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*Research Article*

# Fleet efficiency in the Pacific hake (*Merluccius productus*) fishery in the Gulf of California, Mexico

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**ABSTRACT.** The control of the fishing effort and establishment of individual catch quotas has been proposed as a strategy to manage the Pacific hake (*Merluccius productus*) fishery in the north of the Gulf of California. In this study, the issues related to the efficiency of hake fishing vessels are analyzed. Two different types of vessels, large and small, were identified using the physical characteristics of 53 vessels in a cluster analysis. Using generalized linear models (GLM), efficiency variation (catch per unit of effort CPUE) was assessed with data derived from onboard observations of 74 trips made by 25 vessels and 814 sets from 2015 to 2019. The variables used to determine their contribution to CPUE were years, vessel types, fishing areas, depth strata, and their interactions. The factors year, fishing area, net type, and vessel type explain the interannual variability in the CPUE. The model, which included the interactions, showed 18% of explained deviance and indicated that interactions between year and area and between depth and vessel were significant and contributed the most to the deviance explained by the model. A GLM exhibited 11% of the explained deviance without considering interactions and indicates that large vessels are 1.5 times more efficient than small vessels.

**Keywords:** *Merluccius productus*; catch quotas; types of vessels; fishing effort; fishing areas; CPUE

## INTRODUCTION

Based on individual per-vessel catch quotas, Fisheries management has contributed to resource and economic sustainability, created incentives that maximize profits, reduced fishing capacity, and offered advantages for management and development (Hoff & Frost 2007, Walden et al. 2012, Hoefnagel & De Vos 2017). The quota system requires good information regarding the resource and the fleet. First, to estimate the total allowable catch and split it into individual quotas among the fleet. For some fisheries, management considers different individual quotas per type of vessel and individual transferable quotas; for others, the quota is the same for each vessel and is not transferable. The manager's decisions depend on the country's fishing laws and policies, the fisher's organization, and support to obtain data for stock assessment and maintenance of management control levels (Arnason 1990, Sutinen 1999, Hatcher 2005).

How many vessels and how large the quota is per vessel depend on their capacities and efficiency and should look to avoid overcapacity and inefficiency in the fishery (Asche et al. 2008, Bonzon et al. 2010, Ramírez-Rodríguez 2017). The capacity is measured as the number of vessels, fishing permits, or characteristics of the vessels and the spatial and temporal distribution of the fishing effort (Soto et al. 2002, Pascoe & Gréboval 2003, Reida et al. 2003, Aisyah et al. 2012). Overcapacity is related to the number of vessels and the increase in the fishing efficiency because of technological innovations (Holland et al. 1999, Bishop 2006, Ye & Denis 2009, Carruthers et al. 2011, Damalas et al. 2014, Quijano et al. 2018, Zhang et al. 2018). It is documented that catch efficiency increases over time through the continuous development of the fishing industry and factors associated with the experience level of the fishermen, the investment in equipment and fishing gears, and the replacement of older vessels (FAO 2008). Therefore, as Ward et al.

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(2004) emphasized, it is important to estimate how the technical efficiency of the ships is related to the opportunities for enhancing fishery performance in the long term.

In the northern Gulf of California, the Pacific hake (*Merluccius productus*) fishery is a recognized important developing fishery. The fleet is part of an industrial fishing complex exploiting different stocks of commercial species throughout the year, including hake, other fish species, and shrimp; it constitutes the main annual income of the vessels (Ramírez-Rodríguez 2017). When the shrimp fishing season ends, vessel owners replace shrimp trawl nets (one or two depending on the vessel's infrastructure) with specific nets for Pacific hake, with a 5-inch mesh size. The shrimp vessels are heterogeneous in size and capacities. This fleet operates north of the Gulf of California, between 100 and 300 m depth (Fig. 1), when the hake is available from January to March. performing an average of three sets per day, in the morning, at noon, and in the afternoon (Ramírez & Almendarez-Hernández 2014, Zamora-García & Stavrinaky-Suárez 2018, Zamora-García et al. 2020).

The managers have proposed looking for sustainability through controlling the fishing effort and establishing individual catch quotas. The commercial catch record began in 2000, with 197 t; between 2004 and 2012, the average catch size was around 2000 t. From 2013 to 2017, 7000 t represents an industry that generates a gross income of approximately 2 million dollars per season (SAGARPA 2018). The maximum number of vessels in the fishery has been restricted to 80 since 2018 (SAGARPA 2018). However, the quota system has not been defined. There is no performance analysis per vessel which also considers the variability associated with spatial and temporal availability of the resource. In this sense, the objective of this paper is to assess the efficiency of the Pacific hake fleet according to factors directly related to their operational dynamics.

## MATERIALS AND METHODS

In this study, an analysis was conducted on the influence of variables associated with the types of hake vessels and their form of operation, according to the recommendations by Hilborn & Walters (1992), Maunder & Punt (2004), and Benoit & Allar (2009). To determine vessel type, the attributes that are most representative of the fishing power of the vessels were analyzed: length (m), beam (m), depth (m), number of nets, gross registered tonnage, hold capacity (t), engine power (Hp) and year of construction. This data corresponds to a group of 53 vessels that were registered between 2000 and 2018 on arrival notices of the National Aquaculture and Fishery Commission (CONAPESCA), with catches of 100 t of hake over at least four years; these vessels were identified in a database of shrimp vessel characteristics in the Mexican Pacific.

The basic idea was to split the fleet into homogenous vessels for their technical characteristics to become management units. The attribute value of each vessel was standardized to homologous units with zero mean and one standard deviation. A cluster analysis was applied using Ward's method, which allows group hierarchization based on the smallest increase in the total value of the sum of the squares of the differences within each group (Everitt et al. 2011). The method described by Charrad et al. (2014) was applied to validate the optimum number of groups and, subsequently, a non-parametric Kruskal-Wallis test was used to confirm significant differences between groups.

To analyze fishing efficiency, fishery-dependent data collected during the 2015 to 2019 fishing seasons by the onboard commercial fleet observer program, sponsored by EDF-Mexico, were used (Zamora-García & Stavrinaky-Suárez 2016, 2018, 2019, Zamora-García et al. 2017). The database includes records of 814 sets made during 74 fishing trips of 25 vessels of the 53 used to determine the type of vessel.

In principle, the variables related to the catch per set were considered as relevant to fishing management (CPUE = kg set$^{-1}$) according to the type of vessel (following the results in this study) (Table 1). The fishing areas were delimited, as a proxy of fishery operation, depending on the position of the sets within quadrants 1° latitude × longitude (Fig. 2).

Following Hilborn & Walters (1992), Soto et al. (2002), Rodríguez-Marín (2003), Maunder & Punt (2004), and Ye & Dennis (2009), the CPUE analysis and its relationship with abundance, type of vessel, depth stratum, fishing area and time of day were based on a generalized linear model (GLM). The type of vessel considers the vessel characteristics related to fishing power. The year was treated as a categorical explanatory variable to detect trends in efficiency over time (Maunder & Punt 2004, Zuur et al. 2009).

Two generalized linear models were developed. The first included all the factors of interest to assess the influence of each one individually (Table 1). The second model considered interactions between factors to evaluate operational efficiency (Hilborn & Walters 1992). For the selection of the model variables in both cases, a stepwise algorithm in R was used to apply the Akaike Information Criterion (AIC) (Venables & Ripley 2002), which penalizes the model according to

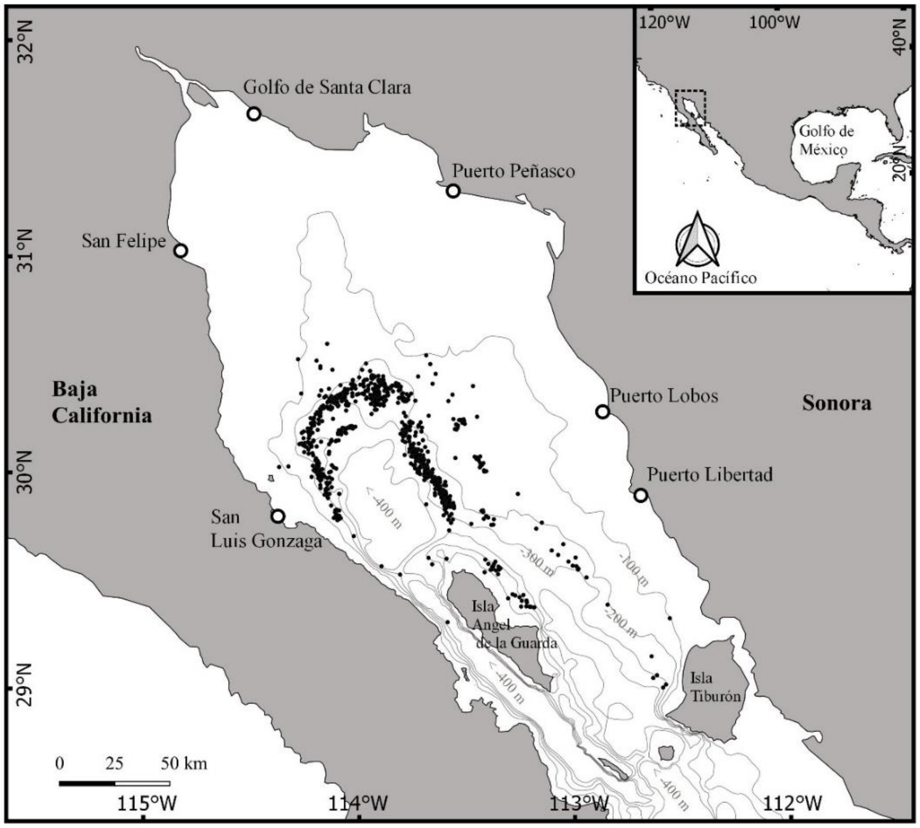


**Figure 1.** Hake fishing zone in the northern Gulf of California.

**Table 1.** Categorical variables and number of sets per category (n).

| Explanatory variable | Category | n |
|---|---|---|
| Year | 2015 | 132 |
| | 2016 | 116 |
| | 2017 | 180 |
| | 2018 | 169 |
| | 2019 | 217 |
| Type of vessel | Small vessels | 350 |
| | Large vessels | 464 |
| Fishing area | Area 1 (30-31°N, 115-114°W) | 224 |
| | Area 2 (30-31°N, 114-113°W) | 351 |
| | Area 3 (29-30°N, 115-114°W) | 55 |
| | Area 4 (29-30°N, 114-113°W) | 184 |
| Depth stratum | 100 to 200 m | 26 |
| | 200 to 300 m | 757 |
| | >300 m | 31 |
| Type of fishing gear | One net | 270 |
| | Two nets | 544 |
| Time of fishing | 06:00 - 09:00 h (morning) | 338 |
| | 09:00 - 13:00 h (at noon) | 301 |
| | After 13:00 h (afternoon) | 175 |

the number of parameters it contains and the percentage of deviation that it explains (Hastie & Pregibon 1992, Maunder & Punt 2004). The model with the lowest AIC was considered the best.

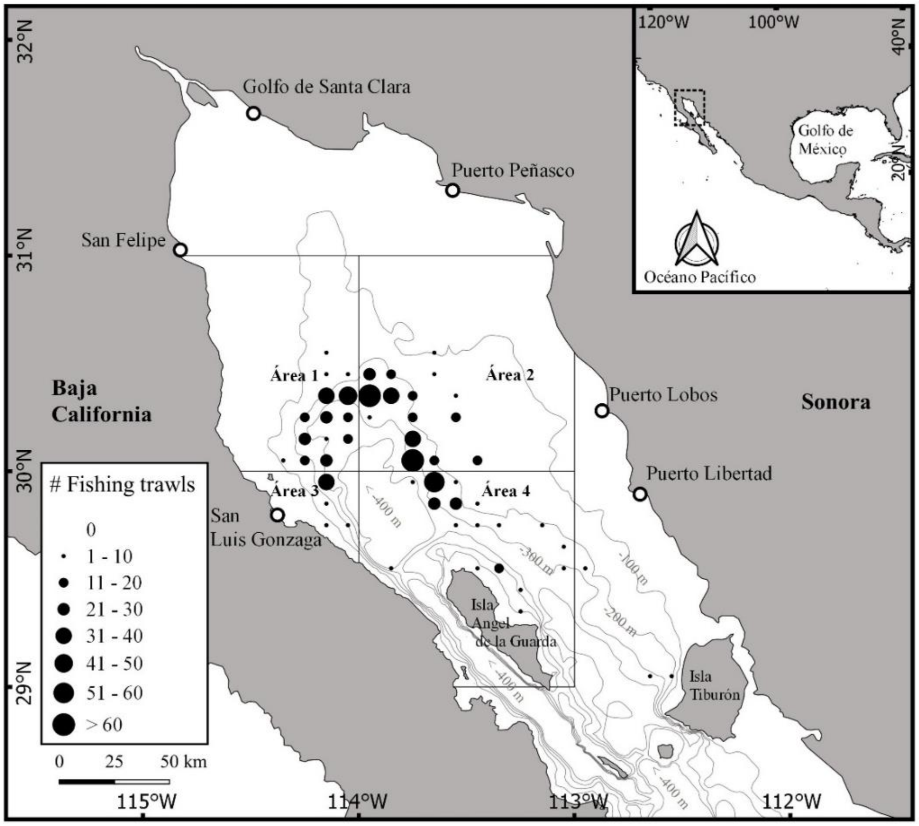


**Figure 2.** Fishing areas and distribution of fishing sets from 2015 to 2019.

The response variable (CPUE) was normalized using a natural logarithmic transformation, and the model was tested by applying two families of distribution of errors, gamma and normal. Still, the distribution of the errors was similar. For the analysis, the normal distribution of errors was chosen because it explained the deviations better. The default link function for the normal distribution is the identity function.

The GLM was conducted using R software through the package Stats based on Hastie & Pregibon (1992). They took the following form:

$$f\,(\mathrm{lnCPUE}) \sim \alpha + y_i + t_s + d_m + a_q + n_e + s_d + \varepsilon$$

$$f\,(\mathrm{lnCPUE}) \sim \alpha + y_i + t_s + d_m + a_q + n_e + s_d + (d_m \times t_s) + (a_q \times t_s) + (a_q \times y_i) + (d_m \times n_e) + (a_q \times n_e) + (t_s \times n_e) + \varepsilon$$

where $\alpha$: intercept, $y_i$: effect of the year; $t_s$: type of vessel; $d_m$: depth; $a_q$: fishing area; $n_e$: type of net; $s_d$: time of day; $\varepsilon$: error term which is assumed to have a normal distribution $N(0, \sigma^2)$.

## RESULTS

The cluster analysis applied to the data of vessel characteristics revealed the presence of four possible groups (Fig. 3). Kruskal Wallis' test showed significant differences between the two groups for all attributes considered, except for the molded depth (Table 2, Fig. 4). Still, Charrad et al. (2014) test led to the definition of two groups as the optimum number. The types of vessels were denominated as small and large (type 1 and type 2, respectively). Of the 53 vessels analyzed, 36 were small, and 17 were large. From the 25 vessels within the observer's program, 13 were large and 12 smalls.

The small vessels were taken as the standard for the generalized linear models because they represent 68% of the vessels in the fleet (Fig. 3). The explained deviance of the GLM model without interactions was 11%, and according to the AIC, all the variables are statistically significant (Table 3).

Results indicate that 2015 catch rates decreased to 42% but in 2016 increased to 69, 78% in 2017 and 2018, respectively, and finally decreased to 56% in 2019 (Table 4). They also suggest that large vessels are 1.53 more efficient than small ones, that two nets are 1.6 more efficient than one net and, that fishing at noon is 11% better than in the morning and, fishing in the afternoon decreases efficiency by 7% compared to

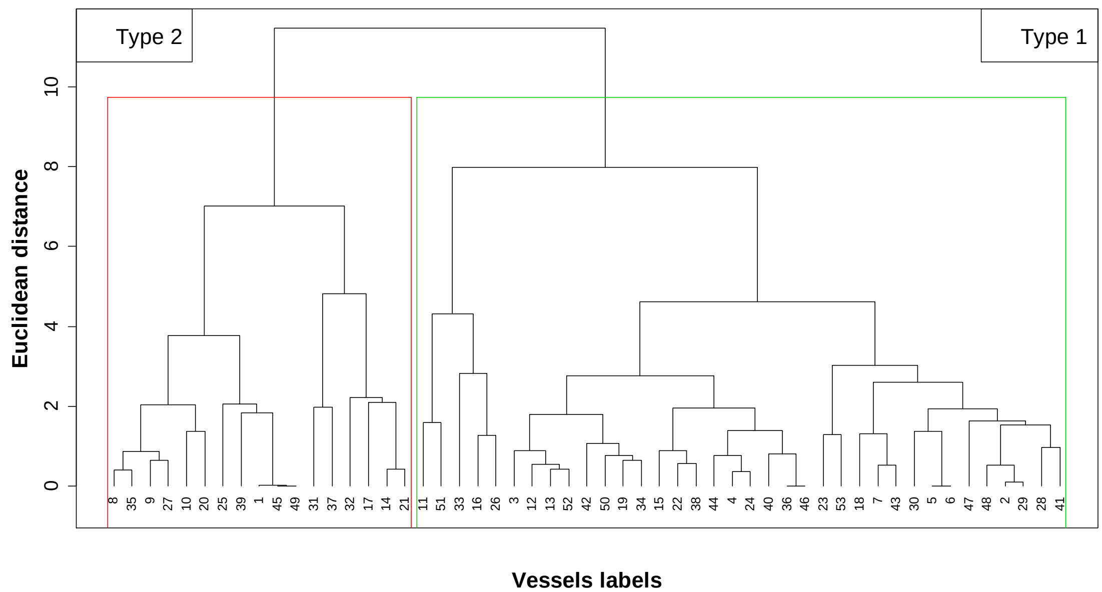


**Figure 3.** Dendrogram of classification of vessels, according to the cluster analysis. Type 1: smalls vessels, Type 2: large vessels.

**Table 2.** Average values of the physical characteristics of the types of hake vessels.

| Vessel type | Gross tonnage | Net tonnage | Carrying capacity (t) | Engine power (Hp) | Length (m) | Beam (m) | Molded depth (m) | Year of construction |
|---|---|---|---|---|---|---|---|---|
| Large | 125.90 | 68.63 | 34.15 | 538 | 22.95 | 6.47 | 3.21 | 1985 |
| Small | 95.56 | 53.68 | 20.31 | 417 | 21.30 | 6.07 | 3.23 | 1979 |

**Table 3.** Analysis of the deviance explained by the first model. Significance codes: *** = 0, ** = 0.001, * = 0.01.

| | Degrees of freedom | Deviance | Residual degrees of freedom | Residual deviance | Probability ($x^2$) | Percentage of deviance explained |
|---|---|---|---|---|---|---|
| Null hypothesis | | | 813 | 1229.96 | | |
| Area | 3 | 33.334 | 804 | 1161.98 | 2.29E-05 *** | 26.23 |
| Net type | 1 | 29.771 | 800 | 1102.88 | 3.37E-06 *** | 23.43 |
| Year | 4 | 27.102 | 809 | 1202.86 | 0.00058 *** | 21.33 |
| Day segment | 2 | 18.771 | 802 | 1143.21 | 0.0011 ** | 14.77 |
| Vessel | 1 | 10.553 | 801 | 1132.66 | 0.0057 ** | 8.30 |
| Depth | 2 | 7.548 | 807 | 1195.31 | 0.0647 * | 5.94 |

fishing in the morning. In addition, the depth strata of 200 to 300 m and more than 300 m are 1.81 and 1.35 times more productive than that of 100 to 200 m, and areas 4, 2, and 3 are less productive than 1 (42% the first and 33% the others).

Graphical diagnosis of GLM without interactions confirmed the fit with a normal error distribution. The absolute residuals against the fitted values do not show a trend, suggesting a constant variance concerning the mean of the data (Fig. 5a).

For the GLM that included interactions, the AIC values indicated that the type of net × depth, type of net × area and type of vessel × area should be excluded. The GLM was as follows:

$$f\,(\mathrm{lnCPUE}) \sim \alpha + y_i + t_s + d_m + a_q + n_e + s_d + (d_m \times t_s) + (a_q \times y_i) + (n_e \times t_s) + \varepsilon$$

This model includes the interactions between area × year ($a_q \times y_i$), depth ×type of vessel ($d_m \times t_s$), and type of net × type of vessel ($n_e \times t_s$). Similar to the first model, the graphical analysis of the residual distribu-

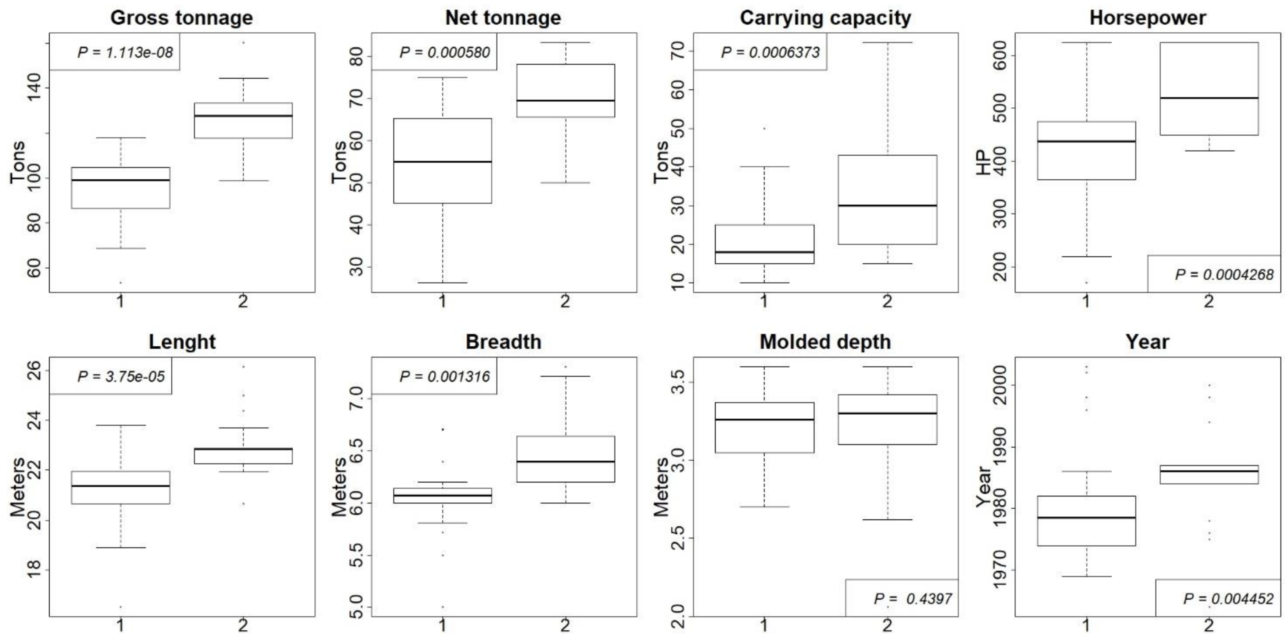


**Figure 4.** Differences in the construction characteristics of the two types of hake vessels.

**Table 4.** Parameters estimated from the Generalized Linear Model without interactions. [1]Represents the average efficiency of the standard vessel (V1) in the year, depth, and area.

| Variables | In coefficients | Coefficients |
|---|---|---|
| (Intercept)[1] | 6.2280 | 506.73 |
| Year 2016 | -0.8540 | 0.42 |
| Year 2017 | -0.3660 | 0.69 |
| Year 2018 | -0.2392 | 0.79 |
| Year 2019 | -0.5679 | 0.57 |
| Depth 2 | 0.5955 | 1.81 |
| Depth 3 | 0.3040 | 1.35 |
| Area 2 | -0.3972 | 0.67 |
| Area 3 | -0.3909 | 0.68 |
| Area 4 | -0.5395 | 0.58 |
| Noon | 0.1049 | 1.11 |
| Afternoon | -0.3134 | 0.73 |
| Vessel type 2 | 0.4288 | 1.53 |
| Net type 2 | 0.4702 | 1.60 |

tion confirmed the fit of the GLM considering the normal error distribution family (Fig. 5b). All the factors were significant independently, and the interactions represented 42% of the total explained deviance (Table 5).

The most significant coefficients correspond to the interaction year × area (32% deviance explained), showing a highly variable influence on the CPUE in areas 3 and 4 but more stable in areas 1 and 2 (Fig. 6).

The partial effect of the type of vessel × depth interaction indicates that large vessels perform better in the 3-depth strata, being stratum-2 the most productive for both types of vessels. The vessel type × net-type interaction suggests that large vessels perform better with the two types of nets, but fishing with two nets is most effective (Fig. 6).

## DISCUSSION

The analysis of the Pacific hake *Merluccius productus* fleet dynamic in the north of the Gulf of California is a useful contribution to developing a system of individual per-vessel catch quota, recognizing changes in the efficiency of two types of vessels associated with spatial and temporal availability of the resource. However, it is necessary to consider that changes in efficiency could be related to technical, economic, and social factors that must be analyzed.

Dividing fishing vessels into discrete vessel classes, small and large, considers the relationship between engine power, hold capacity, and length size, which are well known to be related to fishing capacity (Maunder & Punt 2004). However, we did not determine which vessel attributes contribute to catching power due to the lack of data on fisheries maneuvers, associated technology, and fisher's experience. Still, it will be important information when the vessels make techno-logical innovations to increase efficiency (Quijano et al. 2018, Zhang et al. 2018). Still, the number of vessels is limited by the total allowable quota.

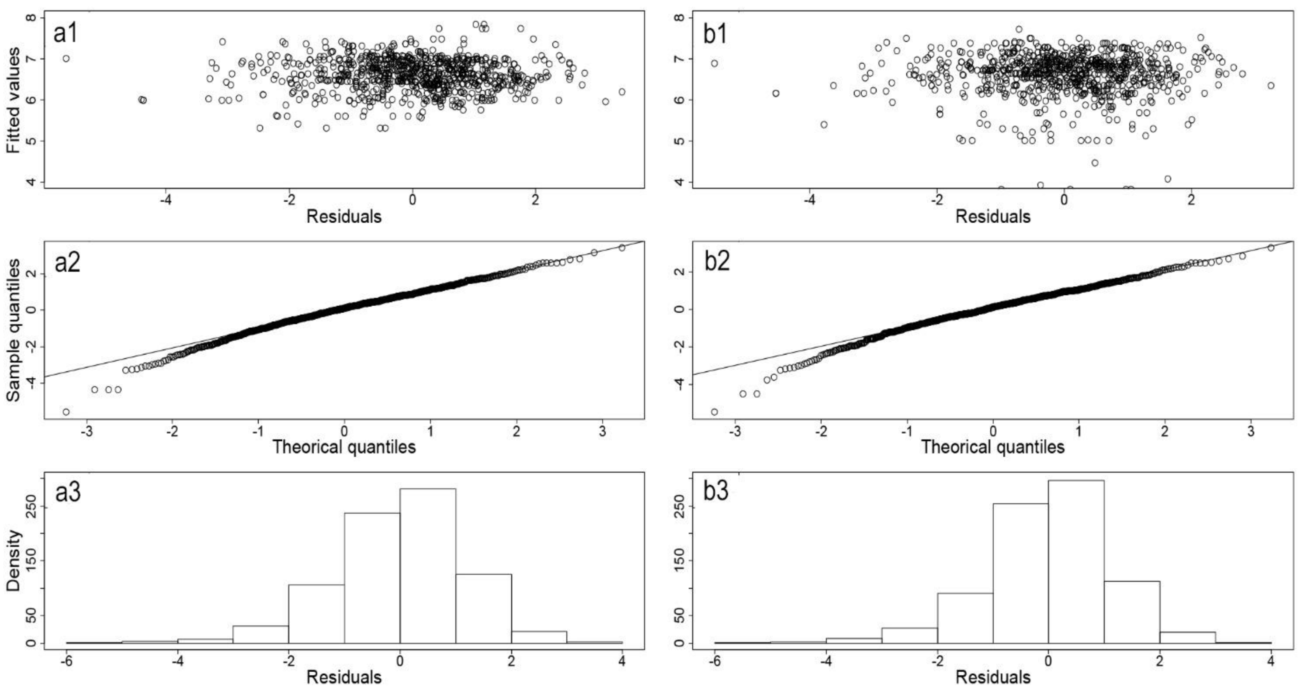


**Figure 5.** Diagnostic graphics for the Generalized linear models. Model without interactions: a1) Fitted values *vs.* residuals; a2) Sample quantiles *vs.* theorical quantiles; a3) Residuals density. Model with interactions: b1) Fitted values *vs.* residuals; b2) Sample quantiles *vs.* theorical quantiles; b3) Residuals density.

**Table 5.** Analysis of the deviance explained by the Generalized Linear Model with interactions. Significance codes: *** = 0, ** = 0.001, * = 0.01.

| | Degrees of freedom | Deviance | Residual degrees of freedom | Residual deviance | Probability ($x^2$) | | Percentage of deviance explained |
|---|---|---|---|---|---|---|---|
| Null hypothesis | | | 813 | 1229.96 | | | |
| Area | 3 | 33.33 | 804 | 1161.98 | 9.92E-06 | *** | 15.13 |
| Net type | 1 | 29.77 | 800 | 1102.88 | 1.50E-06 | *** | 13.51 |
| Year | 4 | 27.10 | 809 | 1202.86 | 0.000306 | *** | 12.30 |
| Day segment | 2 | 18.77 | 802 | 1143.21 | 0.000677 | *** | 8.52 |
| Vessel | 1 | 10.55 | 801 | 1132.66 | 0.004177 | ** | 4.79 |
| Depth | 2 | 7.55 | 807 | 1195.31 | 0.053166 | * | 3.43 |
| Year × area | 12 | 69.63 | 786 | 1016.86 | 2.58E-07 | *** | 31.60 |
| Depth × vessel type | 2 | 16.39 | 798 | 1086.50 | 0.001710 | ** | 7.44 |
| Vessel type × net type | 1 | 7.25 | 785 | 1009.61 | 0.017582 | * | 3.29 |

It is assumed that the data used to construct the general linear model was measured consistently and precisely and contributed to a good estimation of the CPUE and the potential implementation of measures related to the fishing efficiency per type of vessel. For this reason, it is important to adapt methods and models based on the available information, remembering that the quality of the data affects the results of the models (Campbell 2015). The variables chosen using the AIC all contributed significantly to the total explained deviance of the GLM model without interactions. In particular, the area's contribution factor, with areas 2 and 3 being the most productive, the use of two nets (1.6 more) that was more efficient than one net, and the negative influence of fishing during the afternoon on CPUE, which was probably related to the nictimeral migration of Pacific hake (Hamel et al. 2015). This GLM model indicates that large vessels are 1.53 times more efficient than small vessels. However, the associated operating costs for each type of vessel were not analyzed, but they are probably related to the vessel's size, and diesel fuel accounted for the highest

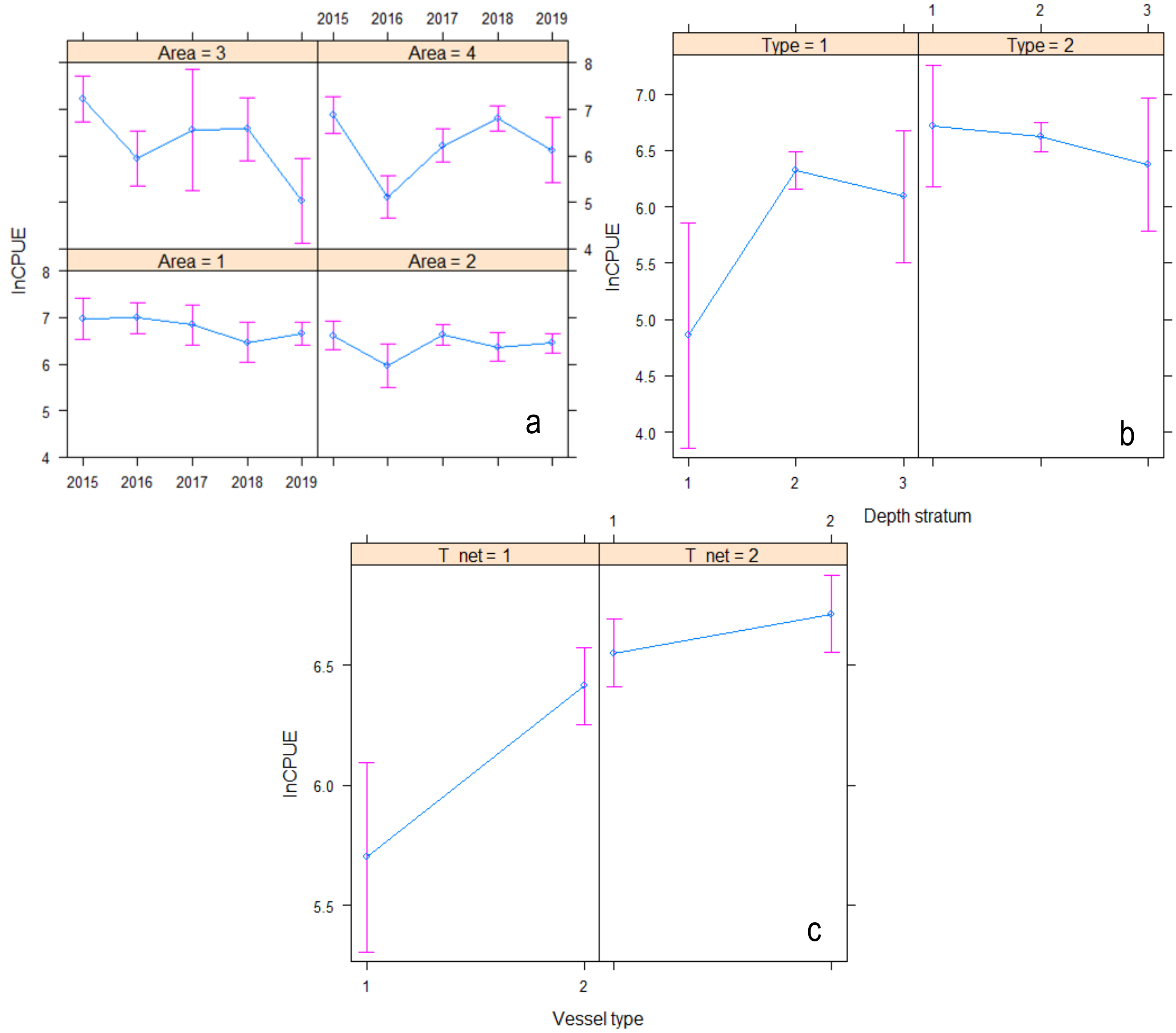


**Figure 6.** Partial effects on the CPUE of statistically significant interactions of the second generalized linear model with 95 percent confidence limits. a) Area × year, b) vessel type × depth, c) vessel type × net type. Type 1: small vessels, Type 2: large vessels, T_net 1: one net, T_net 2: two nets.

cost. The vessel's profitability depends on total catch and ex-vessel product price, so each type's total number of vessels, individual catch quotas, and allowable catch must be well related (Ramírez-Rodríguez 2017).

The year coefficient variability shows a 42% decrease in abundance at the beginning of the series and an increase of 79%. Zamora et al. (2020) found similar results, suggesting that the catch rate is not proportional to abundance (Hilborn & Walters 1992, Maunder et al. 2006). It could be related to the Pacific hake reproductive behavior (Zamora-García et al. 2020) and the influence of climate factors (Sánchez-Velasco et al. 2009, Marrari et al. 2019). It is therefore advisable to pay attention to the CPUE and annual catch trends.

The interactions in the GLM are important to understanding the operating dynamics of the fleet. The area × year interaction was the most significant, and the depth × vessel interaction could indicate that the Pacific hake abundance varies by area. Alternatively, their distribution has been variable over the years; as previously discussed, it also shows the possibility of defining specific fishing areas for management.

The net type × vessel type interaction was also significant, and because large vessels with two nets are the most efficient, it is advisable to strive for improvement of the fleet, changing one for two nets and increasing the number of large vessels. Also, it is well known that investment in new catch technology like radars, fish, and depth sounders would, in principle, lead to a greater catch (FAO 2008). As Rijnsdorp et al. (2006) suggest, it would be important to consider investments to improve their performance, establishing differences in equipment and maintenance costs. In addition, the captain's abilities and the environmental variables can affect the catch rate (Punt et al. 2000, Battaile & Quinn 2004, Mahévas et al. 2004, Carruthers et al. 2011).

The per vessel catch quota must consider the economic income necessary to sustain the vessels' profitable operation without affecting the resource's availability (Ramírez-Rodríguez 2017). The results indicate that small and large vessels make a difference that should be considered when distributing individual quotas.

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