



**Abstract**—The fishery for Pacific hake (*Merluccius productus*) was established in the northern Gulf of California (NGC) in Mexico in 2000. To describe relevant features of the fishery and biology of Pacific hake, we analyzed 5 years of data from an on board observers program. Using generalized additive models, we standardized catch per unit of effort (CPUE), mean standard length (SL), and sex ratio. Also, we investigated by year the joint effect of maturity stage and sex on size distribution, biometric relationships, and the effect of maturity stage (juvenile or adult) on sex ratio. For all characteristics, significant inter-annual variability was observed. An average decrease was observed both in CPUE (52%) and mean SL (7%) during January–March. Adult males were more abundant in catch, with a male-to-female ratio of 1.12:1.00 ( $P < 0.05$ ), and adult females were larger than males ( $F = 807.09$ ,  $P < 0.05$ ). Our results support the previously suggested hypothesis that the NGC is the winter spawning ground for Pacific hake in the region. Further research is needed to determine the status of the stock in the NGC and to outline specific potential management strategies.

## Catch rate, length, and sex ratio of Pacific hake (*Merluccius productus*) in the northern Gulf of California

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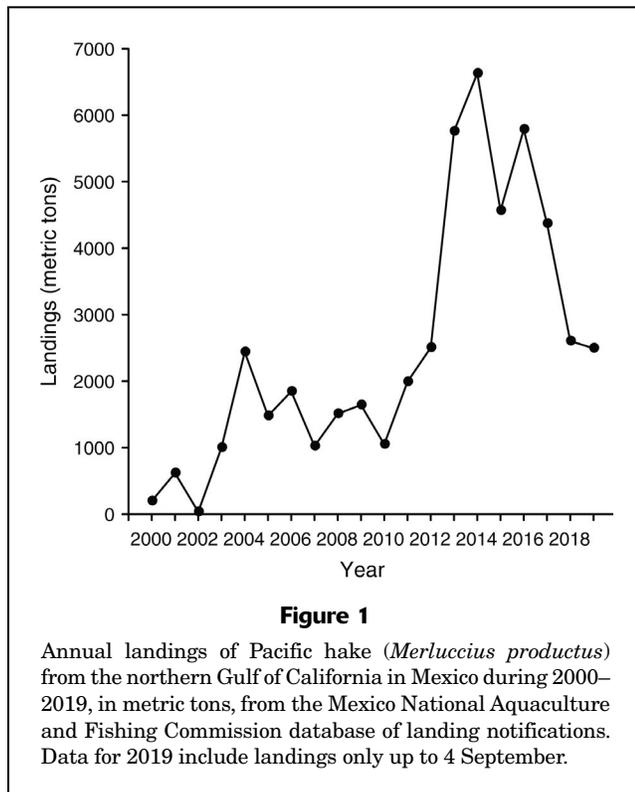
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The Pacific hake (*Merluccius productus*) is the most productive and economically important fish species on the west coasts of the United States and Canada (Hamel et al., 2015), with landings exceeding 400,000 metric tons (t) in recent years (Grandin et al., 2020). This species is distributed from the Gulf of Alaska to Costa Rica, including the Gulf of California (Lloris et al., 2003). In Mexico, early estimates of biomass of Pacific hake in the northern Gulf of California (NGC) ranged from 30,000 to 65,000 t (Mathews et al., 1974; Padilla-García, 1981), and the maximum sustainable yield was 2288–11,453 t. Despite the known abundance of Pacific hake, trawlers licensed to catch shrimp

and finfish species were not interested in commercial use of Pacific hake until the late 1990s (Ramírez-Rodríguez, 2017). Total landings of Pacific hake have ranged from 197 t (in 2000) to a peak of 6628 t (in 2014), with a mean of approximately 2225 t for 2000–2019 in the NGC (Fig. 1).

The Pacific hake, one of the most abundant fish species in the California Current Large Marine Ecosystem, plays a significant ecological role as a link between species of low (euphausiids) and high (sharks and seals) trophic levels (Ressler et al., 2007). Because of the commercial importance of this demersal species, its biological, ecological, migratory, and fishery traits have been widely



studied in the United States and Canada (McFarlane and Beamish, 1985; Smith et al., 1992; Saunders and McFarlane, 1997; Benson et al., 2002; King et al., 2012). However, studies of Pacific hake in Mexico are few and scattered.

The government of Mexico began issuing permits for the commercial catch of Pacific hake in 2018 to states around the Gulf of California (Sonora, Baja California, and Sinaloa). Currently, the only rule to control fishing effort is a limit of the number of permits to 80 (DOF, 2018). The fishing season for this species occurs, on average, during winter and spring (January–March) each year, and the largest portion of landings come from Sonora.

Little is known about the biology and population dynamics of Pacific hake in the NGC. It has been hypothesized that this population belongs to a different species, the Cortez hake (*M. hernandezii*) (Mathews, 1985), mainly because of its maximum size of 107 cm total length (TL), much larger than that of the unfished population of what had been considered Panama hake (*M. angustimanus*), a species that was also called the dwarf hake, from the southern Gulf of California and Baja California Sur (33.5 cm TL) (Mathews, 1975; Balart-Páez, 2005). Nevertheless, results from molecular and meristic studies indicate the presence of a single species, *M. productus*, in North America with different population units (Silva-Segundo et al., 2011; García-De León et al., 2018).

This study aimed to describe relevant features of the fishery and biology of the Pacific hake caught in the NGC. We report for the first time the variability of catch rates and population structure, by length and sex, of this species

in this region, as well as the morphometric relationships (length–weight and length–length). This information can be used as a baseline for future stock assessments and fisheries management.

## Materials and methods

### Data and sample collection

The fishery was monitored by an on board observer program from 2015 through 2019 during the January–March fishing season with a percentage of coverage of total trips ranging from 5% (in 2016) to 12% (in 2019). The fleet that targeted Pacific hake was based in Puerto Peñasco (76%) and Guaymas (12%), Sonora; Mazatlán, Sinaloa (8%); and San Felipe, Baja California (4%). During 77 trips on board 25 commercial ships, 817 trawl tows were completed.

The fishery used diurnal bottom trawling, and vessels deployed trawl net sets from 0600 to 1800. The width of the net mouth was 30 m on average and opened vertically (to about 4 m) as a result of a floating line in the top rope and a ballast chain in the lower rope of about 450 kg. The mesh size in the codend of nets ranged from 6.35 to 12.70 cm (2.5–5.0 in), and the most common (89%) mesh sizes were 10.16 cm (58%), 7.62 cm (18%), and 8.89 cm (13%). The average speed and duration of trawl tows were 4.37 km/h (standard deviation [SD] 0.55) (2.36 kt [SD 0.30]) and 3.53 h (SD 1.27), respectively. The depth of trawl tows varied, with a range of 111–335 m and a mean of 253.2 m (SD 28.75). Trawl tows followed the slope of the Delfín Basin, always south of the Upper Gulf of California and Colorado River Delta Biosphere Reserve and a refuge for vaquitas (*Phocoena sinus*) in a fishing zone called *the horseshoe* by fishermen because of its shape (Fig. 2).

On board fishing vessels, fishermen head and gut Pacific hake. A total of 2853 Pacific hake were weighed before and after processing. We estimated that an average of 38.74% (SD 7.30) of total weight was lost during processing. Then, to account for the percentage of loss, the processed weight was multiplied by a conversion factor (FAO<sup>1</sup>) of 1.65 (SD 0.19).

After processing, fish are arranged in plastic boxes that weigh ~70 kg, washed with seawater, and stored between ice layers in the cargo hold. During this process, small (<40 cm TL) and damaged Pacific hake are discarded. Nominal catch (NC) of Pacific hake per tow was estimated with the following equation:

$$NC = CF (B \times W) + D, \quad (1)$$

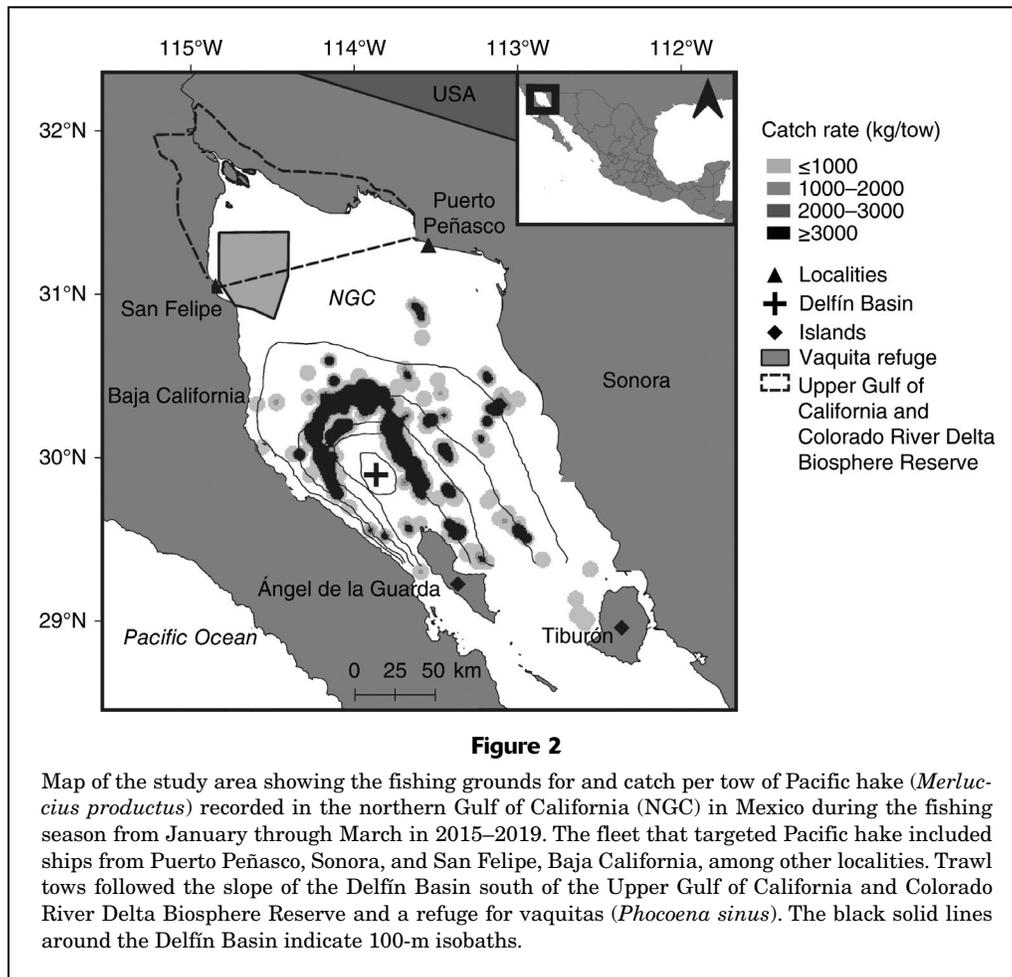
where  $CF$  = the conversion factor needed to estimate live weight from Pacific hake gutted and headed;

$B$  = the number of boxes stored;

$W$  = the weight of each box (~70 kg); and

$D$  = an observer's estimate of the weight of Pacific hake discarded.

<sup>1</sup> FAO. 2000. Conversion factors: landed weight to live weight. FAO Fish. Circ. 847, 176 p. FAO, Rome. [Available from [website](#).]



The NC was divided by the duration of the trawl tow (from the end of net launch until the start of net collection), to obtain the catch rate, or catch per unit of effort (CPUE), in kilograms per hour.

Observers recorded biometrics, including standard length (SL) and total fresh weight, from ~60% of tows per trip: 98 of 131 trips in 2015, 69 of 118 trips in 2016, 93 of 181 trips in 2017, 105 of 170 trips in 2018, and 108 of 217 trips in 2019. They selected random samples of fish (maximum of 100 fish per set) and identified them to species following Lloris et al. (2003). Standard length of fish was measured from the tip of the mouth to the caudal peduncle to the nearest 0.1 cm. Total fresh weight was measured by using a digital balance with an accuracy of 1 g. The specimens were dissected to determine sex and maturity stages. We used a 5-stage morpho-chromatic key to determine the maturity of Pacific hake, according to Holden and Raitt (1975): immature (stage 1), developing (stage 2), mature (stage 3), spawning (stage 4), and postspawning or spent (stage 5). To ease comparisons, we considered fish that had signs of recent, current, or imminent spawning (stages 3–5) to be adults. Fish assigned to stages 1 and 2 were considered juveniles.

## Data analysis

**Catch rate standardization** From all the trawl tows completed (number of tows [ $n$ ]=817), we excluded 3 tows because of gear malfunction, according to Maunder and Punt (2004), and 9 tows completed in April 2019 because of incomparability. A log-transformed index of catch per unit of effort (logCPUE) of the positive values (number of values=805) was used for hypothesis testing because these values followed a log-normal-like frequency distribution. The geometric mean was used as the index for mean CPUE.

First, we developed generalized linear models (GLMs) to test the effect of the selected explanatory variables. However, we found several nonlinear effects, a result that violates the main assumption of GLMs. Then, we used generalized additive models (GAMs), which are semiparametric extensions of GLMs with an additive predictor (Guisan et al., 2002), to identify significant explanatory variables (speed of trawl, mesh size in the codend, depth, and the hour of the day, month, and year) and the nature of the relationships with the logCPUE. We considered a normal probability distribution of

logCPUE and used its canonical link function (*identity*), meaning that a proportional rate of change between the set of explanatory variables and logCPUE was expected, and we evaluated each model's residuals to verify compliance with assumptions. To avoid confounding effects, we tested multicollinearity in explanatory variables through tests of correlation and analysis of variance inflating factors. We used only variables with variance inflating factors <3 (Zuur et al., 2009). Model formulations were tested according to our previous knowledge of the system. Stepwise addition of terms was conducted, and we kept only variables that reduced the Akaike information criterion (AIC) by at least 2 units and that had a significant increase of explained deviance (Marín-Enríquez et al., 2020). Also, variables with effective degrees of freedom greater than 8 were excluded because they are considered highly nonlinear and difficult to interpret (Zuur et al., 2009). The model with the lowest AIC was considered the best (Burnham and Anderson, 2004). Equal fishing power for the entire fleet was assumed.

**Variability of length and sex composition** The length and sex composition of the catch of Pacific hake were assessed by using a 2-step approach. First, using GAMs, we repeated the analysis previously described to identify significant explanatory variables and the nature of the relationship. For this purpose, we used only tows for which biometrics were recorded ( $n=469$ ) and estimated the mean SL and sex ratio for each one. An index of the natural logarithms of sex ratios (logSR) and mean SL were used as response variables of the GAMs.

The second step involved a detailed analysis of the distribution of SL in catch related to the factors of sex and maturity stage (juvenile or adult) by using a 2-way analysis of variance with interaction. For significant effects, we included the year factor to evaluate temporal consistency. A Tukey's honestly significant difference test was carried out to identify level-specific differences.

Also, we performed a set of chi-square tests to examine significant departures from the null hypothesis of an equal sex ratio (ratio of the number of males to the number of females: 1:1) according to Zar (1999).

**Biometric relationships** The length–weight relationship (LWR) was estimated by fitting a power model:

$$TW = a(SL)^b, \quad (2)$$

where  $TW$  = the total weight (in grams);

$a$  = the intercept; and

$b$  = the slope (allometric coefficient).

Models were fit hierarchically to each data set for Pacific hake caught in this study, starting with the full data set and continuing with data sets for each sex, maturity stage, and year. Parameter optimization for each model was conducted by minimizing the residual sum of squares (RSS). Statistical differences in the LWR by sex, maturity stage, and year were assessed by a series of “extra sum

of squares” tests (Ritz and Streibig, 2008) defined by the following equation:

$$F = \frac{(RSS_0(\beta_0) - RSS_1(\beta_1)) / (df_0 - df_1)}{RSS_1 / df_1}, \quad (3)$$

where  $F$  = the Fisher's parameter;

$df$  = the degrees of freedom;

$\beta_0$  = the nested model; and

$\beta_1$  = subset of each model.

To describe the relationships of TL and fork length (FL) to SL, we used linear regression models:

$$y = a + b(SL), \quad (4)$$

where  $y$  = TL or FL.

Pearson's correlation coefficient ( $r$ ) was used to evaluate the level of association of each pair of variables. The existence of differences between males and females for each relationship was determined by using analysis of covariance.

All data and statistical analyses were carried out by using a significance level of 0.05, Microsoft Excel<sup>2</sup> 2016 (Microsoft Corp., Redmond, WA), and statistical software R, vers. 3.6.1 (R Core Team, 2019).

## Results

### Catch rate standardization

Year and the interaction of month and year were the most important variables (explained 10.69% of total deviance). Also, nonlinear effects (explained by smoothers) were found between tow speed, mesh size of trawl net, depth of tow, and hour of the day of tow in logCPUE (Table 1). The final model explained 19.9% of the total deviance. Levels of CPUE were higher during tows with speeds of 3.50–4.70 km/h (1.89–2.54 kt) and declined inversely with speed (Fig. 3A). Tows of trawl nets with mesh sizes of 7.62–8.16 cm (3.00–3.25 in) had the highest CPUE values, followed by tows of nets with mesh sizes of 9.80–10.00 cm (Fig. 3B). Values of CPUE remained mostly stable with depth. However, lower CPUE levels were observed for tows at depths >280 m, with a consequent increase in the uncertainty (Fig. 3C). The highest CPUE values were recorded during the morning from 0800 to 1000 with a significant decrease beginning after 1400 (Fig. 3D).

Estimated mean CPUE was the highest in 2015 with 633 kg/h (95% confidence interval [CI]: 484–830 kg/h) and the lowest in 2016 with 199 kg/h (95% CI: 158–250 kg/h), and estimates indicate less variability for 2017 (529 kg/h [95% CI: 368–773 kg/h]), 2018 (379 kg/h [95% CI: 310–464 kg/h]),

<sup>2</sup> Mention of trade names or commercial companies is for identification purposes only and does not imply endorsement by the National Marine Fisheries Service, NOAA.

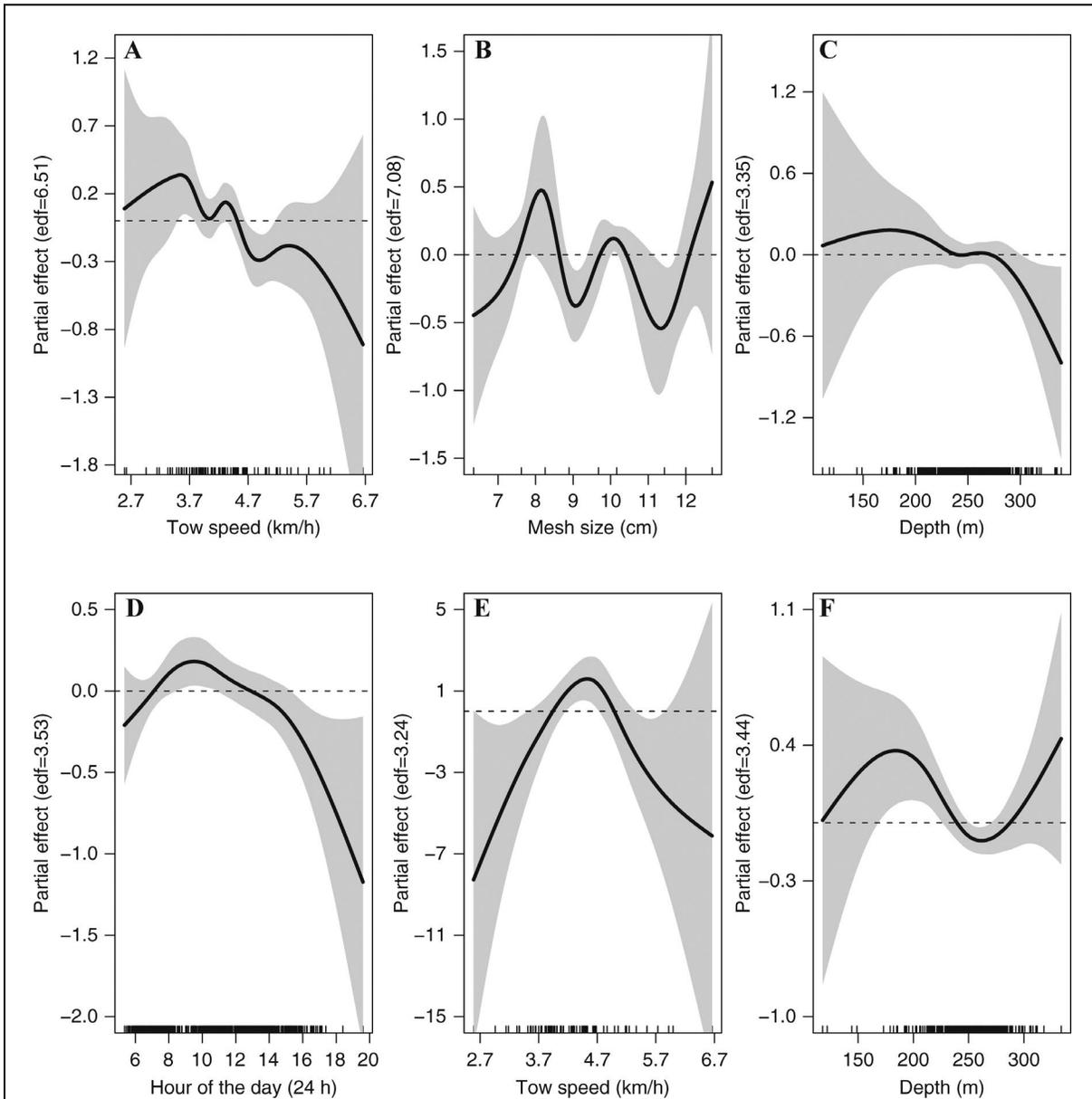
**Table 1**

Summary of variables in the generalized additive models used to standardize the natural logarithm of catch per unit of effort (logCPUE), the mean standard length (SL), and the natural logarithm of the sex ratio (logSR) for Pacific hake (*Merluccius productus*) in the northern Gulf of California. The model with the lowest Akaike information criterion (AIC) was considered the best. Also provided are the differences in AIC values between the best model and each of the other models ( $\Delta$ AICs). The explanatory variables used in the models include tow speed (in kilometers per hour), mesh size in the codend (in centimeters), average depth of trawl tow (in meters), hour of the beginning of the tow (with hours expressed as numerals between 1 and 24), month, year, and the interaction of month and year. Models were fit to data for Pacific hake caught in 2015–2019 during the fishing season from January through March. Asterisks (\*) indicate variables that were excluded from the final models because their inclusion did not reduce AIC in at least 2 units along with a significant increase in the explained variance. The variable hour in the model for mean SL was excluded because it had high nonlinearity (effective degrees of freedom=8.59), considered difficult to interpret.

Response variable	Explanatory variable	Explained deviance (%)	Cummulative deviance explained (%)	AIC	$\Delta$ AIC
logCPUE	Null	0.00	0.00	2603.70	
	Covariates				
	+s(Speed)	2.43	2.43	2598.48	-5.22
	+s(Mesh)	3.69	6.12	2580.93	-17.55
	+s(Depth)	2.04	8.16	2571.97	-8.96
	+s(Hour)	1.05	9.21	2454.34	-117.63
	Factors				
	+Month	1.09	10.30	2449.98	-4.36
	+Year	2.10	12.40	2439.75	-10.23
	Interactions				
	+Month $\times$ Year	7.50	19.90	2380.46	-59.29
Mean SL	Null	0.00	0.00	3505.75	
	Covariates				
	+s(Mesh)*	0.17		3505.59	-0.15
	+s(Hour)*	4.35		3391.07	-114.68
	+s(Speed)	8.68	8.68	3473.78	-32.97
	+s(Depth)*	1.32		3472.30	-1.47
	Factors				
	+Month	4.40	11.70	3460.61	-13.71
	+Year	4.60	15.00	3448.03	-12.53
	Interactions				
	+ Month $\times$ year*	1.90		3449.56	+1.41
logSR	Null	0.00	0.00	1042.23	
	Covariates				
	+s(Mesh)*	2.40		1042.15	-0.08
	+s(Depth)	4.90	4.90	1026.90	-15.25
	+s(Speed)*	2.43		1026.00	-0.90
	+s(Hour)*	0.40		985.29	-40.71
	Factors				
	+Month*	-0.29		1030.00	-44.71
	+Year	7.14	7.14	1024.37	-2.53
	Interactions				
	+ Month $\times$ year	5.76	12.90	1013.30	11.08

and 2019 (433 kg/h [95% CI: 321–590 kg/h]) (Fig. 4A). In addition, a negative trend in CPUE was observed on a monthly basis (Fig. 4B). On average, January had the highest mean CPUE (719 kg/h [95% CI: 493–1057 kg/h]), followed by significant decreases of 43% and 52% in

February (376 kg/h [95% CI: 305–454 kg/h]) and March (312 kg/h [95% CI: 253–385 kg/h]), respectively. However, this pattern was not consistent across years, as indicated by the relevance of the month and year interaction term (Table 1).



**Figure 3**

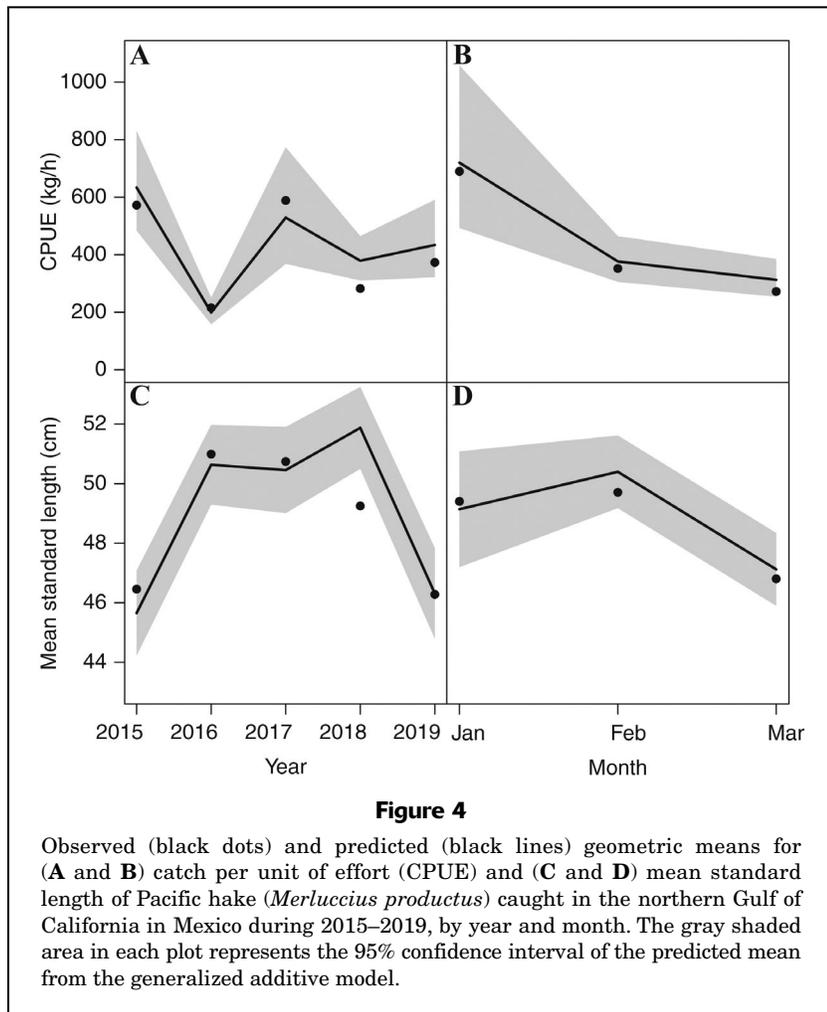
Partial effect plots of generalized additive models fit to the (A–D) natural logarithm of catch per unit of effort, (E) mean standard length, and (F) natural logarithm of sex ratio of Pacific hake (*Merluccius productus*) in the northern Gulf of California in Mexico. Explanatory variables in the models include speed of trawl tow, mesh size of trawl net, depth of trawl tow, and hour of the day of trawl tow (with hours expressed as numerals between 1 and 24). Data used in models are from Pacific hake caught in 2015–2019 during the fishing season from January through March. The gray shaded area in each plot represents the 95% confidence interval, and black lines just above the x-axis represent the density of observations for each covariate. edf=effective degrees of freedom.

### Variability of mean length

The final model for mean SL did not include mesh size, the hour of the day, or depth (Table 1). This model explained 15% of deviance and used just a smoother for tow speed as well as the factors of month and year without interaction. The smoother for speed indicates that tows made

slower and faster than the interval of 4.00–5.00 km/h (2.16–2.66 kt) caught Pacific hake with sizes under the mean SL of fish caught in this study (Fig. 3E).

The minimum annual mean SL occurred in 2015 (45.7 cm [95% CI: 44.2–47.1 cm]), and the maximum was observed in 2018 (51.8 cm [95% CI: 50.5–53.2 cm]). Although yearly differences in mean SL were significant



( $P < 0.05$ ), a specific trend in mean SL was not observed (Fig. 4C). The monthly variability of mean SL indicates that the highest mean SLs occurred during January (49.1 cm [95% CI: 47.2–51.1 cm]) and February (50.3 cm [95% CI: 49.2–51.6 cm]) and that CPUE decreased 7% by March (47.1 cm [95% CI: 45.9–48.3 cm]), as shown in Figure 4D.

#### Variability of sex ratio

The final model of logSR explained 12.9% of the total deviance. The GAM used only a smoother for depth and the parametric effect of year as well as the interaction of month and year (Table 1). Results from the use of a smoother of depth indicate that tows with male-biased catch were conducted at depths  $< 225$  m and  $> 275$  m and that, at depths of 225–275 m, logSR tended to be zero (1:1 male-to-female ratio) or below (Fig. 3F).

No difference was found between months in logSR, but a difference was observed between years. However, the relevance of the month and year interaction means that there is no consistent trend of change of logSR during the fishing season.

#### Size distribution, sex ratio, and maturity

The sizes of Pacific hake sampled ranged from 11.8 to 89.2 cm SL (15.2–108.8 cm TL) with a mean of 47.49 cm SL (SD 13.7) (58.2 cm TL [SD 17.6]). During 2015–2017, the length-frequency distribution was bimodal. Pacific hake in the size class of 15–25 cm SL were most common, and fish in the size classes of 30–45 cm SL and 45–65 cm SL were caught in low numbers. In 2018 and 2019, a more normal distribution of SLs was observed with no clear size classes or flattened intervals. The dominant sex of Pacific hake at SLs  $> 70$  cm was female, and females had significantly larger sizes ( $F = 807.09$ ,  $P < 0.05$ ) than males (Table 2, Fig. 5). As expected, adults had significantly higher SL than juveniles ( $F = 5174.49$ ,  $P < 0.05$ ), and there was a trend across years ( $F = 135.91$ ,  $P < 0.05$ ).

Adults accounted for 72% of all sampled Pacific hake, 70% of females, and 73% of males. Results of the Tukey's honest significant difference test indicate that all mature females were significantly larger than mature males, and the difference was consistent across years. In 2015 (adjusted  $P = 0.99$ ) and 2019 (adjusted  $P = 0.99$ ), no difference was detected in SL between sexes in juveniles (Fig. 6).

Results from the series of chi-square tests indicate a male-skewed sex ratio for all sampled Pacific hake (male-to-female ratio of 1.12:1.00,  $P < 0.05$ ), but

particularly for adult specimens (male-to-female ratio of 1.16:1.00,  $P < 0.05$ ). For juveniles, the sex ratio was 1.00:1.00 ( $P = 0.70$ ). There was no specific annual trend in the sex ratio for juveniles, but for adults, there were significantly more males in 4 out of 5 years. In 2018, we observed a female-biased sex ratio for all sampled Pacific hake (male-to-female ratio of 0.91:1.00). However, data split by maturity stage indicate that the sex ratio of adults favored males (male-to-female ratio of 1.09:1.00) and that females were dominant among juveniles (male-to-female ratio of 0.36:1.00). Although there was no significant bias in the sex ratio in 2019 ( $P = 0.09$ ), males were still more abundant (Table 3).

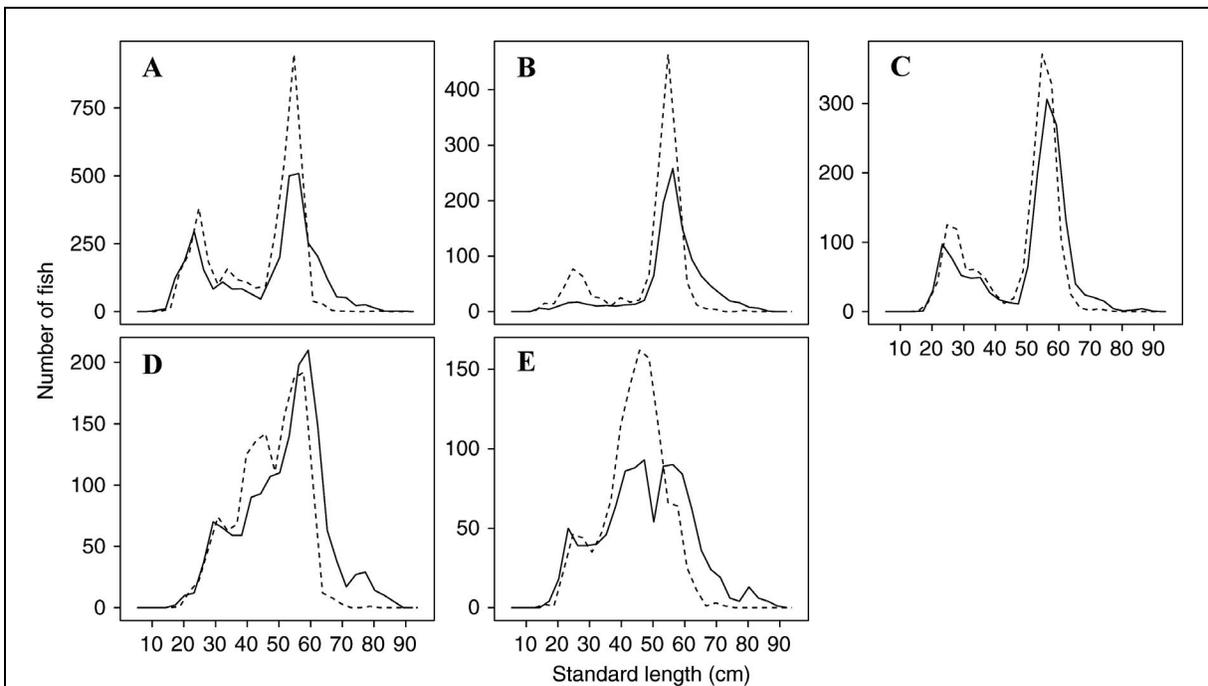
#### Biometric relationships

We found differences in the LWR between years ( $F = 216.55$ ,  $P < 0.05$ ). The highest allometric coefficient ( $b$ ) was estimated for 2015, followed by the lowest estimate for 2016; no differences were observed between 2016 and 2017 ( $F = 1.96$ ,  $P = 0.34$ ). For 2018 and 2019, an increasing tendency was observed, but differences remained present ( $F = 86.81$ ,  $P < 0.05$ ). Differences in the LWR by sex were found in the

**Table 2**

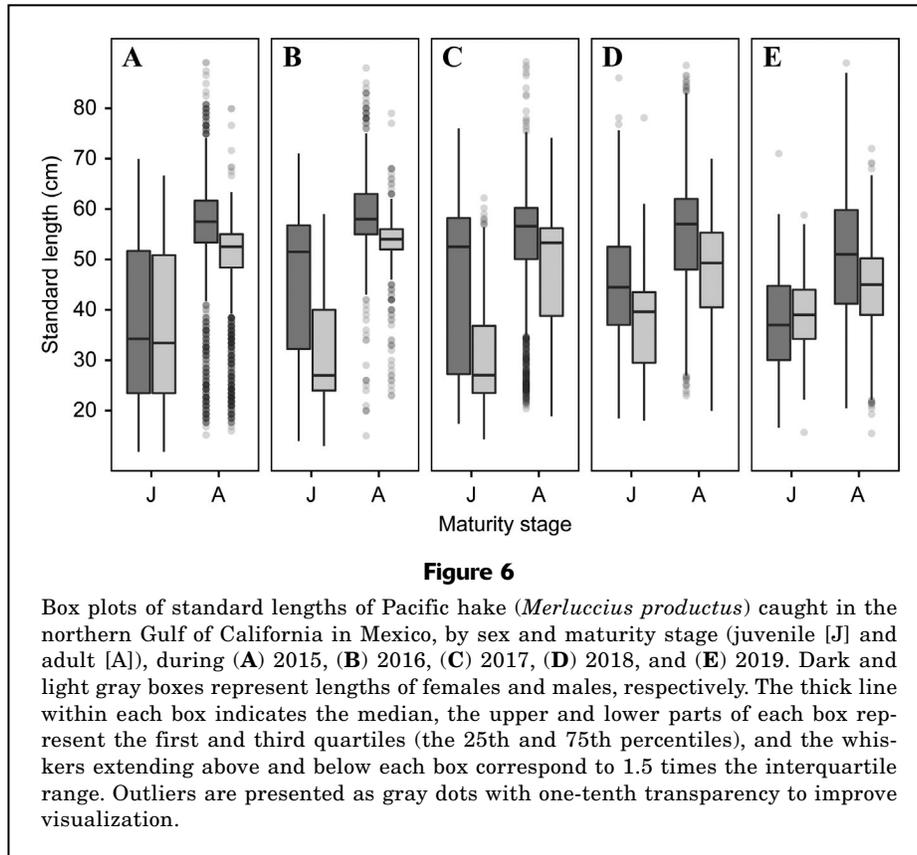
Standard lengths and total weights of Pacific hake (*Merluccius productus*) caught in the northern Gulf of California during the fishing season from 2015 through 2019, by year and sex. Lengths and weights also are provided for all years and both sexes combined. *n*=number of samples; SD=standard deviation.

Year	Sex	<i>n</i>	Standard length (cm)		Total weight (g)	
			Range	Mean (SD)	Range	Mean (SD)
All	All	18,207	11.8–89.2	47.1 (13.7)	22.0–9823.0	1489.9 (1016.2)
2015	All	7255	11.8–89.1	44.8 (14.7)	22.0–9823.0	1347.8 (1021.0)
	All	3322	11.9–89.1	46.7 (16.1)	25.0–9823.0	1558.4 (1228.1)
2016	M	3933	11.8–79.9	43.2 (13.3)	22.0–7120.0	1169.8 (761.5)
	All	2564	13.0–88.0	51.7 (12.3)	26.4–7420.0	1741.8 (892.9)
2017	F	1097	14.0–88.0	56.4 (11.3)	36.0–7420.0	2148.9 (1003.2)
	M	1467	13.0–79.0	48.3 (11.8)	26.4–4607.0	1442.5 (657.8)
2018	All	3129	14.3–89.2	48.7 (13.6)	49.0–7970.0	1547.4 (919.5)
	F	1503	17.4–89.2	51.0 (14.0)	79.0–7970.0	1742.0 (1036.8)
2019	M	1626	14.3–74.1	46.6 (12.9)	49.0–4685.4	1366.3 (751.2)
	All	3077	18.0–88.5	49.6 (12.0)	47.0–8435.0	1633.2 (1075.7)
2019	F	1613	18.5–88.5	52.4 (13.0)	57.0–8435.0	1931.1 (1266.4)
	M	1464	18.0–78.1	46.4 (10.0)	47.0–4805.0	1305.7 (679.6)
2019	All	2182	15.5–89.0	45.8 (12.0)	57.2–8678.0	1395.9 (1083.6)
	F	1059	16.6–89.0	48.4 (13.9)	66.0–8678.0	1691.5 (1358.1)
2019	M	1123	15.5–72.0	43.3 (9.60)	57.2–4288.0	1116.4 (616.9)



**Figure 5**

Distribution of standard lengths of Pacific hake (*Merluccius productus*) caught in the northern Gulf of California in Mexico, by sex, during (A) 2015, (B) 2016, (C) 2017, (D) 2018, and (E) 2019. The solid and dashed lines in each panel represent lengths of females and males, respectively.



**Table 3**

Ratio of the number of males to the number of females, by maturity stage (juvenile [J] or adult [A]) and by year, for Pacific hake (*Merluccius productus*) caught in the northern Gulf of California in 2015–2019. Sex ratios also are provided for all years and both maturity stages combined. The critical value for each chi-square ( $\chi^2$ ) test was 3.81. Asterisks (\*) indicate significant departures from the null hypothesis of an equal sex ratio (a male-to-female ratio of 1.00). M=male; F=female; and N=none.

Year	Maturity stage	Sex ratio	Observed $\chi^2$	P	Sex bias
All	Both	1.12	57.03	<0.05*	M
All	J	1.01	0.15	0.70	N
All	A	1.16	75.09	<0.05*	M
2015	J	1.15	15.66	<0.05*	M
2016	J	1.57	28.64	<0.05*	M
2017	J	0.69	12.63	<0.05*	F
2018	J	0.36	120.37	<0.05*	F
2019	J	0.94	0.23	0.63	N
2015	A	1.22	37.36	<0.05*	M
2016	A	1.28	29.18	<0.05*	M
2017	A	1.15	13.40	<0.05*	M
2018	A	1.09	4.34	<0.05*	M
2019	A	1.08	2.72	0.09	N

general case—with all years pooled—( $F=129.16$ ,  $P<0.05$ ) and consistently in every single year evaluated (Table 4; Fig. 7, A–E). Similarly, the model fits for 2015 and 2018 were close to each other (Fig. 7F); even so, statistical differences were detected ( $F=80.67$ ,  $P<0.05$ ). Females always had higher values of  $b$  than males. However, no significant differences were found in the LWR between juveniles and adults ( $F=0.72$ ,  $P=0.97$ ).

Both analyses of covariance revealed no significant effect of sex in the TL–SL ( $P=0.22$ ) and FL–SL ( $P=0.49$ ) relationships and a high level of correlation for both ( $r>0.99$ ). The resulting estimates of the regression parameters for the TL–SL relationship were 0.89 for  $a$  and 1.21 for  $b$ , and estimates of the parameters for the FL–SL relationship were 0.51 for  $a$  and 1.10 for  $b$ .

**Discussion**

Reports from previous studies have highlighted that the NGC is the winter spawning ground for the Pacific hake because its larvae are dominant in larval fish assemblages (Aceves-Medina et al., 2004; Sánchez-Velasco et al., 2009; Peiro-Alcantar et al., 2013). Also, the high proportion of adults in the catch in this zone (70%) and the sudden increase of catch rates in a relatively limited area found in this study indicate that the fishery for Pacific hake

**Table 4**

Estimated means of the parameters  $a$  (intercept) and  $b$  (slope or allometric coefficient) from the regression power model used for analysis of the length–weight relationship of Pacific hake (*Merluccius productus*) caught in the northern Gulf of California during the fishing season in 2015–2019, by year, sex, and maturity stage (juvenile [J] or adult [A]). Estimates also are provided for all years, both sexes, and both maturity stages combined. Degrees of freedom (df), the coefficient of determination ( $r^2$ ), and the standard error of the mean (SE) are provided for each estimate.

Year	Sex	Maturity stage	df	Regression parameter		
				$a$ (SE)	$b$ (SE)	$r^2$
All	All	All	18,101	0.02 (0.00)	2.89 (0.01)	0.98
All	F	All	8588	0.02 (0.00)	2.93 (0.01)	0.97
All	M	All	9511	0.05 (0.00)	2.63 (0.01)	0.97
All	All	J	5075	0.02 (0.00)	2.90 (0.01)	0.98
All	All	A	1,2941	0.02 (0.00)	2.82 (0.02)	0.98
2015	F	All	3323	0.01 (0.00)	3.06 (0.01)	0.97
2016	F	All	1100	0.03 (0.00)	2.78 (0.02)	0.98
2017	F	All	1487	0.02 (0.00)	2.86 (0.02)	0.99
2018	F	All	1613	0.02 (0.00)	2.90 (0.02)	0.99
2019	F	All	1057	0.02 (0.00)	2.90 (0.02)	0.99
2015	M	All	3923	0.01 (0.00)	3.02 (0.01)	0.97
2016	M	All	1406	0.03 (0.00)	2.74 (0.02)	0.97
2017	M	All	1595	0.03 (0.00)	2.77 (0.02)	0.98
2018	M	All	1461	0.02 (0.00)	2.87 (0.01)	0.97
2019	M	All	1118	0.02 (0.00)	2.90 (0.01)	0.98

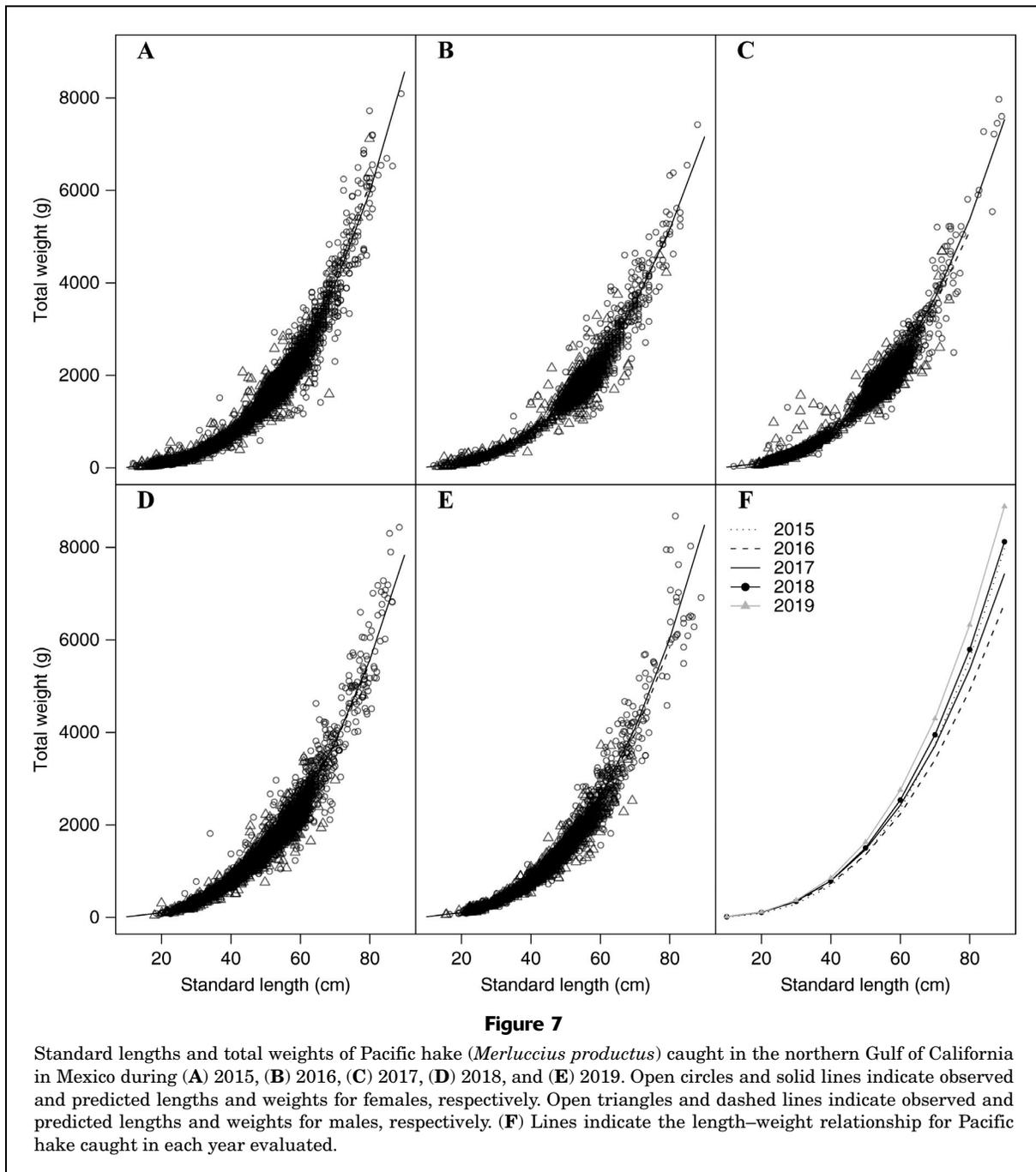
in the NGC occurs during a transient spawning aggregation (Domeier, 2012). Additionally, spawning aggregations of Pacific hake have a male-biased sex ratio, as has been reported for the offshore population of Pacific hake (Saunders and McFarlane, 1997). Several explanations have been proposed for this phenomenon in other hake species, including early arrival and late departure of males to the spawning ground, females spawning in mid-water and a consequently higher proportion of males at the bottom, and a biological strategy to ensure fecundation (Botha, 1986; Di Giacomo et al., 1993; Pájaro et al., 2005; Bustos et al., 2007; Korta et al., 2015).

It is essential to note that the sampling period (and the fishing season for Pacific hake) begins once fishermen obtain high catch rates and once Pacific hake reach commercial size (>40 cm SL). The season ends once the catch rate and mean SL diminish to unprofitable levels. Given the low ex-vessel prices of Pacific hake, with an average price of \$0.61/kg (in 2019 U.S. dollars) during the study period, the profitability of the fishery for Pacific hake depends on achieving high catch rates with low fishing effort (i.e., few fishing days). In addition, the presence of other aggregated and more highly valued finfish species, such as the Gulf croaker (*Micropogonias megalops*), for which the fishing season occurs during March–August (Ramírez-Rodríguez, 2017; Arzola-Sotelo et al., 2018), could offer a concomitant explanation for the shift in the species targeted by the trawler fleet during the spring.

A pattern of catch rates of Pacific hake decreasing during January–March has been observed in other studies in the Gulf of California (Mathews et al., 1974; Grande-Vidal, 1983; Godínez-Pérez, 2016). The reduction in the catch rates in this study and in these other studies could be related to the end of the spawning aggregation of Pacific hake in the NGC. The progressive absence of large (in length and weight) adults reduces the number of individuals of Pacific hake in the fishing grounds and the mean size of the fish caught.

In the NGC, the high concentrations of larvae of Pacific hake are related to the ephemeral presence of an anticyclonic eddy during winter (Sánchez-Velasco et al., 2009). The presence of this eddy seems to influence the spawning areas of other fish species that inhabit the Gulf of California (Contreras-Catala et al., 2012). Therefore, the spawning areas of Pacific hake could be associated with the winter eddy in this zone. The influence of oceanographic structures on spawning areas has been reported for other hake species (Di Giacomo et al., 1993; Marrari et al., 2019).

Results from previous studies indicate that at depths >100 m, winter temperatures (<18°C) in the NGC remain vertically homogeneous (Lavín and Marinone, 2003). Water temperature homogeneity might partially explain the absence of a clear depth-dependent profile of catch rate or mean SL because the fleet deploys trawl nets at depths >200 m during the daytime, when fish have been



observed to migrate nearer to the bottom (Godínez-Pérez, 2016). Diel vertical migration has been reported for Pacific hake in other regions (Hamel et al., 2015).

Winter spawning of Pacific hake has been reported for other populations in the eastern Pacific Ocean (Saunders and McFarlane, 1997). However, slight differences exist between the spawning time and sites of Pacific hake from the NGC and those for Pacific hake from the coastal stock and from Baja California Sur. The Pacific hake in the coastal stock spawn during January–March

several kilometers offshore (Agostini et al., 2006), and Pacific hake from Baja California Sur spawn during February–May, peaking in May (Balart-Pérez, 2005). Pacific hake in NGC spawn only during December–May, peaking in December–February (Denton-Castillo, 2018). The difference in spawning times and sites between these stocks could serve as a gene flow barrier that fosters the genetic isolation indicated by results of other studies (Iwamoto et al., 2015; García-De León et al., 2018).

**Table 5**

Transformed standard lengths (SLs) reported in the literature for Pacific hake (*Merluccius productus*), by source, sex, season, region, and original type of length measurement (total length [TL], fork length [FL], or SL). Regions used in sources include Canada (CAN), Strait of Georgia (SG), Vancouver Island (VI), Washington (WA), Oregon (OR), California (CA), Baja California Sur (BCS), and the northern, central, and southern Gulf of California (NGC, CGC, and SGC).

SL (cm)		Sex	Season	Region	Original length type	Source
Range	Mean					
≤62.3	48.2	F	All	CA	TL	Best (1963)
≤54.0	44.9	M	All	CAN, WA, OR, CA	TL	Alverson and Larkins (1969)
24.2–65.7	42.3	All				
9.5–61.3	–	All				
9.5–72.2	–	F	Spring–summer	CA, OR, WA	FL	Dark (1975)
9.5–59.5	–	M				
9.2–28.7	16.7	All	Spring	CGC–SGC	TL	Mathews (1975)
15.9–88.1	–	All	All	NGC	TL	Mathews (1985)
9.5–72.2	39.5	All	All	SG	FL	McFarlane and Beamish (1985)
37.7–63.6	42.8	All				
37.7–67.7	46.8	F	All	VI	FL	Beamish and McFarlane (1985)
37.7–59.5	49.0	M				
11.7–53.2	33.6	All	Spring	WA, OR, CA	TL	Stepanenko (1989)
–	41.2	F	Winter	WA, OR, CA	FL	Saunders and McFarlane (1997)
–	40.2	M				
7.5–33.5	17.3	All	All	BCS	SL	Balart-Páez (2005)
32.5–40.7	40.7	All	Spring	NGC	TL	Mazorra-Manzano et al. (2008)
–	34.9	F	Summer			
–	33.0	M				
–	35.0	F	Fall	CAN	FL	King et al. (2012)
–	27.4	M				
–	30.4	F	Winter			
–	25.9	M				
10.4–81.5		All	Winter	NGC	TL	Godínez-Pérez (2016)
11.9–89.2	47.4	All				
11.9–89.2	50.0	F	Winter–spring	NGC	SL	This study
11.9–79.9	45.0	M				

Our results indicate that Pacific hake in the NGC present sex dimorphism because adult females had greater maximum lengths, weights, and allometric coefficients than males. These findings are similar to those of other studies that observed differences in size at age after sexual maturity (Dark, 1975; Mathews, 1975; Francis, 1983; Balart-Páez, 2005; King et al., 2012). Additionally, the maximum size that has been reported for Pacific hake was observed in the NGC in this study (Table 5).

In all years except 2015, the allometric coefficient was lower than 3 but above the threshold of a  $b$  value of 2.5 that Pauly (1984) and Froese et al. (2011) considered an indication of negative allometric growth. Furthermore, we did not find differences in the LWR between maturity stages, indicating that length and weight increase proportionally throughout the life of Pacific hake. In this regard, the variability of the allometric coefficient could be interpreted as seasonal growth in weight, as suggested by Bailey et al. (1982). They found that Pacific hake lose 5–10% of total weight during their spawning season (because of inanition) and gain 11–30% during

their feeding season. Unfortunately, because all Pacific hake were sampled during winter (spawning season) and no stomachs were collected in our study, it was not possible to provide evidence of seasonal changes in weight.

Our data indicate that there was no effect of mesh size on mean SL. Homogeneity in mean SL can be explained by smaller individuals escaping because of the mesh size of nets and then, once the net becomes clogged with large individuals, selectivity of nets remaining constant. Likewise, the low abundance of fish in the size class of 30–45 cm SL during 2015–2017 might be evidence of a size-dependent migratory pattern, ontogenetic differences in their spatial distribution, or interannual variability of abundance and distribution linked to environmental conditions (Agostini et al., 2008).

Although these results shed light on the basic biology and fishery of the Pacific hake in the NGC, future studies should address management questions to foster sustainable development. Although population characteristics, such as age structure, growth, maturity, and mortality, and fisheries ecology remain poorly understood for this

species in the NGC, data-limited stock assessments could provide temporary reference points for management.

The maximum size of Pacific hake in the NGC (108.8 cm TL) is at least 3-fold of that reported for Pacific hake in the southern Gulf of California and Baja California Sur (33.5 cm TL), and information about that stock is very limited (Mathews, 1975; Balart-Páez, 2005; Salinas-Mayoral, 2018). In the short term, focusing commercial fishing for Pacific hake on the NGC is a potential management strategy.

As a precautionary measure, the specification that only vessels licensed to take Pacific hake can take individuals of this species in the NGC could help to eliminate fishing effort over the currently allowed level that is a result of illegal, or incidental, catch by other ships that fish in the NGC. In future research, particular attention must be set on examining the possible adverse effects of fishing over a reproductive aggregation.

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