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# Length Selectivity and Size-Bias Correction for the North American Standard Gill Net

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***Abstract***
**Gill nets are inherently size selective, but selectivity curves can correct this bias. We sampled eight reservoirs with the North American standard gill net to develop a large length-specific data set for six species: Channel Catfish *Ictalurus punctatus*, hybrid Striped Bass (White Bass *Morone chrysops* × Striped Bass *M. saxatilis*), saugeye (Sauger *Sander canadensis* × Walleye *S. vitreus*), Walleye, White Bass, and White Crappie *Pomoxis annularis*. We then used the SELECT (share each lengthclass's catch total) method to find the best-fit selectivity model to adjust the gill-net catch for contact selectivity. To determine the magnitude of these selectivity corrections, we compared adjusted and unadjusted length frequencies and size indices for each species at each reservoir. The bimodal model was the best fit selectivity model for all species. When selectivity-adjusted length-frequency data were compared with the original data, one-third of hybrid Striped Bass length frequencies and two-thirds of White Bass length frequencies were significantly different (unadjusted distributions underestimated smaller length classes). Roughly one-third of the proportional size distributions (PSDs) from all species analyzed showed meaningful changes (≥5 PSD units) after selectivity adjustments were made (unadjusted PSDs were too large). By correcting for contact selectivity the data are improved, and at times the adjustments can be large enough to alter management decisions. Therefore, we recommend that selectivity adjustments should become a part of routine data analysis for the design of the North American standardized gill net as this will improve data for fisheries management.**

Gill nets are one of the most widely used fisheries sampling gears (Gabelhouse et al. 1992). With this gear, fish are caught when they penetrate the mesh of the net and become wedged by mesh around the body or "gilled" by the mesh slipping behind the opercula, although sometimes fish are tangled by spines, teeth, or other protrusions without actually penetrating the mesh. Because of the capture mechanism involved, mesh size is an important factor influencing the size of fish captured in gill nets (Reddin 1986; Holst et al. 1996; Miranda and Boxrucker 2009; Hubert et al. 2012). Fish caught in a given size of mesh typically differ in length by no more than 20% of the optimum length (i.e., the length most efficiently retained by the mesh: Hamely 1975, 1980) causing gill nets to be strongly size selective. To minimize the length bias, "gangs" of differing mesh sizes (i.e., experimental gill nets) are often fished simultaneously. But using multiple mesh sizes does not completely eliminate selectivity (Hamely 1975). As a result, length-frequency distributions and associated size-structure indices, such as proportional size distribution (PSD; Guy et al. 2007), from gill-net catches may not give a true representation of the fish that contact the net (Hamely 1975; Willis et al. 1985; Wilde 1993). Therefore, it is important to quantify gill-net contact selectivity so corrections can be made to length-frequency data collected with this gear.

There are two methods for estimating gill-net size selectivity, direct and indirect (Millar and Fryer 1999), with the indirect method being most commonly used. Direct estimates are made when a known population is sampled and the catch of a gear is directly compared with the known population. Although direct studies may be common with other gear types

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and systems, few true direct studies using gill nets in reservoirs can be found in the literature because the low capture rates and high mortality associated with gill nets make traditional mark–recapture approaches required for direct estimates impractical (Millar and Holst 1997; Millar and Fryer 1999). Only a few direct studies have been conducted using gill nets in inland reservoirs (Hamely and Reiger 1973; Borgstrom 1989; Pierce et al. 1994; Jensen 1995; Anderson 1998).

Selectivity is most commonly estimated with the indirect method, in which different mesh sizes are fished simultaneously and size-specific selectivity is derived by comparing the catch of each fish length class among mesh sizes (Holt 1963; Millar and Holst 1997; Carol and Garcia-Berthou 2007; Vandergoot et al. 2011). Indirect estimates only evaluate gill-net selectivity for fish that make contact with the net (i.e., contact selectivity) and not the fish population as a whole (i.e., encounter selectivity is not accounted for: Hamely 1975). Much of the gill-net size bias is thought to relate to the physics of retaining fish that contact the net rather than differences in size-specific encounter rates (Hamely 1975, 1980; Booth and Potts 2006; but see Rudstam et al. 1984; Henderson and Wong 1991), suggesting that indirect selectivity can account for at least a large portion of the size bias observed for this gear.

Indirect gill-net selectivity is often quantified with contact selectivity curves. Contact selectivity curves are developed using data from multiple mesh sizes that were fished simultaneously and the probability of capture for each size-class of fish by each mesh size is calculated as a proportion of the total catch of the size-class across all mesh sizes (assuming all mesh sizes had the same encounter rate). The height of the curve corresponds to how efficiently that mesh size catches fish of the optimum length (i.e., the length of fish with the most retainable size in a given mesh). The mesh size with the highest catch rate is used to scale the relative probability of capture in all other mesh sizes. Selectivity curves were first modeled as unimodal, bell-shaped curves (Hamely 1975). The mode of the selectivity curve represents the optimum length of fish caught in a given mesh size and the width represents the selection range. As understanding of gill-net selectivity progressed, other unimodal models were developed with longer right-skewed limbs to account for fish that are caught in ways other than wedging (Millar and Fryer 1999). A bimodal model was also developed to account for fish caught by multiple methods (e.g., tangling and "gilling": Hamely 1975). The five most commonly applied selectivity models are: normal, normal location, log normal, gamma, and bimodal (Millar and Fryer 1999; Table 1). Developing selectivity curves for individual lakes is impractical on a large scale (Wilde 1993). Because contact selectivity is a function of fish morphology and the physics involved in the entanglement process (Hamely 1975), selectivity curves developed from a large data set for a species should be applicable to other similar systems where that species occurs.

TABLE 1. Equations and model parameters (constants) for five selectivity models used in Passgear II version 2.4 software. Equations relate the mesh size $j$ ($m_j$) with the number of fish of length $l$ captured in that mesh size. Other symbols used in equations are constants. Fitted constants describing contact selectivity for six sport fish species captured in the North American standard gill net are provided in Table 3.

| Model (constants) | Selection curve equation [$s_j(l)$] |
|---|---|
| Normal scale ($k_1$, $k_2$) | $\exp\left(-\frac{(l-k_j\times m_j)^2}{2k_2^2\times m_j^2}\right)$ |
| Normal location ($k$, $\sigma$) | $\exp\left(-\frac{(l-k\times m_j)^2}{2\sigma^2}\right)$ |
| Log normal ($\mu$, $\sigma$) | $\frac{m_j}{l\times m_1}\exp\left(\mu-\frac{\sigma^2}{2}-\frac{\left(\log(l)-\mu-\log\left(\frac{m_j}{m_1}\right)\right)^2}{2\sigma^2}\right)$ |
| Gamma ($\alpha$, $k$) | $\left(\frac{l}{(\alpha-1)\times k\times m_j}\right)^{\alpha-1}\exp\left(\alpha-1-\frac{l}{k\times m_j}\right)$ |
| Bimodal ($k_1$, $k_2$, $k_3$, $k_4$, $c$) | $\exp\left(-\frac{(l-k_1\times m_j)^2}{2k_2^2\times m_j^2}\right)+c\exp\left(-\frac{(l-k_3\times m_j)^2}{2k_4^2\times m_j^2}\right)$ |

Recently a new voluntary standard sampling protocol was developed for the use of gill nets in North America (Bonar et al. 2009). The design of the North American standard gill net is 24.8 m long by 1.8 m deep with eight 3.1-m panels that have bar mesh sizes of 19, 25, 32, 38, 44, 51, 57, and 64 mm, constructed of clear monofilament lines with diameters of 0.28, 0.28, 0.28, 0.33, 0.33, 0.33, 0.40, and 0.40 mm, respectively, and with a 0.5 hanging ratio. These standard nets could prove useful for managers who want to compare gill-net catches among lakes or even agencies, and several state agencies and research groups have recently adopted the standard. However, no one has examined the contact selectivity of these nets. Once selectivity biases of a gear type are identified, catch data from the gear can be adjusted to more accurately reflect the population sampled (Henderson and Wong 1991; Millar and Fryer 1999). Therefore, to quantify contact selectivity bias for the design of the new North American standard gill net, we developed selectivity curves from pooled data for six species commonly monitored for sport fish management. Because contact selectivity is an attribute of fish shape relative to mesh size, these selectivity curves provide a tool that would be applicable to other reservoirs in North America. We then applied correction factors derived from the developed selectivity curves to data sets from each lake to illustrate their use and demonstrate the magnitude of the corrections on length-based metrics derived from gill-net data.

## METHODS

In 2009 and 2010, we sampled eight Oklahoma reservoirs (Canton, Thunderbird, Kaw, Waurika, and Tom Steed reservoirs in 2009; Foss, Fort Cobb, Skiatook, and Tom Steed reservoirs in

2010) with 30 net-nights of effort in a given sample year (except Fort Cobb Reservoir, which is smaller and only received 20 net-nights). We followed the standard protocol recommended by Miranda and Boxrucker (2009) for warmwater fish in large standing waters. Gill nets were bottom-set perpendicular to shore at depths typically ranging from 1.8 to 4.6 m during the months of October and November. Nets were fished overnight for a mean set duration of 18.8 h (SD, 1.6). We recorded gill-net catch (number of fish per net-night) by mesh size, and measured TL (mm) and weight (g) for six target species: Channel Catfish *Ictalurus punctatus*, hybrid Striped Bass (White Bass *Morone chrysops* × Striped Bass *M. saxatilis*), saugeye (Sauger *Sander canadensis* × Walleye *S. vitreus*), Walleye, White Bass, and White Crappie *Pomoxis annularis*. Average relative weights ($W_r$) were also calculated for all target species.

We pooled the catch data for each species across lakes and sites and calculated selectivity curves for each target species using the SELECT (share each lengthclass's catch total) method with Pasgear II version 2.4 software (Institute of Marine Research 2010) following the approach of Millar and Holst (1997). Catch rates were summarized by 10-mm length classes. Because fish abundance typically decreases with age, it is expected that there would be more small fish than large fish in the population. Many gears are biased against young-of-year fish, resulting in length distributions with low abundances of small fish (Van Den Avyle and Hayward 1999). Therefore, we excluded from analysis smaller length classes that had low catch (mean catch < 2% of total across lakes) and for which no smaller length class had higher abundance (see Table 2 for final length range analyzed for each species). Five different log-linear models (normal scale, normal location, log normal, gamma, and bimodal) were fit for each species by maximum likelihood. The best-fit model for each species was then determined based on the lowest model deviance and most randomly distributed residuals (Millar and Holst 1997).

To illustrate the magnitude of the size bias of the North American standard gill net, we used the selectivity curves to adjust length-frequency distributions of each species at each lake (i.e., to correct the estimated length frequency of fish that contacted the net; Holst et al. 1996; Hansen et al. 1997) and compared selectivity-adjusted data with the unadjusted data. Relative selectivity ($S_l$) values for the entire experimental gill net (i.e., normalizing selectivity across all mesh sizes) were calculated as

$$S_l = \sum_j \left( \frac{s_j(l)}{max_l} \right),$$

where $s_j(l)$ = selectivity of size class $l$ in mesh size $j$, and $max_l$ = the largest selectivity [$s_j(l)$] observed among all length classes (Holst et al. 1996; Hansen et al. 1997). Adjustments to the abundance of each length class (i.e., adjusted length frequency) were made by dividing the total number of fish captured in a given length class (catch from all mesh sizes pooled) by the overall net selectivity value ($S_l$) for that length class. We then compared unadjusted (raw observed data) and $S_l$-adjusted length-frequency data (i.e., estimated length-frequency data for fish that contacted the net) in two ways. First, we used a Kolmogorov–Smirnov (KS) test to test for differences ($P \leq 0.05$) in adjusted and unadjusted length distributions for each species that was a major part of the fishery within each lake. To avoid analyzing length frequencies for species that were not common in a given lake, we did not analyze species that had catch rates below the lower end of that species' 95% CI of the statewide mean catch rate for the species (based on the past 15 years of statewide gill-net data; Oklahoma Department of Wildlife Conservation [ODWC], unpublished data). This resulted in three lakes for Channel Catfish, six lakes for hybrid Striped Bass, four lakes for saugeye, two lakes for Walleye, six lakes for White Bass, and five lakes for White Crappie. Second, we compared PSDs of quality-size (PSD-Q), preferred-size (PSD-P), and memorable-size fish (PSD-M) from unadjusted and adjusted data for each species at each sample lake. Changes of more than 5 PSD units (i.e., 5%) were considered relevant for management decisions (Miranda 1993).

## RESULTS

Sample sizes of 242–1,399 fish were used to develop selectivity curves for each species (Table 2). Sampled fish had a wide range of TLs and $W_r$ (Table 2). For all species,

TABLE 2. Range of TLs (mm), relative weights ($W_r$), and sample sizes ($N$) of fish used to fit selectivity models for the North American standard gill net (Bonar et al. 2009) using the SELECT (share each lengthclass's catch total) method. Fish were sampled from eight Oklahoma reservoirs. Average $W_r$ and $W_r$ SE are also shown.

| Species | TL (mm) | $W_r$ range | Mean $W_r$ | $W_r$ SE | $N$ |
|---|---|---|---|---|---|
| Channel Catfish | 120–859 | 62–113 | 85 | 0.37 | 769 |
| Hybrid Striped Bass | 120–659 | 56–119 | 83 | 0.27 | 1,041 |
| Saugeye | 190–669 | 66–119 | 92 | 0.38 | 528 |
| Walleye | 190–719 | 62–106 | 85 | 0.59 | 242 |
| White Bass | 120–509 | 40–133 | 91 | 0.30 | 1,399 |
| White Crappie | 110–379 | 68–134 | 98 | 0.41 | 954 |

the bimodal model had the best fit, accounting for 71–88% of the variability in fish lengths caught among different mesh sizes (Table 3). For all species, some degree of size bias existed. Length classes with the lowest selectivity were retained 10–40% as frequently as the length classes with the highest selectivity, indicating these experimental gill nets were 2.5–10 times more likely to retain some length classes than others (Figure 1; Table 4). Selectivity was typically lowest for smaller size classes. For White Crappie, White Bass, and saugeye, peak selectivity occurred for larger fish in the length distribution. For hybrid Striped Bass, Walleye, and Channel Catfish, peak selectivity occurred at slightly smaller lengths, and selectivity strongly declined for both smaller and larger fish lengths.

TABLE 3. Model parameters, residual deviance, degrees of freedom (df), and $R^2$ for five gill net selectivity models (Normal Scale [N. Scale], Normal Location [N. location], Log-Normal, Gamma, and Bimodal) estimated using the SELECT (share each lengthclass's catch total) method. The model with the lowest deviance for each of six species is indicated in bold text. Input for models came from gill-net catches from eight Oklahoma reservoirs using the North American standard gill net (Bonar et al. 2009). Model parameters are defined in Table 1.

| | Constants | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Model | Parameter 1 | Parameter 2 | Parameter 3 | Parameter 4 | Parameter 5 | Deviance | df | $R^2$ |
| | | | **Channel Catfish** | | | | | |
| N. Scale | $k_1$ = 11.87 | $k_2$ = 4.11 | | | | 366.48 | 260 | 0.67 |
| N. Location | $k$ = 10 | $\sigma$ = 129.09 | | | | 315.59 | 260 | 0.73 |
| Log-normal | $\mu$ = 5.41 | $\sigma$ = 0.34 | | | | 323.27 | 260 | 0.73 |
| Gamma | $\alpha$ = 1.26 | $k$ = 9.67 | | | | 323.89 | 260 | 0.72 |
| **Bimodal** | **$k_1$ = 10.04** | **$k_2$ = 1.28** | **$k_3$ = 14.75** | **$k_4$ = 6.05** | **$c$ = 0.28** | **225.09** | **257** | **0.81** |
| | | | **Hybrid Striped Bass** | | | | | |
| N. Scale | $k_1$ = 10.71 | $k_2$ = 4 | | | | 646.45 | 244 | 0.65 |
| N. Location | $k$ = 9.09 | $\sigma$ = 108.51 | | | | 460.49 | 244 | 0.76 |
| Log-normal | $\mu$ = 5.3 | $\sigma$ = 0.31 | | | | 480.67 | 244 | 0.75 |
| Gamma | $\alpha$ = 1.05 | $k$ = 10.45 | | | | 520.24 | 244 | 0.72 |
| **Bimodal** | **$k_1$ = 8.99** | **$k_2$ = 1.18** | **$k_3$ = 15.73** | **$k_4$ = 6.05** | **$c$ = 0.2** | **303.55** | **241** | **0.84** |
| | | | **Saugeye** | | | | | |
| N. Scale | $k_1$ = 13.06 | $k_2$ = 4.64 | | | | 288.48 | 182 | 0.66 |
| N. Location | $k$ = 11.2 | $\sigma$ = 116.53 | | | | 207.31 | 182 | 0.77 |
| Log-normal | $\mu$ = 5.5 | $\sigma$ = 0.29 | | | | 227.39 | 182 | 0.75 |
| Gamma | $\alpha$ = 1.15 | $k$ = 11.61 | | | | 245.13 | 182 | 0.72 |
| **Bimodal** | **$k_1$ = 11.4** | **$k_2$ = 1.72** | **$k_3$ = 19.84** | **$k_4$ = 7.65** | **$c$ = 0.15** | **173.45** | **179** | **0.79** |
| | | | **Walleye** | | | | | |
| N. Scale | $k_1$ = 12.49 | $k_2$ = 2.57 | | | | 143.5 | 105 | 0.65 |
| N. Location | $k$ = 11.14 | $\sigma$ = 105.66 | | | | 169.57 | 105 | 0.62 |
| Log-normal | $\mu$ = 5.47 | $\sigma$ = 0.25 | | | | 154.28 | 105 | 0.67 |
| Gamma | $\alpha$ = 0.66 | $k$ = 19.35 | | | | 147.75 | 105 | 0.67 |
| **Bimodal** | **$k_1$ = 10.97** | **$k_2$ = 1** | **$k_3$ = 13.62** | **$k_4$ = 3.32** | **$c$ = 0.55** | **130.43** | **102** | **0.71** |
| | | | **White Bass** | | | | | |
| N. Scale | $k_1$ = 8.94 | $k_2$ = 1.89 | | | | 610.56 | 173 | 0.78 |
| N. Location | $k$ = 8.08 | $\sigma$ = 73.48 | | | | 711.45 | 173 | 0.76 |
| Log-normal | $\mu$ = 5.13 | $\sigma$ = 0.24 | | | | 646.97 | 173 | 0.80 |
| Gamma | $\alpha$ = 0.46 | $k$ = 19.75 | | | | 603.42 | 173 | 0.80 |
| **Bimodal** | **$k_1$ = 7.97** | **$k_2$ = 0.73** | **$k_3$ = 10.02** | **$k_4$ = 2.75** | **$c$ = 0.3** | **335.72** | **170** | **0.88** |
| | | | **White Crappie** | | | | | |
| N. Scale | $k_1$ = 7.43 | $k_2$ = 1.82 | | | | 655.9 | 146 | 0.60 |
| N. Location | $k$ = 6.43 | $\sigma$ = 66.32 | | | | 666.96 | 146 | 0.59 |
| Log-normal | $\mu$ = 4.94 | $\sigma$ = 0.27 | | | | 600.22 | 146 | 0.65 |
| Gamma | $\alpha$ = 0.05 | $k$ = 15.92 | | | | 594.32 | 146 | 0.65 |
| **Bimodal** | **$k_1$ = 6.48** | **$k_2$ = 0.61** | **$k_3$ = 9.16** | **$k_4$ = 3.27** | **$c$ = 0.18** | **285.63** | **143** | **0.87** |

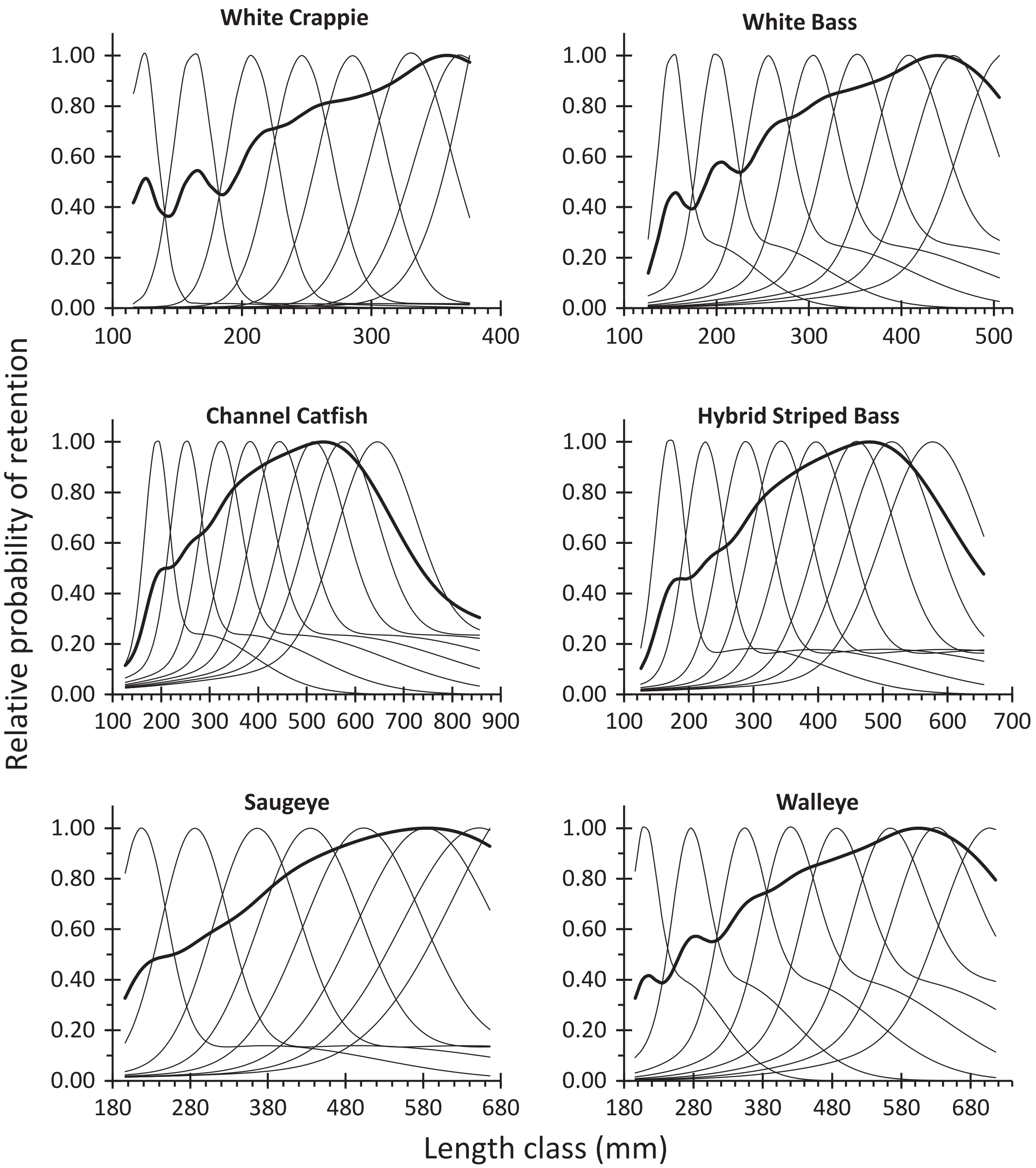

FIGURE 1. Overall selectivity curves (thick dark line) for the North American standard gill net (Bonar et al. 2009) using a bimodal model for six sport fish species based on data from eight reservoirs. The eight individual curves (thin lines) represent relative selectivity of individual meshes (19-, 25-, 32-, 38-, 44-, 51-, 57-, and 64-mm bar mesh from left to right).

Adjusted and unadjusted length distributions were similar at all lakes for Channel Catfish, saugeye, Walleye, and White Crappie. Significant differences occurred between adjusted and unadjusted data for one-third of the hybrid Striped Bass length frequencies (Figure 2) and two-thirds of the White Bass length frequencies (Figure 3), and there was a noticeable increase in the smaller length classes of the adjusted length distributions. The number of fish in the length-frequency distributions ranged from 59 individuals (saugeye in Fort Cobb Reservoir) to 456 individuals (White Bass in Tom Steed Reservoir) with an average of 162 fish per lake and species combination.

TABLE 4. Relative probability of retention (Rel $S_l$) values for the North American standard gill net (Bonar et al. 2009) derived from a bimodal model for six species. These values can be used to correct for gill-net size bias resulting from contact selectivity by dividing the number of fish captured in each length class by the Rel $S_l$ value for that length class.

| | Rel $S_l$ value | | | | | |
|---|---|---|---|---|---|---|
| Length class (mm) | Channel Catfish | Hybrid Striped Bass | Saugeye | Walleye | White Bass | White Crappie |
| 110–119 | | | | | | 0.42 |
| 120–129 | 0.12 | 0.10 | | | 0.14 | 0.51 |
| 130–139 | 0.14 | 0.16 | | | 0.27 | 0.39 |
| 140–149 | 0.18 | 0.24 | | | 0.41 | 0.37 |
| 150–159 | 0.23 | 0.33 | | | 0.46 | 0.49 |
| 160–169 | 0.31 | 0.41 | | | 0.41 | 0.54 |
| 170–179 | 0.38 | 0.45 | | | 0.40 | 0.48 |
| 180–189 | 0.45 | 0.46 | | | 0.47 | 0.45 |
| 190–199 | 0.49 | 0.46 | 0.33 | 0.33 | 0.56 | 0.52 |
| 200–209 | 0.50 | 0.47 | 0.39 | 0.40 | 0.58 | 0.63 |
| 210–219 | 0.50 | 0.49 | 0.44 | 0.42 | 0.55 | 0.69 |
| 220–229 | 0.51 | 0.52 | 0.47 | 0.40 | 0.54 | 0.71 |
| 230–239 | 0.53 | 0.55 | 0.48 | 0.39 | 0.57 | 0.73 |
| 240–249 | 0.56 | 0.57 | 0.49 | 0.41 | 0.64 | 0.76 |
| 250–259 | 0.59 | 0.58 | 0.50 | 0.47 | 0.70 | 0.80 |
| 260–269 | 0.61 | 0.61 | 0.51 | 0.53 | 0.73 | 0.81 |
| 270–279 | 0.63 | 0.64 | 0.52 | 0.57 | 0.75 | 0.82 |
| 280–289 | 0.64 | 0.68 | 0.54 | 0.57 | 0.76 | 0.83 |
| 290–299 | 0.66 | 0.72 | 0.57 | 0.56 | 0.78 | 0.85 |
| 300–309 | 0.69 | 0.75 | 0.59 | 0.55 | 0.81 | 0.87 |
| 310–319 | 0.72 | 0.78 | 0.60 | 0.56 | 0.83 | 0.89 |
| 320–329 | 0.75 | 0.81 | 0.62 | 0.59 | 0.85 | 0.92 |
| 330–339 | 0.78 | 0.83 | 0.64 | 0.63 | 0.86 | 0.96 |
| 340–349 | 0.81 | 0.85 | 0.66 | 0.67 | 0.87 | 0.99 |
| 350–359 | 0.83 | 0.87 | 0.69 | 0.70 | 0.88 | 1.00 |
| 360–369 | 0.85 | 0.88 | 0.72 | 0.72 | 0.89 | 1.00 |
| 370–379 | 0.86 | 0.90 | 0.74 | 0.74 | 0.90 | 0.97 |
| 380–389 | 0.88 | 0.91 | 0.77 | 0.75 | 0.92 | |
| 390–399 | 0.89 | 0.93 | 0.80 | 0.76 | 0.94 | |
| 400–409 | 0.90 | 0.94 | 0.82 | 0.78 | 0.96 | |
| 410–419 | 0.92 | 0.95 | 0.84 | 0.80 | 0.98 | |
| 420–429 | 0.93 | 0.96 | 0.86 | 0.81 | 0.99 | |
| 430–439 | 0.94 | 0.97 | 0.87 | 0.83 | 1.00 | |
| 440–449 | 0.94 | 0.98 | 0.89 | 0.84 | 1.00 | |
| 450–459 | 0.95 | 0.99 | 0.90 | 0.85 | 0.99 | |
| 460–469 | 0.96 | 1.00 | 0.92 | 0.86 | 0.97 | |
| 470–479 | 0.97 | 1.00 | 0.93 | 0.87 | 0.95 | |
| 480–489 | 0.98 | 1.00 | 0.94 | 0.88 | 0.92 | |
| 490–499 | 0.98 | 0.99 | 0.95 | 0.89 | 0.88 | |
| 500–509 | 0.99 | 0.99 | 0.96 | 0.90 | 0.83 | |
| 510–519 | 1.00 | 0.97 | 0.97 | 0.91 | | |
| 520–529 | 1.00 | 0.95 | 0.98 | 0.92 | | |
| 530–539 | 1.00 | 0.93 | 0.98 | 0.93 | | |
| 540–549 | 1.00 | 0.90 | 0.99 | 0.95 | | |
| 550–559 | 0.99 | 0.87 | 0.99 | 0.96 | | |
| 560–569 | 0.98 | 0.83 | 1.00 | 0.97 | | |

TABLE 4. Continued.

| | Rel $S_l$ value | | | | | |
|---|---|---|---|---|---|---|
| Length class (mm) | Channel Catfish | Hybrid Striped Bass | Saugeye | Walleye | White Bass | White Crappie |
| 570–579 | 0.97 | 0.79 | 1.00 | 0.98 | | |
| 580–589 | 0.96 | 0.75 | 1.00 | 0.99 | | |
| 590–599 | 0.94 | 0.71 | 1.00 | 1.00 | | |
| 600–609 | 0.91 | 0.67 | 1.00 | 1.00 | | |
| 610–619 | 0.89 | 0.63 | 0.99 | 1.00 | | |
| 620–629 | 0.86 | 0.59 | 0.98 | 0.99 | | |
| 630–639 | 0.83 | 0.55 | 0.97 | 0.98 | | |
| 640–649 | 0.80 | 0.51 | 0.96 | 0.97 | | |
| 650–659 | 0.76 | 0.48 | 0.95 | 0.95 | | |
| 660–669 | 0.73 | | 0.93 | 0.94 | | |
| 670–679 | 0.69 | | | 0.91 | | |
| 680–689 | 0.66 | | | 0.89 | | |
| 690–699 | 0.62 | | | 0.86 | | |
| 700–709 | 0.59 | | | 0.83 | | |
| 710–719 | 0.56 | | | 0.80 | | |
| 720–729 | 0.52 | | | | | |
| 730–739 | 0.50 | | | | | |
| 740–749 | 0.47 | | | | | |
| 750–759 | 0.44 | | | | | |
| 760–769 | 0.42 | | | | | |
| 770–779 | 0.40 | | | | | |
| 780–789 | 0.38 | | | | | |
| 790–799 | 0.37 | | | | | |
| 800–809 | 0.35 | | | | | |
| 810–819 | 0.34 | | | | | |
| 820–829 | 0.33 | | | | | |
| 830–839 | 0.32 | | | | | |
| 840–849 | 0.31 | | | | | |
| 850–859 | 0.30 | | | | | |

Proportional size distribution changes of ≥5 PSD units occurred for 35% of lake and species combinations (Table 5). For most species, changes of ≥5 PSD units typically occurred for PSD-Q and PSD-P categories. Only hybrid Striped Bass in Fort Cobb, White Crappie in Tom Steed, and White Crappie in Skiatook reservoirs had PSD-M values with selectivity adjustments that caused changes by ≥5 PSD units. The largest change between adjusted and unadjusted size indexes occurred for the White Crappie PSD-Q in Skiatook Reservoir, which was 15 PSD units lower after adjustment using the selectivity curve. None of the Channel Catfish PSDs changed by ≥5 PSD units with selectivity adjustments.

## DISCUSSION

To reduce size bias, the selectivity curves we derived for these six sport fishes can be used by other researchers and managers to adjust catch data when using the North American standard gill net (Bonar et al. 2009). Data can be adjusted by dividing the number of fish caught within a given 10-mm length class (from all mesh sizes combined) by our derived $S_l$ value (the overall probability of retention; Table 4) for that length class (Holst et al. 1996; Hansen et al. 1997). For example, if a given net captures five White Crappies within the 180–189-mm length class (where $S_l = 0.45$) during one net-night, the catch per net-night should be adjusted to 11.1 fish/net-night (i.e., 5 ÷ 0.45) to adjust for the size bias against this length class. Where $S_l$ values are <1, this will increase the number of fish captured to account for fish that were expected to have contacted the net without being retained. This procedure should then be completed with all other length classes before summing total CPUE. Length-frequency data that have been corrected for contact selectivity using the procedure described above will provide more

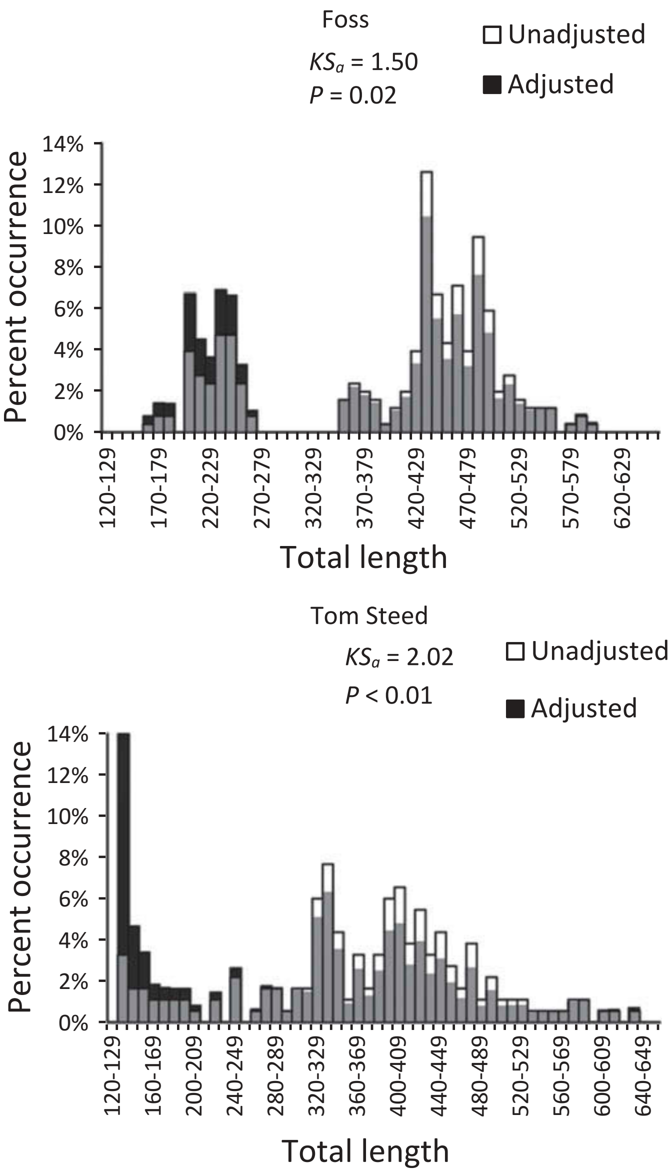

FIGURE 2. Hybrid Striped Bass length distributions in Foss and Tom Steed reservoirs before (white bars) and after (black bars) adjustment for contact selectivity. $P$-values and $KS_a$ are from Kolmogorov–Smirnov tests comparing selectivity-adjusted and unadjusted distributions. Gray-colored portions of bars represent areas of overlap between black (adjusted) and white (unadjusted) bars.

accurate assessments of fish populations for length-based metrics such as PSDs, length-frequency histograms, and age-related metrics obtained via age–length keys such as mean length at age and mortality rate. However, other sources of bias (e.g., bias related to encounter rates) may still exist.

Our species-specific selectivity values were derived using pooled data from eight reservoirs to produce a generalized selectivity curve that can be applied to samples from other lakes within North America. However, these curves should not be applied outside of the scope for which they were developed (Hamely 1975; Willis et al. 1985). Specifically, these selectivity curves should only be applied in similar contexts to where they were derived (i.e., applied to the species for which they were developed using fall sampling data from the North American standardized gill net: Bonar et al. 2009). If fish are sampled using nets with different specifications or fish are sampled during different seasons and have length–girth relationships that may differ (i.e., spawning season), selectivity will not be the same as during our study.

The mechanical process of fish capture in a gill net depends on the relative geometry of the mesh and the fish (Hamely 1975). As such, fish with dramatically different $W_r$ may have different selectivity in the same mesh size. As long as there are no major differences in body condition of a species in a prospective body of water, these selectivity curves could be used for adjusting the catch of that population (Kurkilahti et al. 2002). To allow $W_r$ to be evaluated, we provide TL and $W_r$ ranges for our study populations (Table 2). Managers and researchers should not apply these curves to length classes that fall outside the TL or $W_r$ ranges presented in Table 2.

Because the gill-net selectivity was lower for large hybrid Striped Bass and Channel Catfish, the addition of the optional large mesh sizes (i.e., 76-, 89-, and 102-mm bar mesh) specified by Bonar et al. (2009) might be useful for sampling these species. Additional research is needed to refine these selectivity curves for a gill-net design with these optional mesh sizes. The Walleye selectivity curve was derived using data from only two populations and was therefore based on a smaller number of fish ($N$ = 242). This produced a data set with less variability in $W_r$ and potentially a less uniform length distribution. Further research is needed to validate this selectivity curve.

The magnitude of a selectivity curve's adjustment on a length-frequency distribution will depend in part on the proportion of fish in length classes that had very high ($S_l$ near 1) or low ($S_l$ closer to 0 than to 1) selectivity. When fish are abundant in length classes with low selectivity, the effect of the selectivity curve's adjustment will be more pronounced (i.e., the number of fish in the length class is divided by a $S_l$ that is close to 0, resulting in a large adjusted value). Adjustments to the number of fish in length classes with high selectivity will be minor (i.e., the number of fish in that length class is divided by a $S_l$ that is very close to 1, resulting in an adjusted value very similar to the original value). Therefore, these selectivity curves could produce strong adjustments in some populations but only minor differences in others. Similarly, PSD values will be most affected by the application of selectivity corrections when one of the two size-classes in the proportion has much lower selectivity (e.g., stock-size fish have low selectivity, resulting in an increase in the denominator of the PSD equation leading to a smaller PSD value).

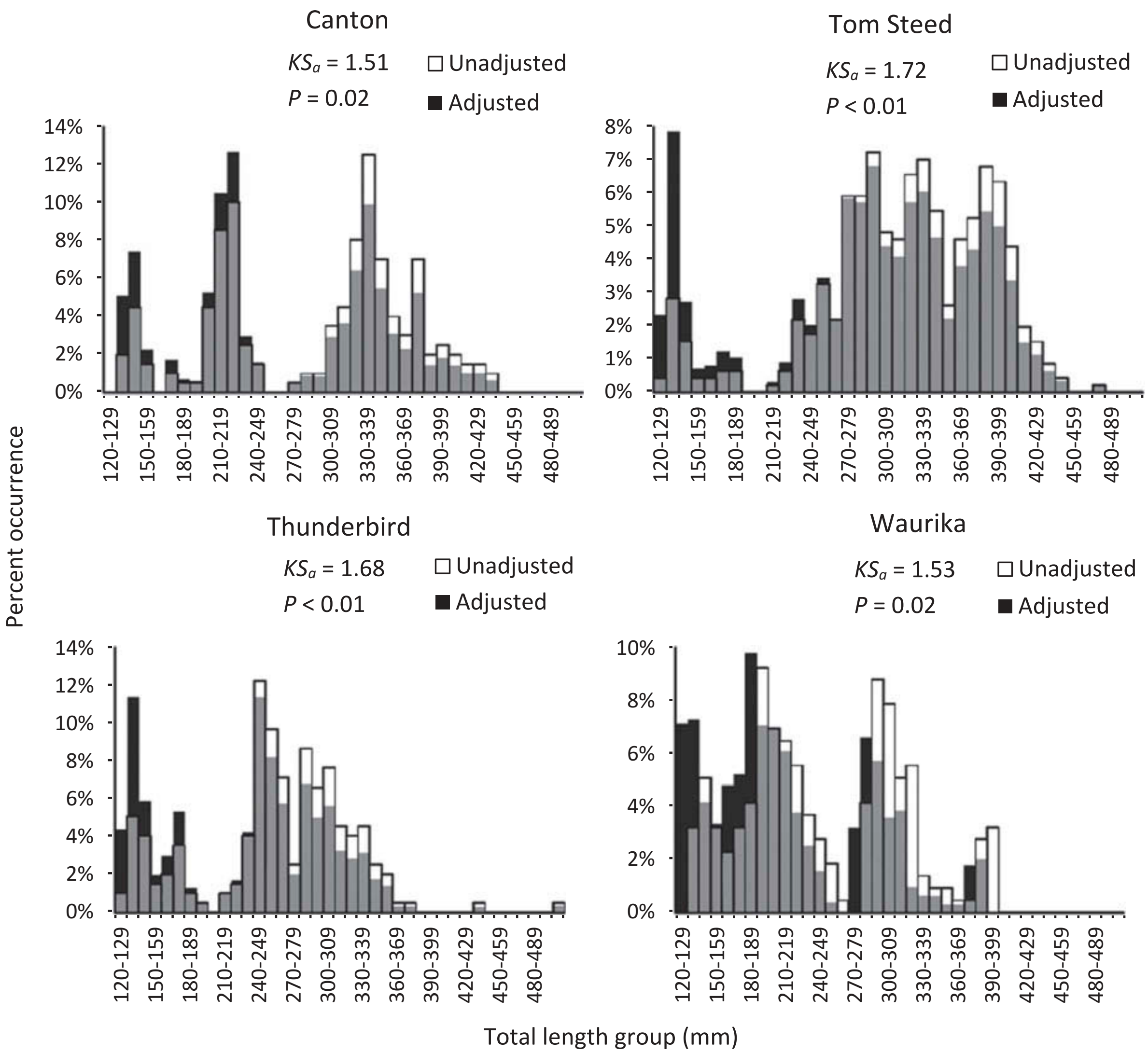

FIGURE 3. White Bass length distributions in Canton, Tom Steed, Thunderbird, and Waurika reservoirs before (white bars) and after (black bars) adjustment for contact selectivity. $P$-values and $KS_a$ are from Kolmogorov–Smirnov tests comparing selectivity-adjusted and unadjusted distributions. Gray-colored portions of bars represent areas of overlap between black (adjusted) and white (unadjusted) bars.

Our selectivity curves indicate that, for most species, the North American standard gill net was most effective at retaining mid-sized fish in the population (i.e., biased against small and large fish). Despite strong (2.5–10-fold) size-specific differences in the probability of retention for all species, the adjusted and unadjusted length-frequency distributions differed for only hybrid Striped Bass and White Bass at some of the sample lakes. This suggests that the use of these selectivity curves will not be necessary in all cases; the magnitude of adjustment will be a function of the number of fish captured in the length classes with low selectivity. Therefore, it is particularly important to use these corrections when very small or large length classes are abundant or of particular interest (except for White Crappie and saugeye where selectivity was high for large fish), such as when looking at recruitment or sampling trophy fisheries, because of the inherent bias of the North American standard gill net against retention of these size-classes.

The effects of the selectivity curve corrections on PSD data were more pronounced and affected more species than the effects of selectivity on length-frequency distributions. Roughly one-third of the lake and species combinations had changes in PSDs that were potentially meaningful to managers. Miranda (1993) suggests that a change in PSD of fewer than 5 PSD units has little practical importance in fishery management situations, presumably because smaller changes would not be perceivable by anglers. Therefore, we used this as a conservative estimate for identifying when

TABLE 5. Proportional size distributions (PSD) of six species for unadjusted and adjusted (via bimodal selectivity curves) gill-net catches from eight Oklahoma reservoirs. Changes of more than 5 PSD units, which may be of importance to fisheries managers, are in bold text.

| | PSD-Quality | | PSD-Preferred | | PSD-Memorable | |
|---|---|---|---|---|---|---|
| Reservoir | Unadjusted | Adjusted | Unadjusted | Adjusted | Unadjusted | Adjusted |
| | | | **Channel Catfish** | | | |
| Canton | 91 | 89 | 4 | 5 | 0 | 0 |
| Foss | 87 | 85 | 10 | 11 | 0 | 0 |
| Fort Cobb | 61 | 57 | 11 | 12 | 1 | 2 |
| Skiatook | 47 | 44 | 2 | 3 | 2 | 3 |
| Thunderbird | 72 | 68 | 0 | 0 | 0 | 0 |
| Tom Steed | 53 | 51 | 14 | 18 | 4 | 7 |
| Waurika | 35 | 31 | 0 | 0 | 0 | 0 |
| | | | **Hybrid Striped Bass** | | | |
| Canton | 94 | 90 | 71 | 67 | 7 | 8 |
| Foss | **78** | **66** | **72** | **61** | 10 | 9 |
| Fort Cobb | **41** | **32** | **41** | **32** | **31** | **25** |
| Skiatook | 97 | 96 | 53 | 50 | 17 | 17 |
| Tom Steed | 91 | 87 | **60** | **55** | 9 | 10 |
| Waurika | 97 | 96 | 85 | 83 | 25 | 27 |
| | | | **Saugeye** | | | |
| Fort Cobb | **88** | **82** | **64** | **57** | 10 | 9 |
| Thunderbird | **85** | **78** | **47** | **40** | 7 | 6 |
| Tom Steed | **90** | **84** | **76** | **68** | 28 | 25 |
| Waurika | 98 | 95 | 98 | 95 | 57 | 56 |
| | | | **Walleye** | | | |
| Canton | **71** | **63** | 10 | 8 | 3 | 2 |
| Foss | **81** | **76** | **33** | **28** | 0 | 0 |
| | | | **White Bass** | | | |
| Canton | **72** | **61** | **65** | **54** | 11 | 9 |
| Fort Cobb | **78** | **73** | 15 | 11 | 6 | 4 |
| Skiatook | 94 | 91 | **82** | **77** | 4 | 4 |
| Thunderbird | **88** | **81** | **31** | **25** | 1 | 1 |
| Tom Steed | 97 | 94 | **67** | **61** | 24 | 20 |
| Waurika | **55** | **44** | **31** | **23** | 7 | 4 |
| | | | **White Crappie** | | | |
| Fort Cobb | 98 | 97 | 90 | 88 | 12 | 11 |
| Kaw | **79** | **70** | **49** | **40** | 18 | 14 |
| Skiatook | **64** | **49** | **47** | **34** | **15** | **10** |
| Thunderbird | **37** | **29** | 10 | 6 | 4 | 2 |
| Tom Steed | **82** | **75** | **45** | **36** | **20** | **15** |
| Waurika | 98 | 97 | 88 | 85 | 12 | 11 |

differences between adjusted and unadjusted PSD values might be relevant for management decisions. Even with this conservative cutoff for determining important changes to PSDs, we found about one-third of the lake and species combinations had contact selectivity adjustments that were this large. The magnitude of change in PSD was pronounced in some cases. The largest magnitude of change occurred for White Crappie at Skiatook Reservoir, in which the unadjusted gill-net catch overestimated PSD-Q by 15 PSD units. For the majority of other comparisons, selectivity curve adjustments made little difference in the PSD values. This was particularly true for Channel Catfish.

It is possible that small sample sizes played a role in the ability to detect changes between unadjusted and adjusted length-frequency or PSD values. Anderson and Neumann (1996) recommend at least 100 fish are required for estimating PSD. Vokoun et al. (2001) suggest 300–400 fish are needed for accurate length-frequency analysis, whereas Miranda (2007) suggests a sample size of 375–1,200 fish may be needed (when using 10-mm length groupings). Miranda (1993) suggests approximately 1,000–1,500 fish are needed to detect a change in PSD of 5 PSD units and 200–400 fish to detect a change of 10 PSD units at an α level of 0.05. Our length-frequency sample sizes averaged 162 per species at each lake, and ranged from 59 to 456 fish. It is likely the inherently low catch rates of gill nets produced too few fish to detect changes of some adjusted length frequencies. We used a larger number of replicate net nights ($N = 30$ for most reservoirs) than is typically used by state agencies (usually $N \leqq 15$; Bonar 2012) or required by the European standard for gillnetting ($N = 24$–$32$ depending on reservoir depth, but never more than 24 nets used to sample fish populations that occur <6 m deep; ECS 2005). Further, mean catch rates of our study lakes were between the 62nd and 99th percentiles for the Oklahoma statewide average catch rate for the target species (ODWC, unpublished data). Therefore, our study had larger numbers of fish than would typically be encountered by most agencies. The number of replicate net sets required to achieve adequate sample sizes for length analyses may be impractical in many cases. In these situations, researchers and managers need to recognize that length-based data will lack precision, and contact-selectivity corrections may be very small relative to the large variability inherent in these smaller data sets. Further, if sampling effort is not sufficient to capture at least some individuals of the most poorly retained fish, no correction for contact selectivity can be made for the uncaptured size-classes (i.e., selectivity factors applied to $n = 0$ fish still results in $n = 0$).

Gill-net selectivity curves have been much more commonly applied to marine fisheries than to inland freshwater systems (e.g., Stewart 2002 compiled a review of 116 publications dealing with gear selectivity in the Mediterranean Sea alone). However, the freshwater studies that do exist suggest that meaningful changes to length-frequency or PSD values can occur when corrections are made, indicating these adjustments are equally important in freshwater. Meaningful differences have been found in selectivity-adjusted PSDs for White Bass, Smallmouth Bass *Micropterus dolomieu*, Walleye, Northern Pikeminnow *Ptychocheilus oregonensis*, and Lake Trout *Salvelinus namaycush* (Willis et al. 1985; Beamesderfer and Rieman 1988; Wilde 1993; Hansen et al. 1997). The net configurations and methods for calibrating selectivity curves differed among these studies, making comparisons of these curves difficult. However, these results and those of the current study illustrate the importance of using selectivity adjustments, at least for some populations. Using selectivity corrections would minimize bias of age- and length-based population models, estimations of population length frequencies, and estimations of mortality derived from standardized gill-net data (Millar and Fryer 1999).

We recommend that researchers and management agencies that adopt the North American standard gill net sampling protocol (Bonar et al. 2009) also incorporate adjustments for selectivity. These adjustments can be easily implemented and will ensure gill net samples have the least possible size bias. Fisheries managers are often limited in the decision-making process by the information provided by biased gears (Krueger and Decker 1999). Although gill nets are inherently size biased, they are still widely used by managers (Gabelhouse et al. 1992). By correcting for contact selectivity, fish length data collected with gill nets will always be improved (even if only subtly in some cases), and the adjustment requires minimal effort or processing time. Therefore, we recommend these adjustments be part of routine data analysis for the North American standard gill net protocol.

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