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San Francisco Estuary and Watershed Science, 20(2)

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Publication Date
2022

DOI
10.15447/sfews.2022v20iss2art4

SAN FRANCISCO ESTUARY & WATERSHED SCIENCE
Sponsored by the Delta Science Program and the UC Davis Muir Institute

RESEARCH

Gill-Net Selectivity for Fifteen Fish Species of the Upper San Francisco Estuary

Marissa L. Wulff*[1], Frederick V. Feyrer[1], Matthew J. Young[1]

ABSTRACT

Gill-net size selectivity for 15 fish species occurring in the upper San Francisco Estuary was estimated from a data set compiled from multiple studies, which together contained 7,096 individual fish observations from 882 gill-net sets. The gill nets considered in this study closely resembled the American Fisheries Society's recommended standardized experimental gill nets for sampling inland waters. Relationships between gill-net mesh sizes and the sizes for each fish species retained in gill nets were estimated indirectly using generalized linear modeling and maximum likelihood. Selectivity curves are provided for each species to inform researchers about the population characteristics of fishes sampled with similar gill nets.

KEY WORDS

Sacramento–San Joaquin Delta, San Francisco Estuary, gill net, gill-net selectivity

SFEWS Volume 20 | Issue 2 | Article 4

https://doi.org/10.15447/sfews.2022v20iss2art4

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INTRODUCTION

Gill nets are frequently used to sample fish assemblages for scientific research studies as well as for commercial fishing purposes. Gill nets deployed for research can be used for a variety of purposes, including monitoring changes in fish abundance and community structure. Gill nets- panels of mesh netting suspended vertically from a line- are passive sampling devices designed to entangle fish within the mesh, either around the body, or by the mesh slipping behind the opercula, spines, teeth, or fins. The size of fish captured is generally correlated with the size of the mesh (Reddin 1986). Gill nets that possess multiple sizes of mesh are commonly known as experimental gill nets, and are often employed to minimize species- and size-selective biases (Hamley 1975; Shoup and Ryswyk 2016). However, even with experimental gill nets, a fundamental understanding of gill-net selectivity is needed to properly characterize the sampled fish populations. In this paper, gill-net selectivity refers to contact selectivity, the probability that a gill-net encounter results in a capture.

Gill-net selectivity curves are useful tools to characterize relationships between mesh size and fish size. Both direct and indirect methods for estimating selectivity exist (described in Hamley 1975), with indirect methods more commonly described in the literature (Carol and Garcia–

Berthou 2007; Millar and Fryer 1999; Shoup and Ryswyk 2016; Smith et al. 2017). Indirect selectivity curves are estimated by comparing catch frequency data across different gill-net mesh sizes that are fished simultaneously (Millar and Holst 1997). Indirect selectivity curves estimate relative selectivity that is scaled to the mesh size with the highest catch rate (Shoup and Ryswyk 2016). Direct estimates of gill-net selectivity are less common because actual length–frequency distributions of sampled fishes are usually unknown (Borgström 1989; Millar and Fryer 1999).

In this study, we use an indirect method to estimate gill-net contact selectivity for 15 fish species that occur in the upper San Francisco Estuary (hereafter estuary). This information will be useful to inform researchers about population characteristics of fishes sampled with similar gill nets and to support appropriate gear selection for scientific and monitoring projects.

METHODS

Data examined in this analysis originated from several field studies implemented in the upper estuary (compiled in Wulff et al. 2019). The Sacramento Splittail study was conducted in November and December of 2010–2011 (Feyrer et al. 2015), and the Ryer Island, Little Holland Tract, and North Delta gill-net studies were conducted year-round from 2016 to 2018 (Farruggia et al. 2019; Steinke et al. 2019). Generally, the studies were located geographically in the west from the Petaluma River and San Pablo Bay, upstream through the estuary into the Sacramento River and the Yolo By-Pass (colloquially, Yolo Bypass; Figure 1). The gill nets employed in these studies closely resembled the American Fisheries Society's recommended standardized experimental gill net for sampling inland waters (Bonar et al. 2009). Specifically, they were 1.8 m high and 45.7 m long with five equal-length panels of 38.1-, 50.8-, 63.5-, 76.2- and 88.9-mm nylon monofilament stretch mesh. The gill nets featured a heavy lead line to ensure the net was set at the bottom, and a floating top line to maintain position in the water column and ensure they were stretched vertically. The gill nets were stretched horizontally with the aid of anchors attached to the ends of the lead line. Gill nets were deployed for a targeted 60-min duration during daylight hours. Data recorded on individual fish captured included identification to species, standard length (mm), and the mesh size in which it was captured.

Selectivity curves describing relationships between mesh size and fish size (standard length) for each species were estimated using the SELECT method (Millar 2018; Millar and Holst 1997) with the gillnetfunction package (Millar 2018) in the R statistical programming language (R Core Team 2021). This method is a generalized linear model that estimates gill-net retention probabilities as selection curves from gill-net catch data. Multiple unimodal statistical distributions were evaluated: a normal distribution model that assumed the spread of the selection curve is proportional to mesh size (normal proportional), a normal distribution model that assumed the spread of the selection curve *is* fixed (normal fixed), a gamma distribution model, and a log-normal distribution model. Both normal models are based on the normal distribution, which has symmetrical tails, meaning that the selection curve is not biased toward larger or smaller fish for a given mesh size. The normal fixed model assumes that the selection curve is of similar width for each mesh size, while the normal proportional model allows the selection curve spread to vary across mesh sizes. Both gamma and log-normal distributions are positively skewed curves, with larger tails at the upper end of the distribution, meaning that larger fish would be more likely to be retained by a given mesh size than smaller fish. The log-normal distribution is more positively skewed than the gamma distribution.

All four models were evaluated for each species, with standard length classes set in 10-mm increments. The selectivity models were generated under the assumption that each mesh size had equal fishing effort. Parameter 1 (k for normal fixed; k_1 for normal proportional; μ_1 for log-normal; α for gamma model) was the model-generated parameter that related modal length (μ)

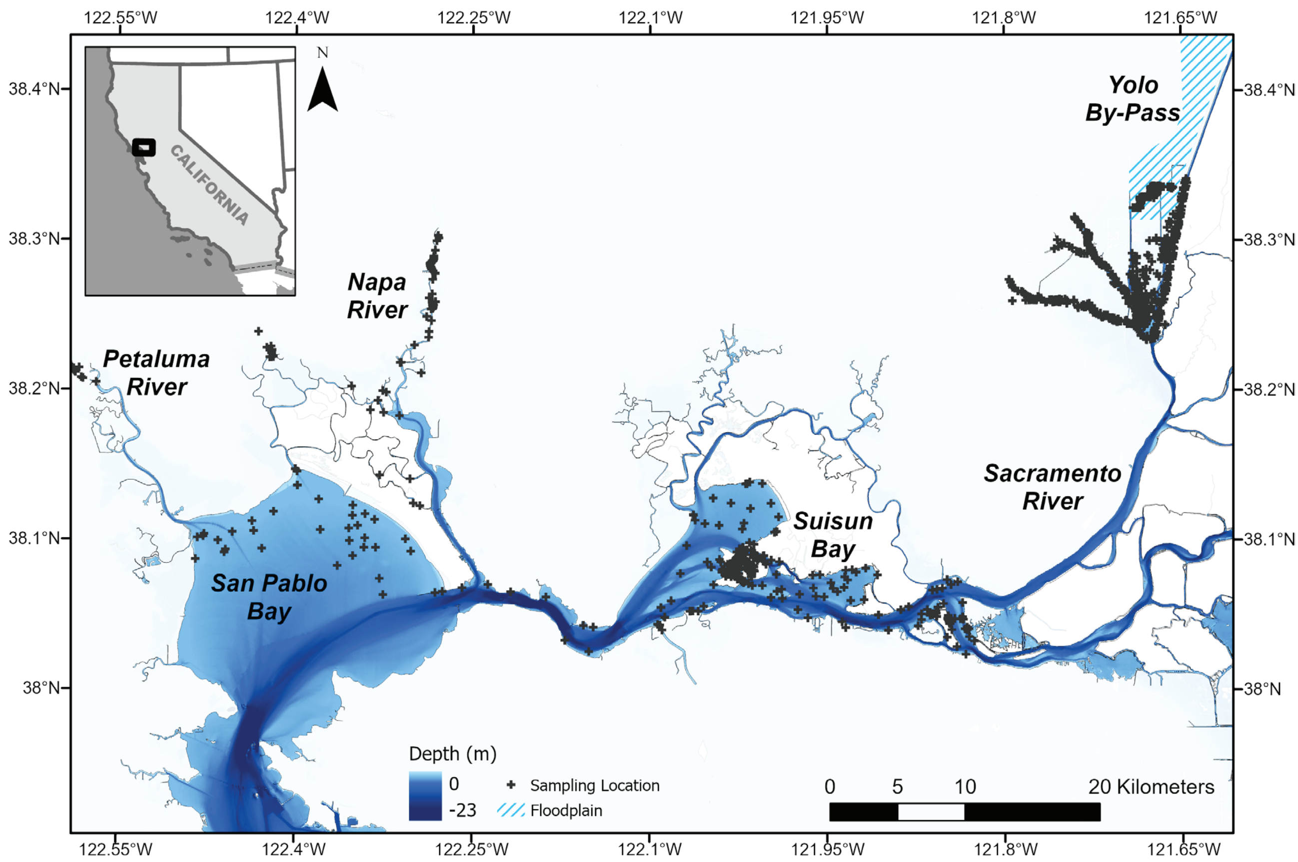

Figure 1 Geographic boundaries of study locations within the upper San Francisco Estuary, with gill-net sampling locations, 2010–2018

and mesh (m_j), where μ = Parameter 1(m_j) could be used to predict the target fish length a given mesh size would capture the most effectively (Carol and Garcia–Berthou 2007; Millar and Holst 1997). Parameter 2 (σ for normal fixed, k_2 for normal proportional, k for gamma, and σ for log-normal) represents the deviance or spread for each model (Millar and Holst 1997; Millar and Fryer 1999).

We determined validation of the goodness of fit for each model by comparing model deviance and examining the deviance residual plots. For each species, the model with the lowest deviance and the smallest, most randomly distributed residual plot was considered the best-fitting model (as in Carol and Garcia–Berthou 2007; Millar and Holst 1997; Santos et al. 2003). We calculated the model deviance of the fitted models from the observed data by summing the squared residual values (Millar and Fryer 1999). Examination of the residual plots gives more information about how well the model is fitting the data, or where the model fails to describe the data. A residual plot with a good fit would show small and randomly distributed residuals, whereas a plot with large or systematically patterned residuals indicates poor fit (Holst et al. 1998). Negative deviance residuals indicate that fewer fish were caught than the model expected, while positive deviance residuals indicate more fish were caught than expected (Millar and Holst 1997).

RESULTS

The data set compiled to estimate the selectivity curves included a total of 7,096 individual fish observations from 882 gill-net sets. Our analyses focused on the 15 most numerous species encountered (Table 1).

The smallest mesh (38.1 mm) was the only size that captured all 15 species in this study, with

Table 1 Results of different models of gill-net selectivity for 15 fish species in the upper San Francisco Estuary with number of fish caught (N); minimum and maximum standard length (SL) in millimeters (mm). Parameters 1 and 2 are: k and σ for normal fixed model; k_1 and k_2 for normal proportional model (spread proportional to mesh size); α and k for gamma model; and $\mu 1$ and σ for log-normal model. Deviance statistic measures goodness of fit (lowest deviance, in **bold**, indicates a better fit).

COMMON NAME *Latin name*	*n*	Min SL (mm)	Max SL (mm)	Model	Parameter 1	Parameter 2	df	Deviance
AMERICAN SHAD	89	105	412	**Normal fixed**	**4.02**	**24.18**	**78**	**30.06**
Alosa sapidissima				Normal proportional	4.18	0.24	78	39.76
				Gamma	68.82	0.06	78	37.15
				Log-normal	5.06	0.12	78	36.48
BLACK CRAPPIE	108	83	250	Normal fixed	2.56	37.27	70	74.22
Pomoxis nigromaculatus				Normal proportional	2.79	0.49	70	89.29
				Gamma	18.50	0.15	70	73.39
				Log-normal	**4.64**	**0.23**	**70**	**67.21**
BLUEGILL	35	68	183	Normal fixed	2.08	20.67	42	41.43
Lepomis macrochirus				Normal proportional	2.28	0.21	42	55.36
				Gamma	29.47	0.08	42	45.40
				Log-normal	**4.43**	**0.18**	**42**	**41.33**
GOLDEN SHINER	82	108	179	Normal fixed	3.55	29.75	30	32.66
Notemigonus crysoleucas				**Normal proportional**	**3.54**	**0.25**	**30**	**27.55**
				Gamma	35.00	0.10	30	31.91
				Log-normal	4.96	0.19	30	34.25
HITCH	87	45	345	**Normal fixed**	**3.93**	**47.65**	**98**	**77.23**
Lavinia exilicauda				Normal proportional	4.23	0.72	98	85.11
				Gamma	23.33	0.18	98	81.50
				Log-normal	5.07	0.22	98	82.16
JACKSMELT	253	186	380	**Normal fixed**	**6.00**	**38.53**	**74**	**95.28**
Atherinopsis californiensis				Normal proportional	6.23	0.59	74	118.81
				Gamma	63.51	0.10	74	105.72
				Log-normal	5.46	0.13	74	102.38
LARGEMOUTH BASS	135	103	390	Normal fixed	3.25	51.27	98	133.48
Micropterus salmoides				Normal proportional	3.60	1.06	98	154.45
				Gamma	16.21	0.23	98	134.64
				Log-normal	**4.91**	**0.25**	**98**	**127.63**
REDEAR SUNFISH	436	73	242	Normal fixed	2.25	25.19	66	181.79
Lepomis microlophus				Normal proportional	2.40	0.24	66	265.26
				Gamma	29.98	0.08	66	196.38
				Log-normal	**4.50**	**0.18**	**66**	**167.59**
SACRAMENTO PIKEMINNOW	379	110	565	**Normal fixed**	**4.82**	**50.95**	**154**	**204.65**
Ptychocheilus grandis				Normal proportional	5.04	0.72	154	205.92
				Gamma	32.45	0.16	154	185.88
				Log-normal	5.24	0.18	154	185.91
SACRAMENTO SPLITTAIL	1933	113	480	Normal fixed	4.09	37.65	118	301.15
Pogonichthys macrolepidotus				Normal proportional	4.28	0.41	118	358.20
				Gamma	44.47	0.10	118	288.27
				Log-normal	**5.09**	**0.15**	**118**	**284.16**

Table 1 Results of different models of gill-net selectivity for 15 fish species in the upper San Francisco Estuary with number of fish caught (N); minimum and maximum standard length (SL) in millimeters (mm). Parameters 1 and 2 are: k and σ for normal fixed model; k_1 and k_2 for normal proportional model (spread proportional to mesh size); α and k for gamma model; and $\mu1$ and σ for log-normal model. Deviance statistic measures goodness of fit (lowest deviance, in **bold**, indicates a better fit). *(Continued)*

COMMON NAME *Latin name*	*n*	Min SL (mm)	Max SL (mm)	Model	Parameter 1	Parameter 2	df	Deviance
SACRAMENTO SUCKER	159	173	490	**Normal fixed**	**3.59**	**52.57**	**110**	**113.33**
Catostomus occidentalis				Normal proportional	2.34	2.56	110	150.33
				Gamma	15.94	0.23	110	134.82
				Log-normal	4.95	0.22	110	124.50
STRIPED BASS	2166	45	904	Normal fixed	4.52	73.28	230	984.21
Morone saxatilis				Normal proportional	4.98	2.06	230	1435.18
				Gamma	15.57	0.32	230	922.83
				Log-normal	**5.21**	**0.25**	**230**	**751.43**
THREADFIN SHAD	124	91	148	Normal fixed	3.49	30.40	22	43.52
Dorosoma petenense				**Normal proportional**	**3.18**	**0.18**	**22**	**33.56**
				Gamma	34.92	0.10	22	36.68
				Log-normal	4.95	0.21	22	37.83
TULE PERCH	253	64	232	Normal fixed	2.13	20.55	58	105.25
Hysterocarpus traskii				Normal proportional	2.27	0.15	58	137.86
				Gamma	36.49	0.06	58	108.50
				Log-normal	**4.44**	**0.17**	**58**	**97.59**
WHITE CATFISH	857	104	383	**Normal fixed**	**3.21**	**44.20**	**106**	**187.58**
Ameiurus catus				Normal proportional	3.57	0.66	106	274.16
				Gamma	19.95	0.18	106	212.12
				Log-normal	4.90	0.23	106	195.81

the 50.8-mm mesh capturing 14 species, the 63.5 and 88.9-mm mesh capturing 11 species each, and the 76.2-mm mesh capturing 10 species. The total number of fish captured in each mesh size generally decreased as mesh size increased, with the exception of the 38.1-mm mesh capturing the second-lowest number of fish (*n* = 1,180). The 50.8-mm mesh captured the greatest number of fish (*n* = 1,992) followed by the 63.5-mm mesh (*n* = 1,639), the 76.2-mm mesh (*n* = 1,371), and the 88.9-mm mesh catching the fewest fish (*n* = 914). In general, fish length increased with gill-net mesh size (Figure 2).

Log-normal and normal, fixed-spread models fitted catch data best for most fish species (Figure 3, Figure 4, Table 1). Log-normal models were generally the best fit for deep-bodied, spiny-rayed fishes, and had the lowest model deviance (Table 1)—indicating better fit—for Black Crappie, Bluegill, Largemouth Bass, Redear Sunfish, and Tule Perch. Sacramento Splittail and Striped Bass also had the best fit for log-normal models. The normal, fixed-spread model usually worked best for soft-rayed, streamlined fishes including American Shad, Hitch, Jacksmelt, Sacramento Pikeminnow, Sacramento Sucker, and White Catfish. The normal, proportional-spread model had the lowest model deviance for Golden Shiner and Threadfin Shad. The gamma model was not the best-performing model for any of the sampled species.

Examination of the deviance residual plots (Figure 4) indicated that the best-fit models appeared to represent the observed data in a

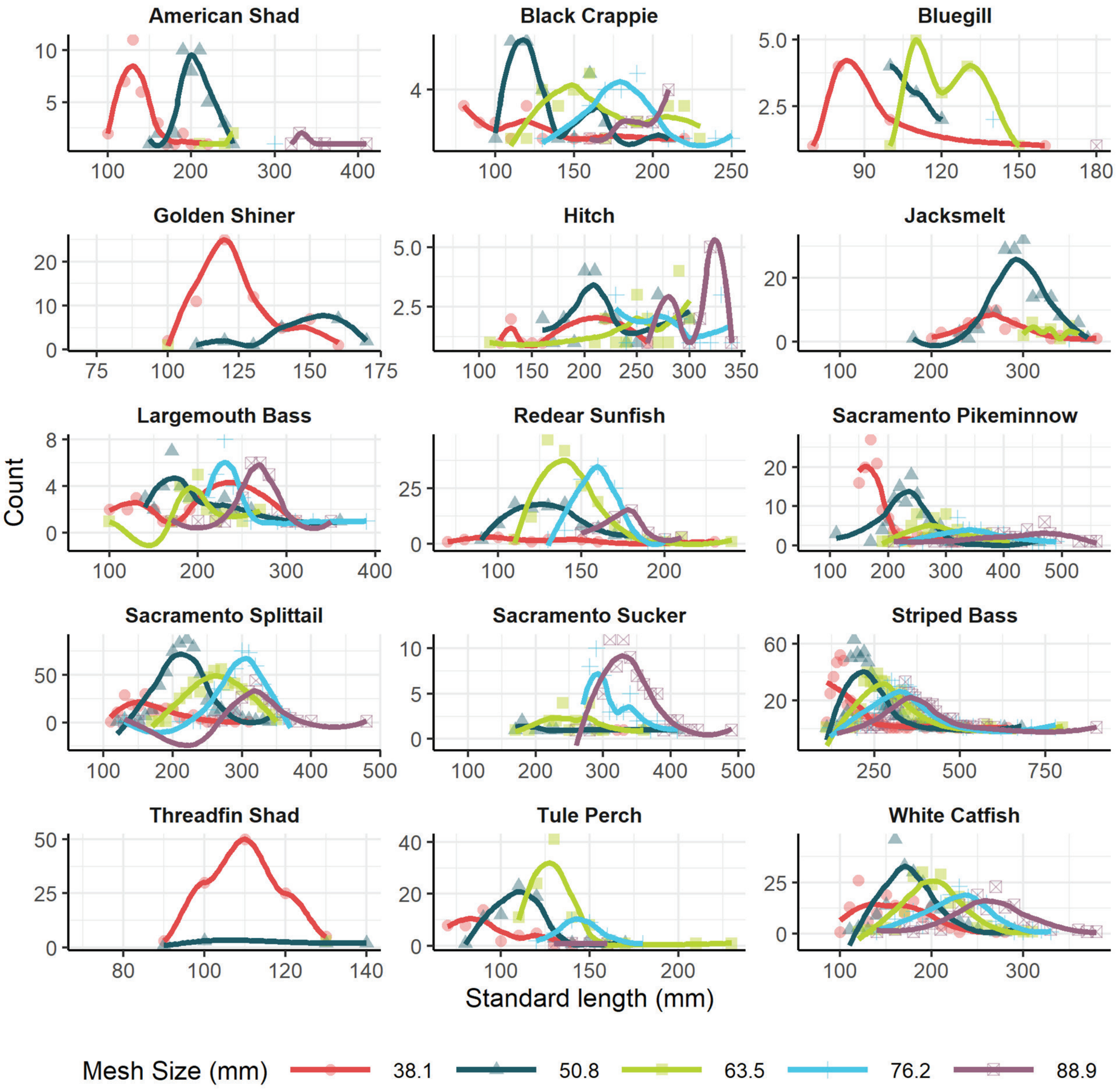

Figure 2 Length–frequency distributions of 15 fish species caught by each gill-net mesh size. *Points* represent raw data; *lines* represent the smoothed conditional mean.

generally unbiased way with small deviances (small circles, Figure 4) that were not strongly clustered either within or across mesh sizes. The majority of deviance residual plots showed a random pattern of residuals, with few obvious groupings of large positive or negative values for any mesh size, with some exceptions. For example, the Striped Bass deviance residual plot indicated that both more larger fish (> 375 mm SL) and fewer smaller fish (< 300 mm SL) were caught with the 38.1- and 50.8-mm mesh than was predicted by the model (Figure 4). The residual plot for Sacramento Splittail shows that the 50.8-mm mesh captured more smaller fish

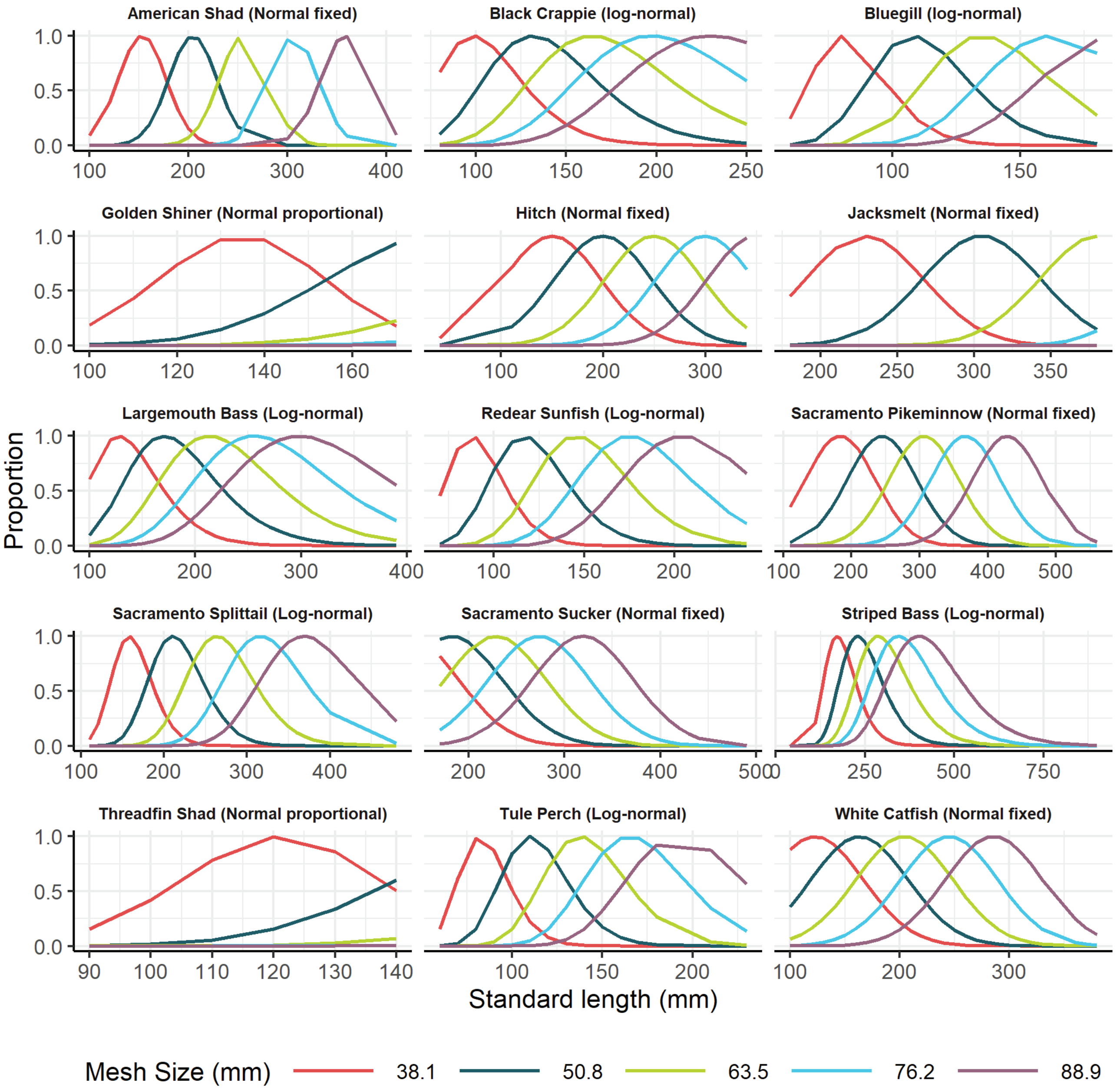

Figure 3 Fitted gill-net selectivity curves of the best-fit model for 15 species in the upper San Francisco Estuary (mesh size denoted by *line color*). Best-fit model name is in *parentheses* next to each species' selectivity curve (*see* Table 1 *for model details*).

(>250 mm SL) than predicted by the model, as well as showing that the larger mesh sizes (76.2- and 88.9-mm mesh) may be catching more smaller fish than the model predicted (Figure 4). The Striped Bass and Sacramento Splittail residual plots showed the greatest residual density because they had the largest number of fish caught (Table 1).

DISCUSSION

The results of this study showed that while all mesh sizes caught fish, the smallest mesh size (38.1 mm) caught the greatest diversity of species (15) but the second-lowest number of individual fish (n = 1,180). The second-smallest mesh size (50.8 mm) caught the second-greatest diversity of species (14) and the greatest number

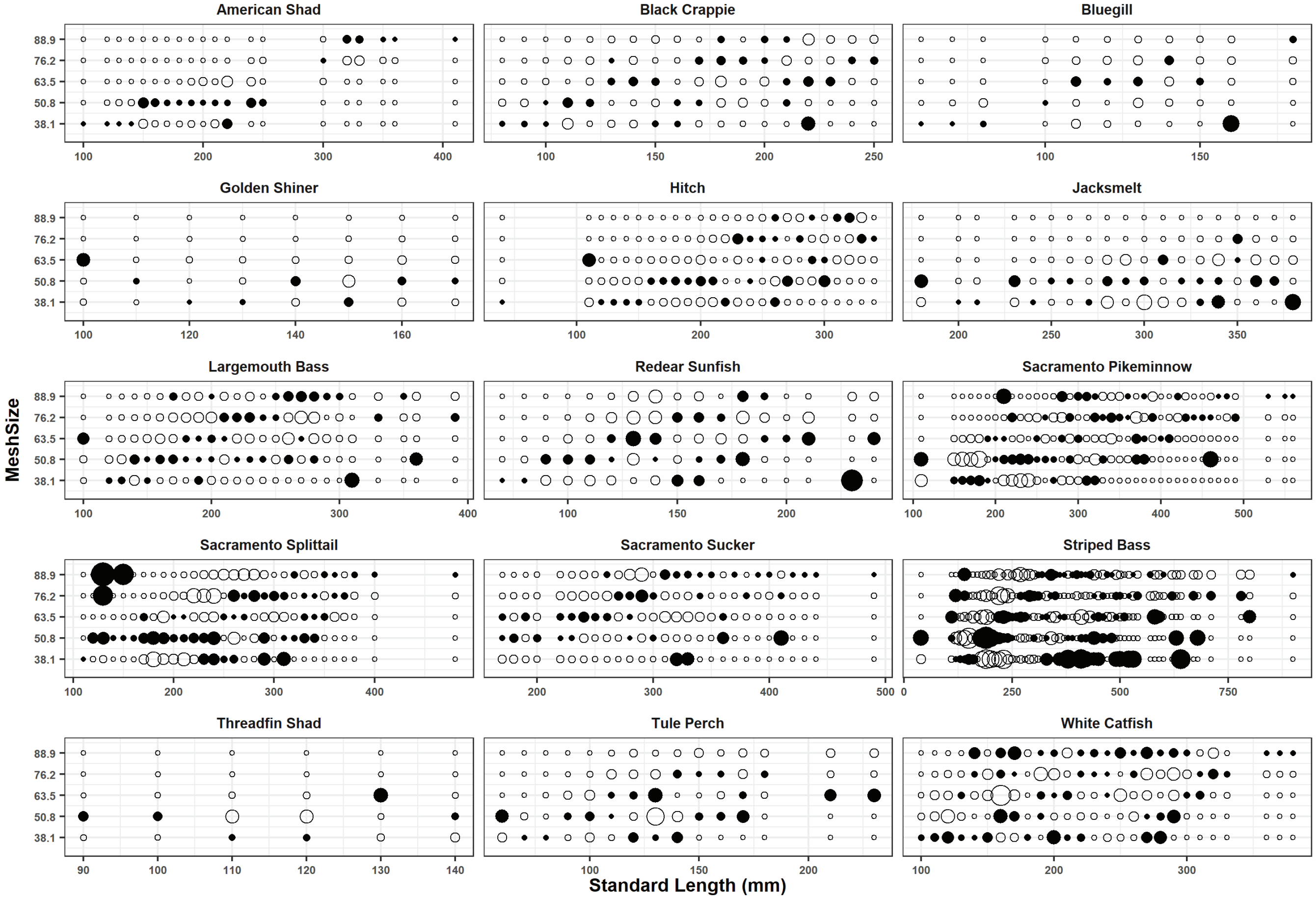

Figure 4 Deviance residual plots of the best-fit model for 15 species in the upper San Francisco Estuary (*see* Table 1 *for model details*). *Solid circles* represent positive residuals, *open circles* represent negative residuals. The area of the circle is proportional to the square of the residual.

of individual fish (*n* = 1,992). For most species encountered in this study we observed a range of sizes, suggesting applicability for each species (Figure 2). Selectivity models for species with fewer data points and/or narrower encountered size ranges (e.g., Bluegill [n=35]) could have been disproportionately affected by large- or small-size outliers; however, they still provide qualitative assessments of relative selectivity for commonly used mesh sizes.

Gill-net selectivity is influenced by both availability (the likelihood of a fish being in the immediate sampling area and encountering the net) and contact selectivity. Availability can be influenced by environmental factors, net placement, deployment duration and timing, and associations between species caught in the net (Berger et al. 2012; Kraus et al. 2017). Contact selectivity is influenced by factors such as net material (e.g., visibility, elasticity, etc.) and fish morphology, including fish depth and girth, as well as the presence of spines or other hard protrusions that become entangled in the nets, rather than the fish being caught as intended (Hamley 1975; Millar and Fryer 1999; Carol and Garcia–Berthou 2007; Grati et al. 2015). The underlying mechanisms that drive observed selectivity (e.g., detection vs. contact) were beyond the scope of this study; however, indirect estimates of gill-net selectivity such as those presented in this study are still valuable for targeting a given species or size class and for contextualizing sampling information.

Size selectivity of sampling gear is important to consider when developing sampling strategies for fisheries research and monitoring projects. Currently, there is little information on gill-net selectivity for species in the upper estuary. The gill-net selectivities presented here can help refine sampling strategies to increase the likelihood of capturing targeted size classes and provide important context for previously published studies and data sets. The selectivity functions from this study could be applied to other length–frequency data sets collected via gill netting, to develop a more accurate assessment of the population size distribution of a targeted species.

ACKNOWLEDGMENTS

Funding was provided by the Bureau of Reclamation (IA# R15PG00085). Special thanks to the staff of the Aquatic Ecology Group of the USGS California Water Science Center and numerous other individuals for collecting the data examined in this study. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US Government.

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