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ARTICLE

Gill-Net Saturation in Lake Erie: Effects of Soak Time and Fish Accumulation on Catch per Unit Effort of Walleye and Yellow Perch

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Abstract
Gill-net saturation was analyzed through a delta model (i.e., two-stage model) by examining the effects of soak time and fish accumulation (number of fish of all species enmeshed per square meter of a given gill net, including the species of interest) on catch per unit effort (CPUE) of walleyes *Sander vitreus* and yellow perch *Perca flavescens* in Lake Erie. The analysis was based on fishery-independent survey data for 1989–2003. In the delta model, the positive values of CPUE were estimated by a generalized additive model (GAM) assuming a log-gamma distribution, and the probability of obtaining nonzero values of CPUE was estimated by a GAM assuming a binomial distribution. Soak time and fish accumulation had significant effects on CPUE. The CPUE of walleyes decreased in gill nets soaked for 10 h and started to decline when fish accumulation was around 2 fish/m^2. We did not observe a substantial decline in the CPUE of yellow perch within the soak time interval we examined, but we did observe a decline when fish accumulation was 6–8 fish/m^2. The decline in CPUE with increasing soak time for walleyes and with increasing fish accumulation levels for both walleyes and yellow perch indicates that gill-net saturation did exist in Lake Erie gill-net surveys for these two species and that the gill nets were saturated faster by walleyes than by yellow perch. We suggest that gill-net saturation be considered when applying CPUE from gill-net surveys to stock assessment and that the generalized linear additive-based modeling approach be considered as an alternative in gill-net saturation analyses.

Gill nets are typically size- or species-selective fishing gears (Hamley 1975; Akiyama et al. 2007), which have been widely used in Great Lakes commercial fisheries and fishery surveys (Hansen et al. 1998; Kinnunen 2003). The efficiency of gill nets can be influenced by both technical and biological factors, including mesh size, net length, soak time, set and lift time, fish abundance, and fish morphology and behaviors, as well as gear saturation (Kennedy 1951; Beverton and Holt 1957; Minns and Hurley 1988; Jensen 1990; Hansen et al. 1998).

Gill-net saturation, often observed as a reduction in catch rate (Hansen et al. 1998; Rotherham et al. 2006) or catchability (Olin et al. 2004), is directly caused by space limitation (Minns and Hurley 1988; Hansen et al. 1998) and avoidance effect (Hamley 1975). As soak time increases, there will be more fish enmeshed in a net and fewer unoccupied spaces left. Meanwhile, the approaching fish can sense and avoid nets because of those dead or struggling fish already caught (Kennedy 1951).

Catch per unit effort (CPUE), used as an index of fish abundance, plays an important role in ecological analyses (Tonn et al. 1990; Jeppesen et al. 2000) and fish stock assessments (Gunderson 1993; Helser and Hayes 1995; Maunder and Punt 2004). However, gill-net saturation encountered in fishery surveys

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reduces the accuracy and reliability of CPUE estimates, which may increase the probability of underestimating the real population size and may result in under-exploitation of a fish stock (Beverton and Holt 1957; Olin et al. 2004; Rotherham et al. 2006).

Due to the importance of CPUE in the fish stock assessment and the potential bias in CPUE estimates caused by gill-net saturation in sampling procedures, some experimental studies have been conducted to assess the effects of soak time, number of fish enmeshed, set or lift time (or both), and net length on catch rate, catchability, catch composition, species richness, and fish length distribution (Kennedy 1951; Beverton and Holt 1957; Minns and Hurley 1988; Yatsu et al. 1995; Hansen et al. 1998; Olin et al. 2004; Rotherham et al. 2006; Akiyama et al. 2007). Variance analyses (Rotherham et al. 2006), logistic models (Hansen et al. 1998), exponential models (Minns and Hurley 1988), and segmented nonlinear models (Olin et al. 2004) have been applied in previous studies to examine gear saturation. Most studies reported a reduction in catch rate or catchability when soak time increased, and some studies developed approaches to correct CPUE estimates by taking gear saturation into account (Kennedy 1951; Hansen et al. 1998; Dauk and Schwarz 2001).

Catch rates need to be standardized before used in the fish stock assessment. There are many factors that may affect CPUE. We are interested in soak time and fish accumulation because (1) these are the only two variables associated with gear saturation and available in this study, and (2) these two variables are often ignored in fishery surveys and CPUE standardization. This does not mean that we should ignore the other factors when we investigate gear saturation. Instead, we need to consider all the possible factors when we standardize catch rates (Lo et al. 1992; Maunder and Punt 2004). Examining the effects of soak time and fish accumulation on catch rates may help us recognize the existence of gear saturation and determine appropriate approaches to deal with it, and, at the same time, encourage scientists in this field to realize the importance of considering gear saturation when standardizing catch rates. We considered all available variables (including fish accumulation and soak time) when developing models in order to construct models with the best predictive power. We first considered all available variables in model building, and then through catch rate standardization we extracted the effects of soak time and fish accumulation on CPUE, which are of specific interest in this study (Maunder and Punt 2004).

This study focused on two major commercial and recreational fish species in Lake Erie, walleye *Sander vitreus* and yellow perch *Perca flavescens*. Data were collected by a fishery-independent gill-net survey (i.e., a fishery survey undertaken independently of commercial or recreational fishing activities), the Lake Erie Partnership Index Fishing Survey (PIS), which has been conducted by the Ontario Ministry of Natural Resources and the Ontario Commercial Fisheries' Association (OCFA) since 1989. The PIS survey has been carried out annually across the Ontario waters of Lake Erie and follows a stratified random sampling scheme using commercial fishing vessels, commercial fishing crews, and experimental gill nets (OCFA 2007).

The PIS data contained a high percentage of zero observations (83%), which invalidated the commonly used assumption of normality in fisheries studies. Elimination of a high percentage of zero observations may result in a loss of information about temporal and spatial distribution characteristics of a fish stock. In earlier studies that addressed the problem of analyzing data with a high percentage of zero observations, Aitchison and Brown (1957) proposed a distribution, named the "delta distribution," to describe a random variable that has a nonzero probability of being equal to zero and whose conditional distribution of nonzero values is some well-known distribution. Pennington (1983) detailed the estimator based on the delta distribution and applied the delta distribution to a fish–plankton survey. Lo et al. (1992) applied the delta distribution in fishery data analyses and called the model the "delta-lognormal model" since he assumed positive values to follow a lognormal distribution. Stefansson (1996) extended the delta-lognormal model to the "delta-gamma model" by assuming positive values to follow a gamma distribution after log-transformation. In fishery studies, the models developed by applying the delta distribution to a generalized linear- or additive-based modeling approach have been widely used to deal with fishery data having a high percentage of zero observations and are generally called the "delta model" or the "two-stage model" (Aitchison 1955; Aitchison and Brown 1957; Pennington 1983; Lo et al. 1992; Pennington 1996; Stefansson 1996; Ortiz et al. 2000; Ye et al. 2001; Maunder and Punt 2004; Murray 2004; Fletcher et al. 2005). In this study, we developed the delta model to investigate possible gear saturation issues in gill-net surveys because of the high percentage of zeros in the PIS data.

In this study, CPUE of walleyes and yellow perch was analyzed to detect gill-net saturation in the PIS survey for these two species, given increased soak time and fish accumulation levels (number of fish of all species enmeshed per square meter of a given gill net, including the species of interest). We aimed to (1) examine the effects of soak time and fish accumulation on CPUE of walleyes and yellow perch in the PIS survey, (2) provide a generalized linear- or additive-based modeling approach (i.e., the delta model with two generalized additive models as an alternative to examine the existence of gear saturation in fishery surveys, especially when the percentage of zero observations in the data are high).

METHODS

Data.—The PIS data from 1989 to 2003 were provided by OCFA. In this survey, gill nets with 14 mesh sizes, ranging from 32 to 152 mm, were set at sites distributed across the Ontario waters of Lake Erie for 10–36 h in the fall (August to November) annually. Catch in weight, species, environmental factors, and fishing factors were recorded. Data from 34,862 gill-net sets

TABLE 1. List of explanatory variables available for analyses. Data were taken from the Lake Erie Partnership Index Fishing Survey for the period 1989–2003.

Predictor variable	Type	Mean	Range
Soak time (h)	Continuous	22.2	9.5–35.9
Fish accumulation[a] (number/m^2)	Continuous	0.5	0–10.0
Mesh size (mm)	Continuous	82.5	32–152
Site depth (m)	Continuous	21.0	3.3–65.5
Gear depth[b] (m)	Continuous	14.4	0.9–65.2
Secchi depth (m)	Continuous	3.3	0.2–11.0
Gear temperature[c] (°C)	Continuous	16.8°C	2.7–26.2°C
Dissolved oxygen mg/L)	Continuous	8.8	0.2–21.4
Site temperature[d] (°C)	Continuous	18.2	1.8–24.9
Longitude	Continuous	81.1°W	0–83.1°W
Latitude	Continuous	42.3°N	0–42.9°N
Basin	Categorical	West, west-central, east-central, east, Pennsylvania Ridge	
Year	Categorical	1989–2008	
Month	Categorical	August–November	
Gear type[e]	Categorical	Canned or bottomed	

[a]Number of fish of all species enmeshed per square meter of a given gill net, including the species of interest.
[b]Water depth at which the gill net was set.
[c]Water temperature at the depth at which the gill net was set.
[d]Water temperature at the surface.
[e]Canned nets are suspended in the water, bottomed nets on the bottom.

were available for both walleyes and yellow perch. The CPUE was expressed as catch (kg) per hour in per kilometer of gill net (kg/[h·km]).

Besides soak time and fish accumulation, 13 explanatory variables were available for analyses (Table 1), including nine continuous variables (i.e., mesh size, site depth, gear depth, Secchi depth, gear temperature, dissolved oxygen, site temperature, longitude, and latitude) and four categorical variables (i.e., basin, year, month, and gear type).

Model building.—A delta model was developed because the PIS data for both walleyes and yellow perch contained around 83% of zero observations (Lo et al. 1992). The delta model handles data in two steps by applying two submodels: one submodel to estimate the CPUE with only positive values of CPUE analyzed, and the other submodel to estimate probability of obtaining nonzero values of CPUE. Estimates of CPUE from a delta model can be obtained by multiplying the estimates from these two submodels (Lo et al. 1992; Pennington 1996; Stefansson 1996; Ortiz et al. 2000; Ye et al. 2001; Maunder and Punt 2004; Murray 2004; Fletcher et al. 2005):

$$\text{CPUE} = d \times p,$$

where d is the estimate of positive values of CPUE and p is the estimate of the probability of obtaining nonzero values of CPUE.

We considered all available variables (Table 1), including fish accumulation and soak time, when developing models. We first considered all available variables in model building and then extracted the effects of soak time and fish accumulation on CPUE, which are of specific interest in this study. When we extract the effect of soak time or fish accumulation, we fixed the values of the other explanatory variables to their means (for continuous variables) or weighted means (for categorical variables), and varied the values of soak time or fish accumulation as they were recorded in the PIS data (Maunder and Punt 2004).

Positive values of CPUE d were analyzed by a generalized additive model (GAM), in which the effect of each variable can be modeled by a smooth function (Hastie and Tibshirani 1990):

$$\log_e(\hat{d}) = \alpha + h_1(T) + h_2(F) + \sum_{j=1} H_j(x_j),$$

where α is the intercept, T is the soak time, F is the fish accumulation, h and H are smoothing functions (a spline), and x_j is the jth explanatory variable besides soak time and fish accumulation.

In the GAM by which positive values of CPUE were analyzed, the error structure was determined between lognormal distribution and log-gamma distribution by comparing their corresponding Akaike information criterion (AIC) values and Akaike weights (w_i), which are defined as follows (Akaike 1974; Burnham and Anderson 2002; Damalas et al. 2007):

$$AIC = -2\log_e[L(\theta/y)] + 2k,$$

and

$$w_i = \frac{\exp(-0.5\Delta_i)}{\sum_{r=1}^{R}\exp(-0.5\Delta_i)},$$

where $\log_e[L(\theta|y)]$ is the numerical value of the maximum log likelihood, k is the number of parameters in the model, R is the number of candidate models, and Δ_i is the difference between the AIC value of the ith model and the smallest AIC value among all candidate models. The same set of explanatory variables was used for each error structure for the purpose of comparison and consistency (Damalas et al. 2007). The model with a smaller AIC value and a higher Akaike weight (i.e., close to 1) was considered to fit the data better.

To estimate probability of obtaining nonzero values of CPUE ($\dot{p}$), values of 0 (no target fish caught) or 1 (at least one target fish caught) were assumed to be independent observations from a binary variable with a probability of success (at least one fish caught) p, which was estimated by assuming a binomial distribution with a logit link function, namely,

$$E(p) = v^{-1}(\eta);$$
$$\eta = \alpha' + g_1(T) + g_2(F) + \sum_{j=1} G_j(x_j),$$

where $E(p)$ is the expectation of p, v is the logit link function, α‘ is the intercept, T and F are soak time and fish accumulation, g and G are smooth functions, and x_j is the jth explanatory variable other than soak time and fish accumulation.

Variable selection.—Correlation coefficients among all explanatory variables were calculated to detect highly correlated variables. A preliminary variable selection was conducted to eliminate one variable from each pair of the highly correlated ones that were detected in the correlation analysis. The variable that had a less significant effect on response variable and yielded a larger AIC value was eliminated from the correlated pair. The variance inflation factor (VIF) of each explanatory variable was calculated to detect those variables that may cause multicollinearity problems. The variable with a VIF value greater than 10 was eliminated because of its multicollinearity with the remaining variables (Marquardt 1970; Mason et al. 1989; Neter et al. 1989; Chatterjee et al. 2000). The remaining variables were selected by both the stepwise approach and the best subset approach based on AIC and statistical test (Akaike 1974; Burnham and Anderson 2002). In the stepwise selection procedure, the variable that reduced the AIC value and showed the most significant effect on the response variable was selected from the remaining variables at each step, and we repeated this step until all the variables that were left showed insignificant effects and the AIC value stopped decreasing. The best subset approach selected the best combination of variables by examining all possible combinations (Miller 1990; Farkas and Heberger 2005).

Biologically important interaction terms were tested in models, including soak time/mesh size/basin/year/month/gear and fish accumulation, and gear depth and dissolved oxygen. Because of their insignificance in explaining the variance of the PIS data, their high correlations, or both with each other and with fish accumulation that was the variable of our interest in this study, we did not include these interaction terms in the following analyses (Maunder and Punt 2004; Damalas et al. 2007).

Comparison with linear model analyses.—To test the superiority of nonlinear model analysis (GAM) compared with linear model analysis, the PIS data for each species were also fitted by two candidate linear models: a delta model comprising two generalized linear models (GLMs), and a delta model comprising two GLMs with polynomial terms up to degree 3 (GLM-Poly). In each candidate model, the two GLM models and the two GLM-Poly models were constructed by selecting explanatory variables to fit the PIS data best, and by assuming the same error structures as the two GAM models we employed in this study (i.e., log-gamma distribution for estimating positive values of CPUE, and binomial distribution for estimating probability of obtaining nonzero values of CPUE). The performances of these two candidate linear models and the delta model with two GAMs were compared based on AIC values and Akaike weights.

RESULTS

Analysis of correlation coefficients among all explanatory variables detected high correlations between site temperature and month (–0.82), longitude and latitude (–0.81), longitude and basin (–0.82), and latitude and basin (0.86) for both walleyes and yellow perch. The preliminary variable selection revealed that the model including month or basin yielded smaller AIC values than the model including site temperature or longitude and latitude. In addition, longitude and latitude had VIF values greater than 10, indicating their high multicollinearity with the remaining variables. Thus, these three variables (i.e., site temperature, longitude, and latitude) were eliminated before variable selection.

Comparisons of AIC values between the model with an assumption of lognormal distribution and the one with an assumption of log-gamma distribution suggested a log-gamma distribution as the best approximation of the error structure for a GAM to model positive values of CPUE (Table 2). In the variable selection, because both the stepwise approach and the best subset approach selected the same combination of variables, we presented the selected variables from the stepwise approach here (Tables 3, 4). The final delta model explained 45% and 69% of the variance of the PIS data when analyzing positive values of CPUE for walleyes and yellow perch, respectively, and 21% and 63% when estimating probability of obtaining nonzero values of CPUE for walleyes and yellow perch, respectively.

Soak time and fish accumulation significantly affected catch rates of walleyes and yellow perch ($p << 0.01$; Tables 3, 4). Fish accumulation had the foremost effect on catch rates of yellow perch, yielding almost 52% and 33% reduction in the deviance when modeling positive values of CPUE and when estimating probability of nonzero values of CPUE, respectively.

TABLE 2. Akaike information criterion (AIC) values and Akaike weights (w_i) for the generalized additive models employing lognormal and log-gamma distributions in the estimation of positive values of CPUE.

Error structure	AIC	Δ_i	w_i
	Walleyes		
Lognormal	108,196	7,189	0
Log-gamma	101,007	0	1
	Yellow perch		
Lognormal	167,854	15,591	0
Log-gamma	152,263	0	1

TABLE 3. Stepwise construction of a generalized additive model to estimate positive values of CPUE. A log-gamma distribution was assumed.

	Variables selected for model	df	Deviance	AIC	P	Deviance decrement	Cumulative% of deviance explained
				Walleyes			
0	Null		5, 750	104, 516			
1	f (mesh size)	1	4, 349	102, 804	$< 2.2 \times 10^{-16}$	1, 401	24.4
2	Basin	5	4, 009	102, 322	$< 2.2 \times 10^{-16}$	340	30.3
3	Year	14	3, 772	101, 904	$< 2.2 \times 10^{-16}$	288	35.3
4	Gear	1	3, 618	101, 738	$< 2.2 \times 10^{-16}$	103	37.1
5	f (soak time)	1	3, 559	101, 647	2.7×10^{-10}	60	38.1
6	f (fish accumulation)	1	3, 203	101, 032	3.9×10^{-4}	355	44.3
7	Month	3	3, 187	101, 007	2.9×10^{-2}	17	44.6
				Yellow perch			
0	Null		16, 570	163, 854			
1	f (fish accumulation)	1	7, 891	156, 354	$< 2.2 \times 10^{-16}$	8, 679	52.4
2	Year	13	6, 686	154, 797	$< 2.2 \times 10^{-16}$	1, 205	59.6
3	Gear	14	6, 648	154, 745	$< 2.2 \times 10^{-16}$	38	59.9
4	Basin	1	6, 470	154, 498	$< 2.2 \times 10^{-16}$	178	61.0
5	f (site depth)	5	6, 325	154, 293	$< 2.2 \times 10^{-16}$	145	61.8
6	f (soak time)	1	6, 198	154, 110	$< 2.2 \times 10^{-16}$	127	62.6
7	f (mesh size)	1	5, 131	152, 356	$< 2.2 \times 10^{-16}$	1, 067	69.0
8	f (gear depth)	1	5, 081	152, 274	3.3×10^{-12}	50	69.3
9	Month	3	5, 072	152, 263	2.1×10^{-4}	10	69.4

In the delta model, results from the submodel to analyze positive values of CPUE showed that soak time had a negative impact on CPUE of both walleyes (Figure 1a) and yellow perch (Figure 1b). The CPUE of walleyes increased with more fish enmeshed and started to decline gradually after fish accumulated to around 2 fish/m^2 (Figure 1c). We did not observe a substantial decline in CPUE of yellow perch with increasing fish accumulation levels from this submodel, where only positive values of CPUE were analyzed (Figure 1d).

Results from the submodel to estimate the probability of obtaining nonzero values of CPUE (i.e., the probability of catching the species of interest) showed that walleyes were more likely to be caught when nets soaked for 20–30 h (Figure 2a). A relatively higher chance of catching yellow perch occurred when nets soaked for more than 20 h (Figure 2b). The probability of catching walleyes and yellow perch started to decline when fish accumulated up to around 2 fish/m^2 and 2–6 fish/m^2, respectively (Figure 2c, d).

By combining the results from the two submodels in the delta model (i.e., one submodel to analyze positive values of CPUE [Figure 1] and the other to estimate probability of obtaining nonzero values of CPUE [Figure 2]), effects of soak time and fish accumulation on CPUE were obtained. The CPUE of walleyes decreased since gill nets soaked for 10 h (Figure 3a) and started to decline when fish accumulated up to its threshold (approximately 2 fish/m^2; Figure 3c), which suggested gill nets had been saturated since the minimum value of soak time we examined (i.e., 10 h). We did not observe a substantial decline in CPUE with soak time for yellow perch within the soak time interval we examined (i.e., 10–36 h), although its CPUE was slightly lower after gill nets soaked for 25 h (Figure 3b). However, we observed a decline in CPUE of yellow perch when fish accumulated up to 6–8 fish/m^2, which indicated the gill nets started to saturate (Figure 3d). The difference in CPUE trends with soak time for these two species indicated that gill nets were saturated faster by walleyes than by yellow perch (Figure 3a, b).

Comparison of model performance between the delta model with two GAMs and the two candidate linear models (i.e., the delta model with two GLMs and the delta model with two GLM-Polys) gave evidence in favor of nonlinear model analyses except for estimating the probability of obtaining nonzero values of CPUE for walleyes (Table 5). When estimating positive values of CPUE for both walleyes and yellow perch, the GAMs had the lowest AIC values (corresponding Akaike weights close to 1). When estimating probability of obtaining nonzero values of CPUE, the GAM yielded the lowest AIC value for yellow perch (corresponding Akaike weights close to 1), whereas the GLM-Poly yielded the lowest AIC value for walleyes (corresponding Akaike weights close to 1).

TABLE 4. Stepwise construction of a generalized additive model to estimate the probability of obtaining nonzero values of CPUE. A binomial distribution was assumed.

	Variables selected for model	df	Deviance	AIC	P	Deviance decrement	Cumulative% of deviance explained
				Walleyes			
0	Null		29, 970	29, 969			
1	Basin	5	26, 578	26, 590	$< 2.2 \times 10^{-16}$	3, 392	11.3
2	Year	13	25, 726	25, 766	$< 2.2 \times 10^{-16}$	852	14.2
3	f (gear depth)	14	25, 347	25, 395	$< 2.2 \times 10^{-16}$	379	15.4
4	f (fish accumulation)	1	24, 042	24, 098	$< 2.2 \times 10^{-16}$	1, 305	19.8
5	Month	1	23, 997	24, 059	2.7×10^{-16}	45	19.9
6	Gear	3	23, 859	23, 923	1.1×10^{-10}	138	20.4
7	f (gear temperature)	1	23, 825	23, 897	2.5×10^{-5}	34	20.5
8	f (Secchi depth)	1	23, 777	23, 857	6.0×10^{-4}	48	20.7
9	f (soak time)	1	23, 754	23, 842	4.4×10^{-4}	22	20.7
				Yellow perch			
0	Null		38, 510	38, 514			
1	f (fish accumulation)	1	25, 665	25, 675	$< 2.2 \times 10^{-16}$	12, 845	33.4
2	Gear	1	22, 295	22, 307	$< 2.2 \times 10^{-16}$	3, 370	42.1
3	f (mesh size)	1	18, 335	18, 355	$< 2.2 \times 10^{-16}$	3, 960	52.4
4	Year	14	17, 080	17, 128	$< 2.2 \times 10^{-16}$	1, 255	55.6
5	f (gear temperature)	5	16, 312	16, 368	$< 2.2 \times 10^{-16}$	768	57.6
6	Basin	1	16, 190	16, 256	$< 2.2 \times 10^{-16}$	122	58.0
7	f (dissolved oxygen)	1	16, 143	16, 217	$< 2.2 \times 10^{-16}$	47	58.1
8	Month	3	16, 107	16, 187	1.2×10^{-14}	36	58.2
9	f (gear depth)	1	14, 627	14, 715	1.1×10^{-10}	1, 480	62.0
10	f (site depth)	1	14, 468	14, 564	$< 2.2 \times 10^{-16}$	159	62.4
11	f (soak time)	1	14, 420	14, 524	6.0×10^{-8}	47	62.6
12	f (Secchi depth)	1	14, 387	14, 499	8.0×10^{-6}	33	62.6

DISCUSSION

This analysis indicated that gill-net saturation did exist in the PIS survey for walleyes and yellow perch, which can be observed from the declines in catch rates when soak time increased for walleyes and when fish accumulation level increased for walleyes and yellow perch. Similar results have been documented in previous studies, including the study on these two species in Lake Ontario by Minns and Hurley (1988). Considering gill-net saturation in fishery surveys and fishery data analyses can increase reliability of nominal CPUE data and accuracy of CPUE estimates (Beverton and Holt 1957; Olin et al. 2004).

When analyzing the effect of soak time on CPUE of walleyes, although the gill-net saturation was suggested by the reduction in catch rates with soak time, it is difficult to make inference on exactly when gill nets started to saturate due to data limitation. Given the PIS data, CPUE of walleyes had already decreased since gill nets soaked for 10 h (the minimum soak time value we examined). The data limitation may also contribute to the result that we did not observe a substantial decline in CPUE with soak time for yellow perch. A longer soak time interval might be needed to observe such a decline for yellow perch.

Other factors may contribute to the decline in CPUE, including gear configuration that may have caused enmeshed fish to drop out from nets, set and lift time confounded with feeding behaviors, gear selection caused by different mesh sizes, removal of fish by scavengers, and fish availability to gears (Minns and Hurley 1988; Yatsu et al. 1995; Damalas et al. 2007). To extract the effect of soak time or fish accumulation on CPUE and to remove the impacts of other factors, we conducted catch rate standardization. In addition, it is appropriate to assume that the samples are representative enough to describe gill-net saturation because 14 different mesh sizes ranging from 32 to 152 mm were used in the PIS survey, and walleyes and yellow perch are relatively abundant in Lake Erie (Kinnunen 2003).

The delta model was preferred in this analysis due to the high percentage of zero observations of response variable in the

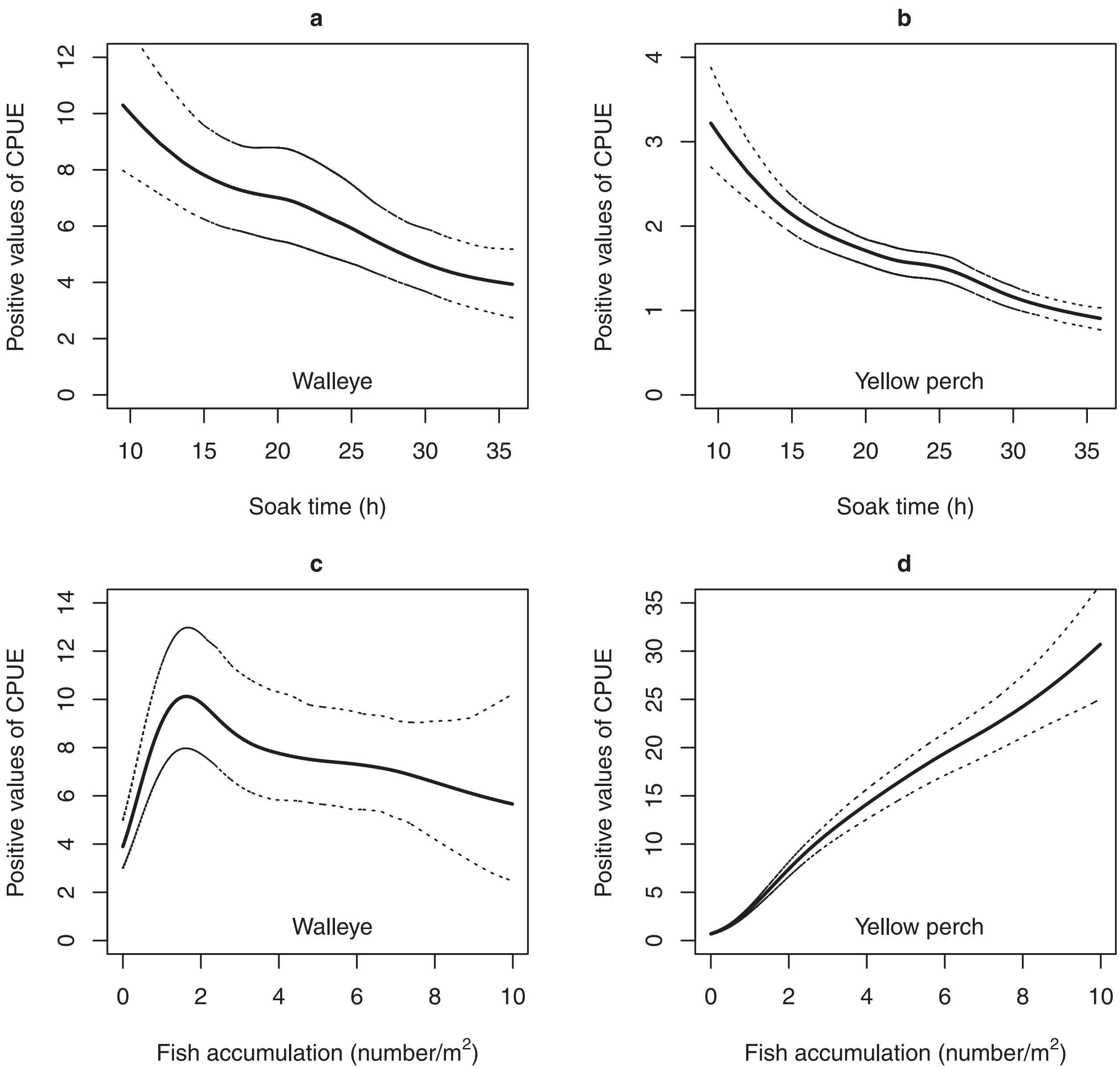

FIGURE 1. Relationships between positive values of CPUE and **(a)**–**(b)** soak time and **(c)**–**(d)** fish accumulation levels for walleyes and yellow perch in Lake Erie, as derived from a generalized additive model (GAM) assuming a log-gamma distribution. The dotted lines represent 95% confidence intervals.

PIS data (Lo et al. 1992; Pennington 1996; Stefansson 1996; Ortiz et al. 2000; Ye et al. 2001; Maunder and Punt 2004; Murray 2004; Fletcher et al. 2005). The nonlinear model analysis (GAM) was preferred in most cases because of its superiority in describing the most likely nonlinear relationships between catch rates and environmental and fishing factors (Damalas et al. 2007). The generalized linear model with polynomial terms up to degree 3 (GAM-Poly) outperformed the GAM when estimating the probability of obtaining nonzero values of CPUE for walleyes in this study. Although we applied the nonlinear model analyses (GAM) in this study for the purpose of consistency and interpretation, we did not suggest nonlinear model analyses be always chosen in any situation because data structure might greatly complicate the model selection. Application of the delta model with two GAMs highlighted a new perspective of methods in gear saturation analyses, especially when the percentage of zero observations in data sets was high. In previous studies, only the variables related to gear saturation were considered in model building (Minns and Hurley 1988; Hansen et al. 1998; Olin et al. 2004; Akiyama et al. 2007), whereas in this study all available variables were considered by applying the GAMs in the delta model.

Gill-net saturation patterns may vary among species due to fish relative abundance, fish morphology, and feeding behaviors

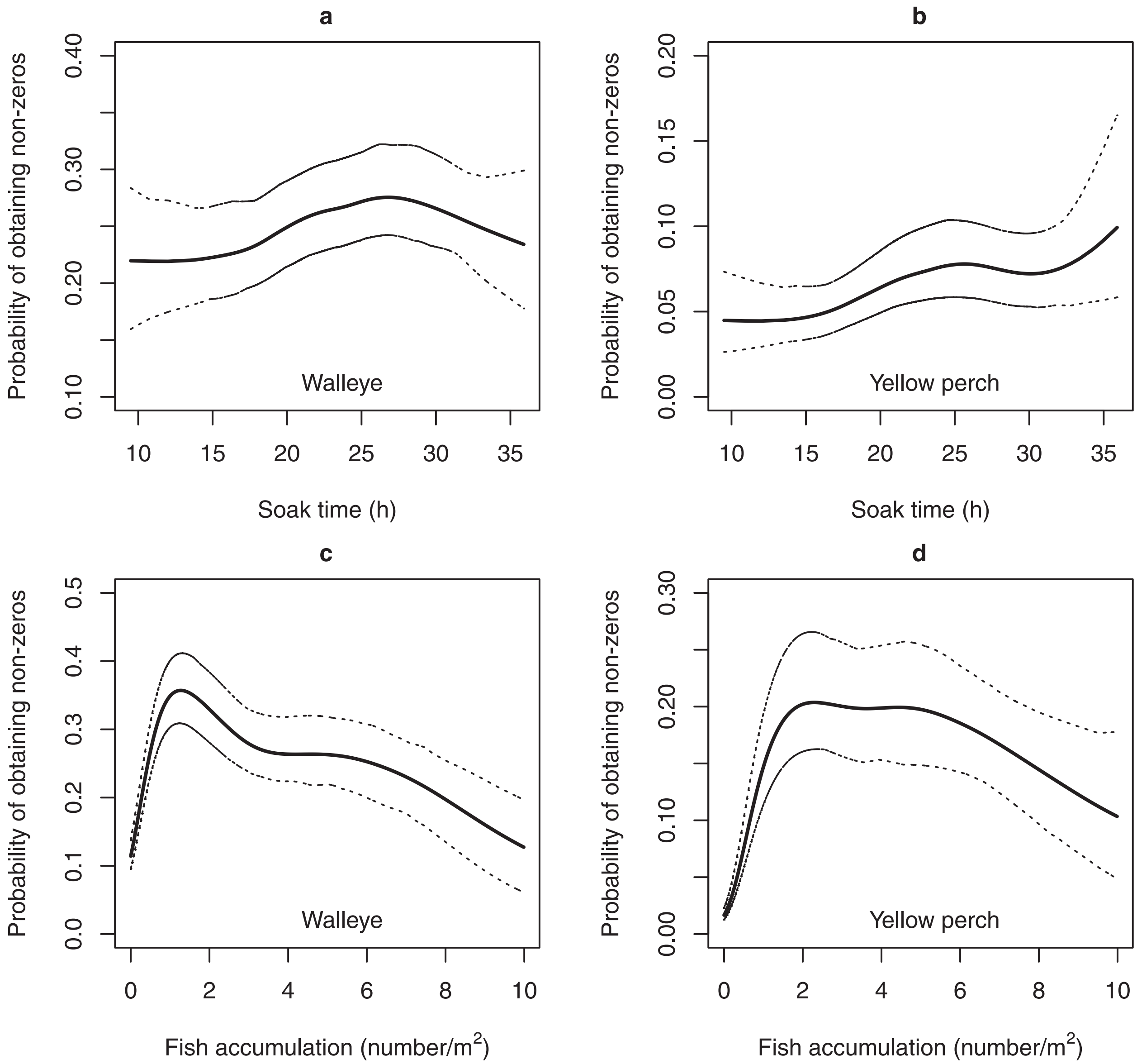

FIGURE 2. Relationships between the probability of obtaining nonzero values of CPUE and **(a)–(b)** soak time and **(c)–(d)** fish accumulation levels for walleyes and yellow perch in Lake Erie, as derived from a GAM assuming a binomial distribution. The dotted lines represent 95% confidence intervals.

(Minns and Hurley 1988; Hansen et al. 1998). Higher CPUEs were observed when gill nets soaked for less than 10 h for both species, which is probably attributed to their feeding behaviors. Since walleyes are a nocturnal species and yellow perch a crepuscular species, both of them were easily caught during nights (Scott and Crossman 1973). In the PIS survey, most gill nets were set during morning to noon; 10 h after set time would be evening to night. This explained why we observed higher CPUE when gill nets soaked for 10 h (i.e., during the first night after gill nets were set). We observed a decline in CPUE with increasing soak time for walleyes, whereas we did not observe a substantial decline for yellow perch within the soak time interval we examined (i.e., 10–36 h), which suggested that gill nets were saturated faster by walleyes than by yellow perch. Differences in their relative abundance and in their morphology may affect space availability in nets for the fish caught later and may have contributed to this difference in saturation time (i.e., the soak time when gill nets got saturated; Minns and Hurley 1988; Hansen et al. 1998). Walleyes have a relatively higher abundance in Lake Erie (27% of total commercial harvest by weight from Lake Erie in 2000) and a larger body size (33–64 cm) compared with yellow perch, which yielded 17% of total commercial harvest (by weight) in 2000 and has a body size of 18–25 cm (Scott and Crossman 1973; Page et al. 1997; Bruch et al. 2001; Kinnunen 2003).

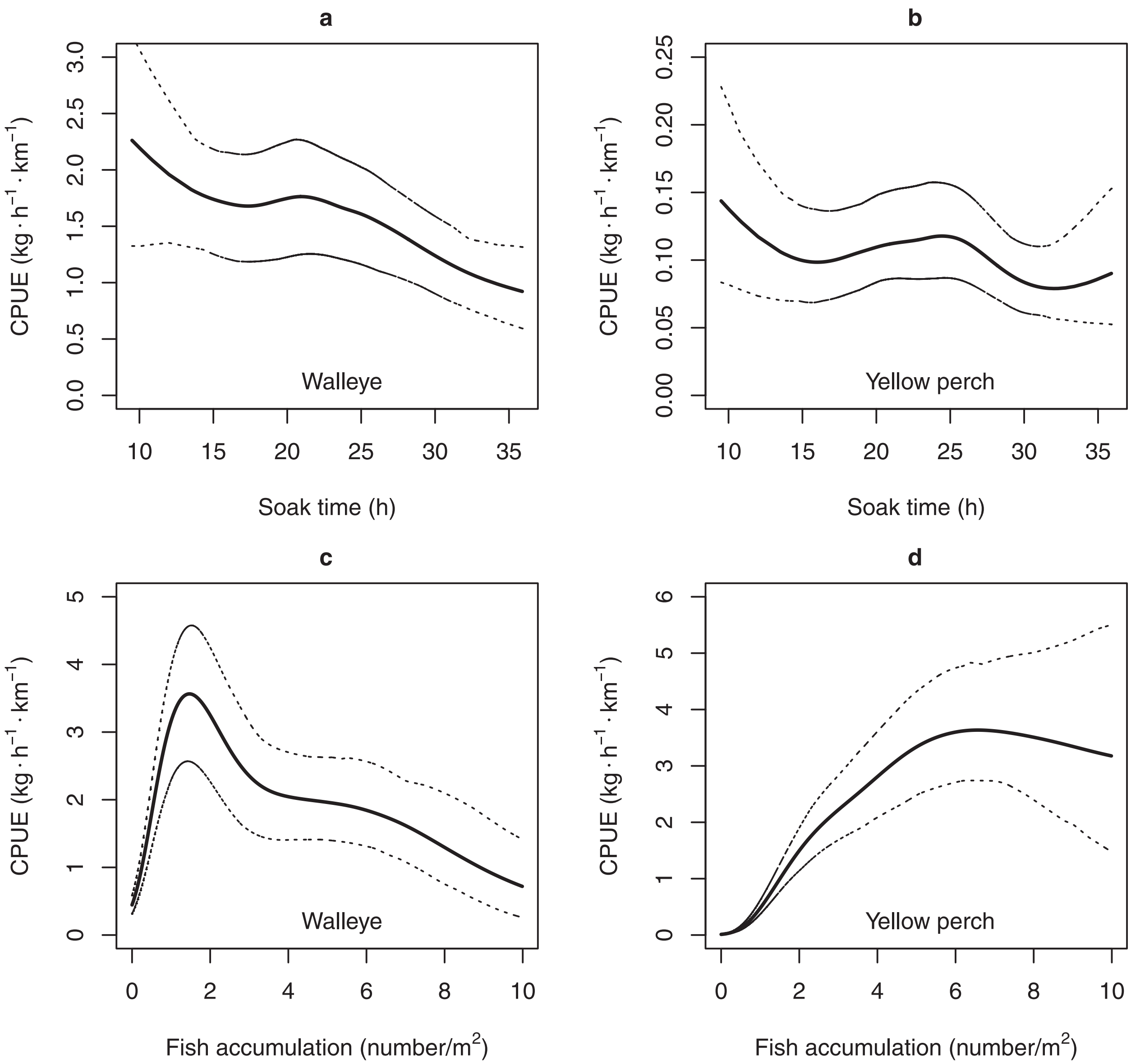

FIGURE 3. Relationships between CPUE and **(a)**–**(b)** soak time and **(c)**–**(d)** fish accumulation levels for walleyes and yellow perch in Lake Erie, as derived from a delta model comprising two GAMs. The dotted lines represent 95% confidence intervals.

In conclusion, gill-net catch rates (derived from the PIS data during 1989 to 2003) decreased with increasing soak time for walleyes and with increasing fish accumulation levels for walleyes and yellow perch, indicating that gill-net saturation by these two species did exist in the PIS survey in Lake Erie. Gill-net saturation should be taken into account when conducting stock assessments using survey data for these two species because survey samples may not represent the fish stock if gill-net saturation exists. Reliability of gill-net CPUE estimates could be improved by three approaches. The first approach is to make corrections to CPUE estimates (Kennedy 1951; Hansen et al. 1998; Dauk and Schwarz 2001). For example, Hansen et al. (1998) corrected catch rates for different soak time durations relative to the catch rate for one-night soak time. The second approach is to improve sampling designs to get more representative samples, such as to design appropriate soak time (Olin et al. 2004). The third approach is to examine the effects of the variables associated with gill-net saturation on catch rates through model analyses as addressed in this study. The generalized linear- or additive-based modeling approach can be considered as an alternative in gear saturation analyses by accounting for a large set of explanatory variables, including those associated with gill-net saturation.

TABLE 5. Akaike information criterion (AIC) values and Akaike weights (w_i) for the two candidate linear models and the delta model with two generalized additive models (GAM). The two candidate linear models included the delta model with two generalized linear models (GLM) and the delta model with two generalized linear models with polynomial terms up to degree 3 (GLM-Poly).

	Estimation of positive values of CPUE			Estimation of the probability of nonzero values		
	GLM	GLM-Poly	GAM	GLM	GLM-Poly	GAM
			Walleyes			
AIC	102, 507	101,060	101, 007	25, 120	22, 092	23, 842
Δ_i	1, 500	53	0	3, 028	0	1, 750
w_i	0	4.4×10^{-12}	1	0	1	0
			Yellow perch			
AIC	156, 272	152,359	152, 263	19, 076	14, 911	14, 499
Δ_i	4, 009	96	0	4, 577	412	0
w_i	0	1.3×10^{-21}	1	0	0	1

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