%	97.5%	β	2.5%	97.5%	β	2.5%	97.5%
Gillnet fishery	1975−1983 (MU1, MU2, MU3); 1975−1987 (MU4)	0.40	−0.20	0.76	0.28	−0.22	0.77	0.23	−0.20	0.66	0.61	0.12	0.81
	1984−2003 (MU1, MU2, MU3); 1988−2003 (MU4)	0.41	−0.17	0.87	0.71	0.28	0.79	0.78	0.63	0.82	0.79	0.56	0.89
Trapnet fishery	1975−1983 (MU1); 1975-1992 (MU2); 1987−1995 (MU3)	0.36	−0.29	0.68	0.15	−0.29	0.70	0.57	0.17	0.74			
	1984−1992 (MU1)	0.11	−0.33	0.68									
	1993−2003 (MU1, MU2); 1996−2003 (MU3); 1990−2003 (MU4)	0.60	−0.01	0.73	0.55	−0.20	0.75	0.30	−0.29	0.70	0.08	−0.47	0.66
Angling fishery	1975−1983 (MU1, MU2, MU3)	0.28	−0.40	0.43	−0.05	−0.59	0.39	−0.09	−0.64	0.39			
	1984−1995 (MU1, MU2, MU3); 1989−1995 (MU4)	0.36	0.02	0.46	−0.07	−0.54	0.44	0.37	−0.20	0.49	0.06	−0.68	0.49
	1996−2003 (MU1, MU2, MU3)	−0.03	−0.52	0.41	0.07	−0.51	0.46	0.22	−0.26	0.46	0.36	−0.37	0.48
Gillnet fishery	When all data are used	0.64	0.28	0.78	0.71	0.36	0.79	0.77	0.62	0.82	0.67	0.38	0.85
Trapnet fishery		0.36	−0.19	0.69	0.52	−0.12	0.73	0.45	0.08	0.71	−0.03	−0.47	0.58
Angling fishery		0.25	0.02	0.44	−0.16	−0.57	0.39	0.34	−0.07	0.47	0.33	−0.03	0.49
Survey		0.58	0.05	0.69	0.51	0.03	0.66	0.57	0.04	0.81	0.59	0.04	0.87

*See Table 1 for explanation of time blocks.

Table 4. Estimates of the power parameter (β) (posterior median and 95% credible interval) for the relationship between cpue for three fisheries of yellow perch in Lake Erie and survey cpue. β is the value in Equation (3). See Table 1 for the explanation of other parameters and estimates in the table.

		MU1			MU2			MU3			MU4		
Cpue	Time blocks	β	2.5%	97.5%	β	2.5%	97.5%	β	2.5%	97.5%	β	2.5%	97.5%
Gillnet fishery	1990–2003	0.84	0.18	1.48	0.84	0.55	1.18	0.91	0.06	1.68	0.77	−0.23	1.63
Trapnet fishery	1990–1995 (MU3)							0.10	−0.90	1.67			
	1996–2003 (MU3)							0.26	−0.87	1.59			
	1993–2003 (MU1, MU2); 1990–2003 (MU3, MU4)	1.16	0.56	1.72	0.61	0.34	0.93	0.11	−0.63	0.82	−0.35	−0.95	0.77
Angling fishery	1990–1995	0.22	−0.77	1.36	0.14	−0.89	1.6	0.01	−0.94	1.59	0.29	−0.87	1.56
	1996–2003	0.04	−0.48	0.56	0.17	−0.42	0.67	−0.09	−0.69	0.63	0.13	−0.78	1.18
	1990–2003	0.26	0.01	0.44	0.34	−0.28	0.72	0.53	−0.52	1.20	0.54	−0.18	1.03

the mid-1990s in all management units, then increased quickly until 2001. Trends in estimated biomass in MU2, MU4, and lake-wide were generally similar over time, declining from the 1970s to a very low level in the mid-1990s. Biomass in MU1 peaked in 1979, and biomass in MU3 decreased and remained low from the late 1970s to the mid-1980s, a trend different from that in MU2 and MU4. By 2001, the estimated biomass of yellow perch in MU2 and MU4 was greater than the greatest biomass previously recorded.

Estimated power parameters (β) were significantly smaller than 1 (Table 3). Estimated β values were significantly different from 0 when the long time period (1975–2003) data were used in the gillnet fishery cpue and survey cpue, in the trapnet fishery cpue in MU3, and in the angling fishery cpue in MU1. Most of the fishery and survey cpue analyses resulted in non-significant relationships between cpue and biomass, when the blocked data were used. Obviously, the shortness of the time period is a likely reason.

Angling fishery cpue resulted in β values far from 1 in almost all MUs and time periods, which implied that it is not a good indicator of population biomass (Table 3). The gillnet fishery, the trapnet fishery, and the survey cpues

Table 5. Estimates of the power parameter (β) (posterior median) for the relationship between catch per unit effort (cpue, both fisheries of yellow perch in Lake Erie and survey) and biomass, and the relationship between cpue of three fisheries and survey cpue when the data from all four management units were considered, and catchability in the whole lake was considered as the same. β is the value in Equation (5). See Table 2 for explanation of the other parameters and estimates in the table. t1, 1975–1983; t2, 1984–2003; t3, 1975–2003; t4, 1984–1992; t5, 1993–2003; t6, 1984–1995; t7, 1996–2003; t8, 1990–2003; t9, 1990–1995.

	$I_g \sim B$			$I_{tr} \sim B$				$I_a \sim B$				$I_s \sim B$	$I_g \sim I_s$	$I_{tr} \sim I_s$	$I_a \sim I_s$		
Parameters	t1	t2	t3	t1	t4	t5	t3	t1	t6	t7	t3	t8	t8	t5	t9	t7	t8
β	**0.52**	**0.51**	**0.49**	0.48	**0.53**	**0.63**	**0.59**	**0.27**	**0.31**	**0.36**	**0.23**	0.00	*0.88*	−0.23	−0.04	0.12	0.06
b_1	0.63	0.58	0.59	0.66	0.64	0.59	0.59	0.67	0.61	0.61	0.60	0.56	0.75	0.72	0.70	0.78	0.67
b_2	0.43	0.45	0.45	0.40	0.39	0.44	0.45	0.40	0.41	0.43	0.44	0.45	0.46	0.41	0.17	0.41	0.41
b_3	0.33	0.34	0.35	0.27	0.32	0.32	0.35	0.29	0.31	0.26	0.34	0.24	0.42	0.23	−0.06	0.31	0.27
b_4	0.58	0.55	0.54	0.60	0.58	0.57	0.54	0.60	0.55	0.59	0.55	0.55	0.60	0.79	0.64	0.75	0.75
b_5	0.15	0.14	0.15	0.17	0.13	0.15	0.15	0.16	0.15	0.21	0.16	0.25	0.27	0.03	0.04	0.19	0.00
b_6	0.07	0.14	0.20	0.08	0.05	0.19	0.21	0.06	0.06	0.29	0.18	0.32	0.42	0.41	0.37	0.41	0.42
b_7	0.60	0.55	0.59	0.67	0.69	0.57	0.58	0.65	0.60	0.61	0.59	0.55	0.73	0.90	0.85	0.90	0.90
b_8	0.31	0.29	0.20	0.23	0.28	0.22	0.19	0.27	0.32	0.13	0.21	0.12	0.35	0.43	0.36	0.43	0.43
b_9	0.36	0.16	0.17	0.34	0.30	0.12	0.17	0.34	0.22	0.11	0.14	0.15	0.40	0.46	0.37	0.42	0.45
b_{10}	0.57	0.73	0.73	0.59	0.60	0.76	0.74	0.59	0.65	0.80	0.76	0.73	0.83	0.96	0.89	0.94	0.96

I_g, cpue of gillnet fishery; I_{tr}, cpue of trapnet fishery; I_a, cpue of angling fishery; and I_s, survey cpue; B, biomass.
The fonts of the β estimates show whether it is significantly different from 0 and/or 1. α of 0.05 is used. Bold, β significantly larger than 0 and smaller than 1; italics, β significantly larger than 0 but not significantly different from 1; underlined, β not significantly different from 0 but significantly smaller than 1; and regular font, β not significantly different from both 0 and 1.

Table 6. Estimates of the power parameter (β) (posterior median) for the relationship between catch per unit effort and biomass (B) or cpue for the three fisheries of yellow perch in Lake Erie and survey cpue. All data from 1975 to 2003 available are used. Priors of inverse-gamma IG(0.001,0.001) for variances of σ_{ε_1} and σ_{ε_2} were used in the Bayesian EIV model.

	MU1			MU2			MU3			MU4		
Cpue	β	2.5%	97.5%	β	2.5%	97.5%	β	2.5%	97.5%	β	2.5%	97.5%
$I_g \sim B$	0.61	0.32	0.78	0.73	0.50	0.79	0.77	0.63	0.82	0.62	0.37	0.84
$I_{tr} \sim B$	0.32	−0.14	0.67	0.54	0.01	0.73	0.42	0.10	0.71	−0.02	−0.46	0.51
$I_a \sim B$	0.33	−0.15	0.68	−0.22	−0.57	0.38	0.36	0.02	0.47	0.33	0.04	0.49
$I_s \sim B$	0.60	0.27	0.69	0.55	0.06	0.66	0.58	0.07	0.81	0.59	0.13	0.88
$I_g \sim I_s$	0.85	0.30	1.45	0.66	0.21	1.21	0.94	0.24	1.76	0.79	0.03	1.69
$I_{tr} \sim I_s$*	1.21	0.83	1.66	0.61	0.41	0.84	0.17	−0.39	0.93	−0.05	−0.88	1.49
$I_a \sim I_s$	0.26	0.05	0.53	0.18	−0.06	0.52	0.16	−0.24	0.81	0.42	0.05	0.86

*1993−2003 (MU1, MU2); 1990−2003 (MU3, MU4).

resulted in higher β values, although they were still significantly smaller than 1.

The relationships between fisheries cpues and survey cpue were quite different in the various fisheries (Table 4). The β values from the gillnet fishery and trapnet fishery in MU1 and MU2 were high and were close to 1. The β values from the angling fishery and the trapnet fishery in MU3 and MU4 were small; most of them were not significantly different from 0 (Table 4).

When the whole-lake gillnet and trapnet and angling cpues were functions of the biomass, each resulted in β values significantly different from 1 (Table 5). The results when fisheries cpues were used were similar to those when each unit was analysed separately. The results when survey cpue was used were quite different. The resulting β values were smaller or even negative, the diagonal values in the correlation matrix were higher, and other b values in the correlation matrix were smaller than those when fishery cpues and biomass were analysed. The results using survey cpue in the spatial EIV model implied less migration among management units. In general, the results from the spatial EIV model suggest that migrations among MUs are considerable. When the whole-lake gillnet cpue was a function of survey cpue, the β value was significantly larger than 0, but it was not significantly different from 1. The whole-lake trapnet and angling fishery cpues resulted in β values not significantly different from 0 (Table 5). Surprisingly, the relationship between whole-lake survey cpue and biomass was not significant.

The analysis indicated that estimated β values and their confidence intervals were robust to priors of variances of $\sigma^2_{\varepsilon_1}$ and $\sigma^2_{\varepsilon_2}$ in the Bayesian EIV model when uniform distribution and inverse-gamma distribution were used, although their left tails seemed to be influenced by the priors (Table 6). The estimated β values were robust to

Table 7. Estimates of power parameter (β) (posterior median) under different prior conditions of b_s in W: C1 (b_1, b_4, b_7, and b_{10} follow uniform distribution between 0.4 and 1; b_2, b_3, b_5, b_6, b_8, and b_9 follow a uniform distribution between −0.5 and 0.4); C2 (b_1, b_4, b_7, and b_{10} follow a uniform distribution between 0.6 and 1; b_2, b_3, b_5, b_6, b_8, and b_9 follow a uniform distribution between −0.5 and 0.6); see Tables 2 and 5 for an explanation of the other parameters and estimates in the table, and the time blocks.

	$I_g \sim B$ (t3)		$I_{tr} \sim B$ (t3)		$I_a \sim B$ (t3)		$I_s \sim B$ (t8)		$I_g \sim I_s$ (t8)		$I_{tr} \sim I_s$ (t5)		$I_a \sim I_s$ (t8)	
Parameters	C1	C2	C1	C2	C1	C2	C1	C2	C1	C2	C1	C2	C1	C2
β	0.49	0.49	0.59	0.58	0.23	0.23	0.00	0.00	0.82	0.85	−0.23	−0.23	0.06	0.05
b_1	0.67	0.62	0.67	0.62	0.60	0.63	0.57	0.64	0.76	0.74	0.78	0.73	0.67	0.70
b_2	0.37	0.42	0.37	0.41	0.44	0.41	0.45	0.38	0.36	0.53	0.33	0.45	0.41	0.42
b_3	0.37	0.32	0.36	0.32	0.34	0.31	0.25	0.40	0.33	0.46	0.18	0.31	0.27	0.34
b_4	0.49	0.62	0.48	0.62	0.55	0.62	0.55	0.64	0.60	0.69	0.75	0.82	0.75	0.78
b_5	0.21	0.11	0.21	0.11	0.16	0.12	0.25	−0.01	0.27	0.19	0.10	−0.03	0.00	−0.06
b_6	0.16	0.17	0.21	0.21	0.18	0.17	0.33	0.04	0.35	0.46	0.34	0.46	0.42	0.47
b_7	0.63	0.64	0.61	0.64	0.59	0.64	0.55	0.64	0.82	0.76	0.94	0.87	0.90	0.87
b_8	0.21	0.17	0.18	0.13	0.22	0.17	0.11	0.30	0.33	0.39	0.36	0.49	0.43	0.49
b_9	0.17	0.17	0.18	0.19	0.14	0.18	0.17	0.13	0.33	0.47	0.37	0.55	0.45	0.54
b_{10}	0.74	0.73	0.72	0.71	0.77	0.73	0.71	0.75	0.89	0.86	0.97	0.96	0.96	0.95

the priors of variances of b_s in the spatial correlation matrix W (Table 7). This was also true for most estimates of b_s. The b_s estimates tended to be more sensitive than the other b_s in the correlation matrix W.

Discussion

For yellow perch fisheries in most management units in Lake Erie, the relationship between cpue and biomass is not proportional, and catchability is not independent of population biomass. The gillnet and trapnet fisheries cpues and the survey cpue were mostly correlated with the estimated population biomass, although in some time periods and some management units, the resulting β values were smaller when trapnet cpue was used.

The angling fishery cpue was not a good indicator of population biomass based on the estimated β values and their significance levels. The angling fishery can be substantially influenced by yellow perch population biomass, prey abundance, weather, and economic factors, such as fuel prices. An increase in stock size is followed by an increase in angler effort and the entry of less experienced, less efficient anglers into the fishery (M.L. Jones, Michigan State University, pers. comm.). The opposite is thought to occur when there is a decrease in stock size and the proportion of experienced, more efficient anglers increases. Selection of fish based on size by anglers may worsen the relationships between angling cpue and estimated population size or survey indices. It may be prudent to use angling harvest data only to reflect estimates of the components of the population removed to project the following year's population size, and to place less emphasis on the relationships between angling and effort to estimate population size in catch-at-age modelling. Further studies on angling catchability, fishing effort, and their relationship to population abundance, economics, and the sampling method are suggested.

The survey cpue examined here was represented exclusively by fishing within Ontario waters, in contrast to sport and trapnet data, which were exclusively from American waters. Some lack of proportionality could be attributed to perch densities that differ between waters from which the gillnet index was deduced vs. those in which sport and trapnet fisheries operated. Both the influence of environmental changes on the catchability of different fishing methods and fishing areas, and the short data series are reasons for the lack of correlation between fishery cpues and survey cpue. Here, water clarity changes because of the invasion of zebra mussel (*Dreissena polymorpha*) are most likely the main reason for the environmental changes during this time period.

Based on our findings, no proportionality exists between cpue and biomass. Power models are suggested for use in tuning population models. Closer examination of the estimates of variation with respect to gear-related catchability is now essential in assessing the goodness-of-fit, and in tuning the population biomass and stock assessment of yellow perch fisheries in Lake Erie.

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