Factors affecting the relative abundance in a senescing fishery: Red grouper (*Epinephelus morio*) in the southeastern Gulf of Mexico (#86116)

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Factors affecting the relative abundance in a senescing fishery: Red grouper (*Epinephelus morio*) in the southeastern Gulf of Mexico

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The most important fisheries are recording catches below the historical average despite the increased effort. This level of fishery senescence is worrisome and requires the establishment of feasible and precise measures to prevent the biomass from continuing to decrease, so determining the factors that produce changes in the abundance and distribution of senescent resources will allow us to identify the strengths and weaknesses of management schemes, in addition to making it possible to estimate more accurate parameters for their evaluation. This work hypothesizes that environmental, temporal, spatial, and operational components contribute to the variation in the relative abundance, so we analyzed the red grouper fishery as the most important demersal fishery in the southeastern Gulf of Mexico (SGM) locally defined as "escama". The Catch Per Unit Effort (CPUE) was employed as an index of relative abundance recorded by the semi-industrial fleet (kg per effective fishing day) and the small-scale fleet (kg per effective fishing hour) that took place during the senescent capture phase (from 1996 to 2019). We fit several variables of the components using generalized additive models (GAM) and the multi-model inference determined the best GAM for each fleet. The results indicated that for both fleets the operational and temporal components (fishing gear and year) have a greater impact on the distribution and abundance of red grouper in the SGM than the spatial and environmental components (place of origin and sea surface temperature), which encourages the exploration of métier schemes for more efficient fishery management. In addition, several strategies have been identified that would support the recovery of the resource for each fleet, such as restricting fishing in the quadrants located to the northeast or normalizing scuba diving. We recommend future research use the indices generated in the present study to evaluate the senescent red grouper fishery.

Running head: Factors affecting the relative abundance of red grouper

Factors affecting the relative abundance in a senescing fishery: Red grouper (*Epinephelus morio*) in the southeastern Gulf of Mexico

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Abstract

The most important fisheries are recording catches below the historical average despite the increased effort. This level of fishery senescence is worrisome and requires the establishment of feasible and precise measures to prevent the biomass from continuing to decrease, so determining the factors that produce changes in the abundance and distribution of senescent resources will allow us to identify the strengths and weaknesses of management schemes, in addition to making it possible to estimate more accurate parameters for their evaluation. This work hypothesizes that environmental, temporal, spatial, and operational components contribute to the variation in the relative abundance, so we analyzed the red grouper fishery as the most important demersal fishery in the southeastern Gulf of Mexico (SGM) locally defined as "escama". The Catch Per Unit Effort (CPUE) was employed as an index of relative abundance recorded by the semi-industrial fleet (kg per effective fishing day) and the small-scale fleet (kg per effective fishing hour) that took place during the senescent capture phase (from 1996 to 2019). We fit several variables of the components using generalized additive models (GAM) and the multi-model inference determined the best GAM for each fleet. The results indicated that for both fleets the operational and temporal components (fishing gear and year) have a greater impact on the distribution and abundance of red grouper in the SGM than the spatial and environmental components (place of origin and sea surface temperature), which encourages the exploration of métier schemes for more efficient fishery management. In addition, several strategies have been identified that would support the recovery of the resource for each fleet, such as restricting fishing in the quadrants located to the northeast or normalizing scuba diving. We recommend future research use the indices generated in the present study to evaluate the senescent red grouper fishery.

Keywords: catch per unit effort, generalized additive model, red grouper, southeastern Gulf of Mexico

Introduction

At the end of the last century, one-third of the world's catch came from fishery resources that were exploited in their senescent phase (low levels of biomass and fishing yield), mainly due to the increase in fishing effort during the 1970s and 1980s (Grainger & Garcia, 1996; Pauly et al., 2002). Overfishing of several fish stocks has contributed to the increase in senescent fisheries and is of growing concern to the fishing industry and decision-makers (FAO, 2020).

The level of overexploitation currently faced by commercial fisheries requires fisheries management that ensures the responsible use of living marine resources based on stock assessment and management of resource dynamics (Hilborn & Walters, 1992; Forrestal et al., 2019), without neglecting the governance or importance of ecological and socioeconomic factors of fishing activities. For this reason, it is necessary to know and understand what factors can produce spatial and temporal changes in the relative abundance of resources. Globally, the relative abundance or Catch per Unit Effort (CPUE) is commonly assumed to be proportional to abundance in fish stock assessments ($\beta \approx 1$) (Hilborn & Walters, 1992; Maunder & Punt, 2004), where an increase or decrease in CPUE may reflect changes in resource abundance and biomass (Forrestal et al., 2019). However, it is common for this assumption not to hold because there are states of hyperdepletion or hyperstability, which makes the CPUE not a reliable indicator of the abundance of the stocks (Maunder & Punt, 2004).

CPUE is often key information used for fitting stock assessment models (Hilborn & Walters, 1992; Forrestal et al., 2019). In this regard, different authors have pointed out that, to strengthen the assessment and management of exploited resources, It is important to use an index of abundance that is fishery-independent; however, fishery-independent data are often extremely expensive or difficult to collect (Maunder & Punt, 2004; Hua et al., 2019) and decision-making for fisheries management must be done immediately. Therefore, nominal CPUE calculated from commercial fisheries data are widely used in stock assessment, which may provide limited information on the state of the resource (Quinn & Deriso, 1999; Maunder & Punt, 2004; Haddon, 2011).

In order to have more reliable and representative data in the stock assessment, nominal CPUE values should be standardized (Quinn & Deriso, 1999; Maunder & Punt, 2004; Hua et al., 2019). This is done to eliminate the impact of environmental, temporal, spatial, and operational factors on the catchability coefficient and, therefore, that the CPUE is a reliable indicator of the abundance of the stock (Watters & Deriso, 2000; Maunder & Punt, 2004; Hua et al., 2019). In the last few decades, many efforts have been made to solve the problems associated with CPUE fitting, and different statistical models have been considered, such as Generalized Linear Models (GLM), Generalized Additive Models (GAM), Generalized Linear Mixed Models (GLMM), Generalized Additive Models of Location, Scale, and Shape (GAMLSS), and, in the last several years, the use of machine learnings methods from Artificial Intelligence (Watters & Deriso, 2000; Maunder & Punt, 2004; Yang et al., 2020). All these methods have proven to be efficient to determine the behavior of the CPUE with respect to different variables (Maunder & Punt, 2004; Tian et al., 2009; Hua et al., 2019).

In this study, the hypothesis was tested that different environmental, temporal, spatial, and operational factors affect the CPUE for red grouper stock in the SGM. Therefore, this work aimed to define what factors contribute to the variability of relative abundance in senescent fisheries, such as the red grouper fishery in the SGM, to understand the dynamics of the resource and identify key variables that can improve its management schemes, focusing on a possible recovery of a fishery that is in critical condition.

Fishery background. Groupers are fishery resources with high commercial value and high demand in the market and show an important ecological role in reef ecosystems. However, they are also among the species most vulnerable to fishing pressure due to the characteristics of their lifecycle, such as slow growth rate, late sexual maturation, protogynous hermaphroditism (change sex from female to male), and great longevity (Sadovy de Mitcheson et al., 2013; Mavruk et al., 2018).

The red grouper (*Epinephelus morio*) is traditionally the main target species of a multispecies demersal fishery in the SGM. This highly valued species in the national and international market has sustained an established fishery in the Yucatan Peninsula (DOF, 2018). The historical trends of red grouper catches have shown the general development phases of a fishery: growth, exploitation, and senescent (Fig. 1) (Hilborn & Walters, 1992). The growth phase (1958–1978), which recorded the highest historical production (~20,000 t), was characterized by investment, technological development, and the entry of new vessels (Monroy-García, Galindo-Cortes & Hernández-Flores, 2014). The exploitation phase (1979—1995), with an evident decreasing trend in the catch, showed high fishing pressure, mainly on juvenile organisms (Arreguín-Sánchez, 1987; DOF, 2014). In the senescent phase (1996—2020), the lowest catch levels in this fishery's more than six decades of development were recorded. During this period, the red grouper in the SGM was reported as overfished (Monroy-García, Galindo-Cortes & Hernández-Flores, 2014), and according to the International Union for Conservation of Nature (IUCN) Red List, this already endangered species has been upgraded to vulnerable (Brule et al., 2018; Sadovy de Mitcheson et al., 2020).

The red grouper fishery involves four fleets with different fishing powers that operate sequentially in the SGM as they catch different components of the stock. It is made up of two

Mexican commercial fleets, a small-scale fleet (approximately 4,200 boats, with lengths ranging from 6 m and 12 m, and outboard engine power from 40 HP to 115 HP) that exerts fishing pressure on juvenile fish. Another semi-industrial fleet (composed of 536 vessels, with lengths ranging from 10 m to 23 m and engine power from 75 HP to 350 HP) focuses its efforts on breeding adults, and a Cuban fleet (22 m in length) that is also semi-industrial (Monroy-García, Galindo-Cortes & Hernández-Flores, 2014) lost its fishing permit in the Campeche Bank in 2022. In addition, a Mexican sport-recreational fishing fleet also operates (López-Rocha, Vidal-Hernández & Bravo-Calderón, 2020), and the number of fishers, vessels, and catch levels of this fleet are still unknown.

Materials and methods

Study area

The Campeche Bank is located in the SGM (20ºN to 24ºN and 86ºW to 93ºW) with an area of 175,000 km^2 and is bounded by the 200 m isobath and coastline (Monroy-García et al., 2019; López-Rocha, Vidal-Hernández & Bravo-Calderón, 2020). In the spatial component, we used the zoning established by INAPESCA (National Fisheries Institute) to classify the range of operation of the semi-industrial fleet. INAPESCA is the Mexican fisheries authority who addresses scientific studies on fisheries in 20 fishing areas, and for the small-scale fleet, the spatial component was addressed by the place of origin of the boats (Fig. 2).

Data records

Data for the semi-industrial fleet correspond to information recorded in the fishing logbooks by fishermen of this fleet from 1996 to 2019 (2011 held no records). Each logbook is part of the record for fishing activities of the vessels that make up this fleet, through which the skipper of the vessel records the name of ship and captain, catches by species (kg), fishing quadrant, fishing gear, date of departure and arrival, crew members, depth, and effective days of fishing. Data for the small-scale fleet are from monthly samplings at the main landing ports along the Yucatan coastline from 2013 to 2019. The fishermen were interviewed upon arrival at the port to obtain general information on the fishing operation in relation to the target species; fishing gear, fishing zone, depth, engine power, as well as the characteristics of the workday (fishing hours, number of fishermen, fishing costs), the total catch (kg) and catch by species were recorded.

The semi-industrial fleet carries out fishing trips lasting between 15 and 26 days and uses at least four different types of fishing gear, such as a dinghy and short longline (DS), longline (LL), bicycle (B), and other vessels that use combined fishing gear methods (CFG). The DS is used on mother ships carrying dinghies (wooden boats of three meters in length, locally named "alijos", without motors and operated by a fisherman). Each dinghy is released and operated independently in the fishing area with a short longline encompassing 80 to 100 hooks. Another vessel in the fleet uses LL with 500 to 3,000 hooks, which consists of a hydraulically driven reel with the mainline that operates directly from the vessel. Another is the B gear, which is a manual mechanism similar to a bicycle that operates with a mainline having four to six hooks (Monroy-García, Salas & Bello-Pineda, 2010; Quijano et al., 2018). It is reported that this semi-industrial fleet commonly operates between 40 m and 200 m in depth and approximately 90% of the total catch is landed in the ports of Progreso and Yucalpeten, Yucatán (DOF, 2014).

The small-scale fleet makes round trips with an average duration of eight effective fishing hours (± 2 effective fishing hours) with an operating range limited to the 40 m isobath and uses different fishing gear, such as short longline (SL) composed of a main line from 300 to 3,000 m with 100 to 1,000 hooks; they are generally bottom longlines, so the extremes are placed with weights or sinkers. Scuba diving (SD) targets Caribbean red lobster (*Panulirus argus*) but also catches a high percentage of escama such as red grouper, hogfish (*Lachnolaimus maximus*), and black grouper (*Mycteroperca bonaci*). Divers mainly use a low-pressure compressor, which consists of a hose approximately 100 m long and a regulator that supplies air to the diver (hookah system); handlines (H) are generally composed of a line of less than 100 m with one to three straight hooks of different sizes accompanied by a sinker and occasionally employs handlines when gillnets (GH) or jimba are used (JH). Jimbas are two to 12 m bamboo poles that usually have up to five lines with crabs as bait (used during octopus season) (Avendaño et al., 2019). Gillnets are rectangular in shape up to 100 m with floats at the top, sinkers at the bottom, and buoys at the extremes (aimed at catching sardines, snook, or croakers).

Environmental data

Sea surface temperature (average and standard deviation) were obtained by monthly compositions from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) at 1 × 1° (Freeman et al., 2019) that agreed, considering the size of the fishing zones proposed by INAPESCA. The files were downloaded from the website https://icoads.noaa.gov/ in hdf format and displayed with the *raster* package (Hijmans, 2020) of the R programming language (R Core Team, 2023). ICOADS data are *in situ* observations from ships, buoys, research reports, and other platforms (Freeman et al., 2019).

Variables used for modeling

Four components were considered, and variables were selected which could have an effect on the spatial and temporal variation of the CPUE of red grouper in the SGM (Table 1). The multicollinearity test was applied to ensure that the candidate variables were not correlated, using the Generalized Variance Inflation Factor (GVIF) method included in the *car* package (Fox & Weisberg, 2011) in the R programming language. The general rule was taken where, GVIF values ≥ 3 indicated collinearity problems (Franke, 2010; Gareth et al., 2013). Candidate variables to describe CPUE variation did not present collinearity problems (GVIF < 3), and all variables were considered in the models.

Relative abundance index modeling

The index of relative abundance through CPUE was defined as kg of red grouper per effective fishing day (kg EFD^{-1}) for the semi-industrial fleet and as kg of red grouper per effective fishing hour (kg EFH^{-1}) for the small-scale fleet. Generalized Additive Models (GAMs) were used to model the dependent variables (CPUE) because they showed better fit and explanatory power (Tian et al., 2009; Hua et al., 2019). Due to there being no zero-catch data, we assumed that the CPUE could fit some exponential family distribution. We used the Cullen and Frey plot representing the kurtosis and skewness of the data and performed a non-parametric bootstrap to take into account the uncertainty of the estimated values using the *fitdistrplus* package (Delignette-Muller et al., 2015) of the R programming language (R Core Team, 2023).

In the semi-industrial fleet, the CPUE did not fit the distributions (Fig. S1A). Thus, its distribution was assumed log-normal (Fig. S1B), and the identity link function was applied, $\mu = \eta = \ln(CPUE)$. The model's residual plot confirmed that the Gaussian error distribution selection was correct (Fig. S1C). Conversely, the CPUE of the small-scale fleet was fitted to the gamma distribution, and the inverse link was applied, $\mu = \frac{1}{\eta} = \frac{1}{CPUE}$ (Fig. S2).

The GAMs were built with the *mgcv* package (Wood, 2021) of the R programming language (R Core Team, 2023); continuous variables were fitted with spline functions (*s*), and categorical variables were assumed to be linear fits. The purpose was to select the explanatory variables of the best candidate model, considering all possible model combinations. For the above, we used the *dredge* function (from *MuMIn* package of the R programming language; Bartoń, 2022) that uses the multi-model approach based on the Information Theory (Burnham & Anderson, 2002), ranking the most parsimonious models according to the lowest value of Akaike's Information Criterion (AIC, Akaike, 1983), as well as calculating Akaike's differences (Δ_i) and Akaike's weights (w_i). For each model, the deviance explained (D%), the pseudo coefficient of determination (Pseudo-R^2), and the adjusted pseudo coefficient of determination (adjusted Pseudo-R^2) were calculated.

For each fleet, the median nominal CPUE (original CPUE) was compared against the median fitted CPUE of the best GAM (the one with the lowest AIC) by year and by month, using Wilcoxon's test (Sokal & Rolf, 1981).

Results

At least 46,542 semi-industrial fleet trips were analyzed from 1996 to 2019, and 2,775 small-scale fishermen were interviewed from 2013 to 2019. The most used fishing gear by the semi-industrial vessels was LL (73.06%), followed by DS (15.64%), B (9.85%), and CFG (1.45%), while the small-scale fleet followed this order SD (54.20 %), H (24.93 %), SL (18.49 %), JH (1.59 %), and GH (0.79 %). In the semi-industrial fleet, the CPUE of the red grouper presented a median of 87.86 kg EFD^{-1} (0.10—2548 kg EFD^{-1}), and in the small-scale fleet, the CPUE of the red grouper recorded a median of 1.15 kg EFH^{-1} (0.04—20 kg EFH^{-1}).

A total of 256 candidate models were fitted for the semi-industrial fleet, and 128 candidate models for the small-scale and multi-model inference determined that there is only one statistically viable model to explain variations in the CPUE of red grouper for each fleet ($w_i > 0.90$, Tables S1, S2). For the semi-industrial fleet, the best GAM included year, month, zone, fishing gear, navigation days, *s*(depth), *s*(sea surface temperature), and number of crew as explanatory variables with a D% = 39.33, Pseudo-R^2= 0.39, and adjusted Pseudo-R^2= 0.43, while in the small-scale fleet, the explanatory variables for the best GAM included year, month, place of origin, fishing gear, number of crew, *s*(depth), and *s*(sea surface temperature) with a D% = 31.93, Pseudo-R^2=0.38, and adjusted Pseudo-R^2= 0.40. The best models on red grouper CPUE are summarized in Tables 2 and 3; the number of crew in the small-scale fleet and sea surface temperature for both fleets were significant ($p < 0.05$), while all other variables were highly significant ($p < 0.001$). For both fleets, the variables with the largest effect size (F) were the fishing gear, followed by the year; those with the smallest effect size for the semi-industrial fleet were sea surface temperature and depth, and for the small-scale fleet, they were sea surface temperature and place of origin. This means that operational and temporal components have a greater impact on red grouper CPUE than environmental and spatial components.

The best GAM for each fleet showed the influence of the explanatory variables in relation to the CPUE of red grouper (Figs. 3, 4). Regarding the environmental component, in the semi-industrial fleet, the relationship between sea surface temperature and red grouper CPUE was relatively stable between 24°C and 30°C; however, an inverse behavior of sea surface temperature on the red grouper CPUE was observed for each fleet. In the semi-industrial fleet, high CPUE values were noted at low sea surface temperatures (Fig. 3), while in the small-scale fleet, the highest CPUE values were found at the highest sea surface temperatures (Fig. 4). Depth showed a wide range in CPUE, demonstrating that both fleets moved into deeper waters over the years associated with the decrease of the resource; however, going to deeper areas does not guarantee to be more efficient due to the wide uncertainty of CPUE. Despite the overlap of fleets with depths of less than 60 m, it is distinguished that in the small-scale fleet, high CPUE values occurred at depths between 16–35 m (Fig. 4), while in the semi-industrial fleet slightly high CPUEs were observed later, 35–70 m, and again at depths greater than 180–240 m (Fig. 3).

In the temporal component, a similar behavior of the CPUE values was observed for both fleets, with a pronounced drop from 2013 onwards, except for an increase in 2015 (Figs. 3, 4). However, in the semi-industrial fleet, it was observed that in previous years, the CPUE of red grouper had remained relatively constant (1996–2012; Fig. 3). Regarding the months, two periods can be distinguished, the period with the lowest CPUE values (May–August) and the period with the highest CPUE values (September–March), even though both fleets recorded a higher number of trips during the period with lower CPUE values (Figs. 3, 4). During the red grouper closure period in the SGM (February–March), the GAMs showed high CPUE values (Figs. 3, 4) because the closure began with one month in 2003 (from February 15 to March 15), but there was no reduction in the fishing effort because trips were concentrated before and after the closure. It was not until the length of the closure was extended to two months in 2017 (from February 1 to March 31) that trips were almost nil.

The spatial component indicated that the CPUE recorded by the semi-industrial fleet decreased from east to west, with the highest CPUE values in the northeastern quadrants (1-B, 5, 6, 7, 11, and 13) (Figs. 2, 3); besides, these quadrants are where most of the fishing effort is concentrated (43.59% of the total trips). While, in the small-scale fleet, no clear trend of the influence of place of origin on CPUE can be supported due to the wide uncertainty of the intervals (Fig. 4).

In the operational component, the trend of decreasing CPUE with the number of navigation days in the semi-industrial fleet was clear for the period between 9–25 navigation days (Fig. 3). Nevertheless, there is wide uncertainty for the rest of the days, which are the ones with the lowest number of fishing trips (< 200). It should be noted that, over the years, the semi-industrial fleet has increased its number of navigation days. For both fleets, it can be observed that carrying more crew members leads to higher CPUE values (Figs. 3, 4), possibly due to an increased fishing effort; however, carrying more crew members does not guarantee higher CPUE values, which are reflected in the increase of their uncertainty (in the semi-industrial fleet, it is not common to operate with more than 17 crew members and in the small-scale fleet, with 4 crew members). The fishing gear that had the greatest impact on the CPUE of red grouper for both fleets were trips that used longlines and fishing methods that used the greatest number of hooks (Figs. 3, 4). It is remarkable that in the semi-industrial fleet, the CFG began to be used in 2013 and was associated with the decrease of the resource, and in the small-scale fleet, the SD registered considerable CPUE values.

For both fleets, the GAM proved to be a suitable method for fitting the CPUE of red grouper because it decreased their dispersion (Figs. 5, 6). The values of the nominal series were higher than the fitted series, although the trend was similar by year and month; Wilcoxon's test showed significant differences for each fleet, except for years 2002, 2005, and 2018 in the semi-industrial fleet (Figs. 5, 6).

Discussion

In the present study, the hypothesis that different variables (environmental, temporal, spatial, and operatives) may affect the behavior of the CPUE was tested. This document considered that several of these components could produce changes in the distribution and abundance of red grouper in the SGM (Hernández & Seijo, 2003; Monroy-García, Salas & Bello-Pineda, 2010; Arreguín-Sánchez et al., 2017), and for the first time, the influence of these factors on the CPUE was determined.

The assessment of senescent resources requires reliable indices that are representative of abundance for establishing management strategies and reference points that allow stock recovery; for this reason, proportionality is necessary when using CPUE which is widely included as inputs in dynamic biomass models (Maunder & Punt, 2004; Haddon, 2011; Hua et al., 2019). In conjunction, determining the factors that affect the CPUE will help to counteract the negative trend in catches by identifying strengths and weaknesses in the management strategies employed, besides making it possible to explore and propose complementary actions to strengthen fisheries management.

The behavior of red grouper with sea surface temperature probably suggests changes in thermal preferences during their life phases, which could be linked to their feeding habits and reproduction. In the SGM, opposite movements of juvenile and adult red grouper have been reported (López-Rocha & Arreguín-Sánchez, 2013). The movement of juveniles along the coast could be because they seek warm waters that provide food and refuge, avoiding intraspecific competition. Sullivan and Garine-Wichatitsky (1994) reported that the optimum growth temperature for juvenile red grouper is between 24°C–26°C, while warm waters have been associated with inhibiting the reproductive process of adults, and due to climate change, this situation has intensified in recent decades (Arreguín-Sánchez et al., 2017, 2019).

The results indicated that, despite the already reported overlap of the fleets (Salas, Torres-Irineo & Coronado, 2019), each fleet is more efficient at depths where they do not interact with each other. We did not consider that fishing trips operating between 40–60 m depth were made by the semi-industrial fleet (Figs. 3, 4), as official records classify them as a small-scale fleet, despite having greater autonomy (~3 days) and fishing power, and they generally reported their origin port in Dzilam de Bravo (Salas, Torres-Irineo & Coronado, 2019). In this case, the small-scale fleet trips that recorded this depth range have their port of origin in the west (Celestun and Sisal). The second increase in CPUE values recorded by the semi-industrial fleet may be associated with the presence of submarine escarpments (ideal for larger red grouper adults for their benthic habits) on the edge of the Campeche Bank (Mendoza & Ortiz-Pérez, 2000).

The year was one of the most important variables in explaining the variation of the CPUE of red grouper, which gives robustness to the index generated since the objective of the CPUE modeling was to generate an accurate annual index that can be used in stock assessment models to support decision-making in fisheries management (Hinton & Maunder, 2004; Maunder & Punt, 2004). The results showed a decrease in the CPUE of red grouper during the senescence period, which is a reflection of its overexploited state (DOF, 2014). The change in the CPUE levels of red grouper observed before and after 2012 in the semi-industrial fleet emphasized that something happened in the fishery and resulted in the decline in the abundance of the resource. We are unable to state with certainty if it was caused by fishing pressure (increase in a number of hooks, vessels, and fishermen), by natural phenomena (historical period of greater activity of hurricanes and tropical storms, 2001–2011; the high impact of red tide, with the most severe in 2002, 2004, 2008, 2009, and 2011) or an interaction of these, but the use of CFG by the semi-industrial fleet since 2013 is an indicator of fishermen's adaptation to this reduction.

The decrease in red grouper CPUE values in the middle of the year is a result of the accumulation of effort. The increases in CPUE and the decrease in fishing trips from September onwards are associated with the fact that fishermen, besides catching red grouper, direct part of their effort to catching octopus (August–December) and lobster (July–February), alternating fishing methods and gear (Monroy-García, Salas & Bello-Pineda, 2010; Salas, Torres-Irineo & Coronado, 2019). This is reflected in the decrease in the use of the main gears for catching red grouper (LL, DS, SL, and H), increasing the use of SD and JH, generating less competition for access to the resource, which would conceal the real abundance of red grouper. As indicated by Hernández and Seijo (2003), the octopus season has a positive effect on red grouper because it decreases fishing pressure on the resource, dampening the fishing mortality of red grouper in the SGM that leads to an increase in CPUE during the first months of the year. A natural phenomenon that also reduces the effort from November to February, because the authorities close the ports to navigation, is the season called "nortes" (Hernández & Seijo, 2003), characterized by strong northeast winds, precipitation due to polar fronts, and low temperatures (~ 23°C).

The effective reduction of effort in the red grouper fishery during the closed season was not achieved until its extension to two months was decreed in 2017. However, in addition to this measure, other factors that have contributed to its compliance are the recognition by fishermen of the overexploitation of the resource, as well as the implementation of support programs for fishermen (“Temporary Employment Program” and “Respect the Grouper Closed Season”; DOGEY, 2010, 2020), awareness campaigns aimed at consumers about the regulations (“I take care of the grouper”; CEDEPESCA, 2018), and the promotion of various activities that generate economic benefits during the red grouper closure (“Grouper closed season festival”; SEPASY, 2019). Nevertheless, illegal fishing exists in some regions of the SGM during these months and is associated with the lack of vigilance in the region.

Several authors have reported high catches of red grouper in the northeastern quadrants (Hernández & Seijo, 2003; López-Rocha & Arreguín-Sánchez, 2013) that are linked to their movement during the reproductive season (winter–spring), which benefits from the intensified upwelling of Cabo Catoche (Merino, 1997). This also explains the high CPUE values recorded by the semi-industrial fleet from November to February. As suggested by López-Rocha and Arreguín-Sánchez (2013), this area would be a key fishing restriction. In the small-scale fleet, we would have expected that sites with more developed port infrastructure and technological capabilities of the boats (Progreso or Dzilam de Bravo) would have higher CPUE values, which was not reflected in the results found. An example of this contrast is Celestun and Chuburna, which registered high CPUE values, have very different fishing contexts, and have opted for different fishing strategies. In Celestun, fishermen land in the harbor, where there are more boats and fishermen; some boats known locally as "lanchones" have been equipped with two outboard motors with power between 60–115 HP each, to make trips of up to 11 days of fishing. Besides these modifications, the lanchones use LL between 2,000–5,000 hooks, similar or greater effort than the vessels of the semi-industrial fleet, and Celestun has intense illegal fishing problems. In Chuburna, on the other hand, fishermen land on the beach, and it has among the lowest number of boats and fishermen in the SGM and does not present intense illegal fishing problems (Monroy-García et al., 2019). This discrepancy in the origin of the boats coupled with the wide uncertainty of their intervals leads us to explore other alternatives to efficiently manage the red grouper fishery.

The effort was defined as effective fishing days and effective fishing hours for the inclusion of fishing gear as explanatory variables because several authors have considered them as indicators of changes in the fishery (Li et al., 2013; Forrestal et al., 2019; Salas, Torres-Irineo & Coronado, 2019). The present study was no exception, as it was variable with the greatest impact on the CPUEs recorded for each fleet. Another factor associated with the decrease in the abundance of red grouper that was not considered in this work, but which we have observed, was the increase in the number of hooks in the gear used, exceeding the established regulatory measures (DOF, 2015a). It is necessary to integrate them in future research as a way to more finely define the CPUE of red grouper. The rule that prohibits the methods and techniques of capture in Mexican waters (NOM-064-SAG/PESC/SEMARNAT-2013; DOF, 2015b) states, in its sections, the prohibition of the speargun, while the rule that regulates the exploitation of grouper and associated species in Mexico (NOM-065-SAG/PESC-2014; DOF, 2015a) prohibits the capture with fisga (trident harpoon to catch larger fish), which can be interpreted as two different things. The prevalence and incidence of SD and speargun use during the lobster season and its impact on red grouper CPUE encourages the need to update sections of the regulations to eliminate gaps in the rules. The observed trend of crew numbers and navigation days with CPUE may mask the profitability of fishing trips, associated with increased operating costs (Quijano et al., 2018; Salas, Torres-Irineo & Coronado, 2019) and profit sharing among crew members (Coronado et al., 2020). The high contribution of the fishing gear in modeling CPUE supports the work of Monroy-García et al. (2010) and Salas et al. (2019) in proposing the métiers scheme (fleet segmentation that allows the integration of groups of vessels or fishing trips with similar characteristics, such as fishing gear, target species, and fishing area) for the management of fishery resources in the SGM. The results of the present study also suggest integrating the number of crew members when defining the métier codes for future research in the region.

Most assessments of red grouper in the SGM have used CPUE nominal and have not considered these components of CPUE variation (DOF, 2014). The results of these assessments may bias estimates of parameters (e.g., catchability) and values of interest (e.g., biomass level at maximum sustainable yield). The results of the GAM with both fleets indicated that the CPUE fitted was significantly lower than the CPUE nominal; however, the CPUE values showed a decreasing trend. Similar results have been reported for red grouper in east Florida from fishery-independent surveys (Christiansen, Winner & Switzer, 2018). Conversely, for the same species, similarities between nominal and fitted series have been reported in the recreational fisheries (headboat) in Alabama and southwest and northwest Florida (Rios, 2015; Sagarese & Rios, 2018), as well as for the Chinese squid fishery in the Northwest Pacific Ocean (Tian et al., 2009) and in the shortfin mako shark fishery in Taiwan (Wu et al., 2021). These authors point out that the similarities between the series may be due to the way CPUE is estimated (e.g., using the monthly average) and to the similar strategies of fishermen to catch the target species, operating in nearby sites, as well as to the low amount of annual data, which tends to decrease the variation and does not reflect clear trends in the series (Tian et al., 2009; Wu et al., 2021). We have considered the situations previously mentioned, and the results of the present study confirm the influence of the CPUE of red grouper by several components, so the differences between the nominal and fitted series may be due to the variability in the strategies of the trips of both fleets (Salas, Torres-Irineo & Coronado, 2019) and to the inherent complexity of mixed fisheries (Tzanatos et al., 2005), such as the one in question, which catches red grouper in the SGM.

Conclusion

The hypothesis on the influence of various components on the senescing red grouper fishery was verified, and it was shown that using the GAM to fit the CPUE of red grouper was adequate because it reduced the variability of the data. We reiterate that the identified components that influence the distribution and abundance of the resource will allow us to adapt and direct feasible strategies to strengthen fisheries management.

The results encourage exploring and integrating several variables for future modeling of red grouper CPUE given the nature of the species (bottom temperature), the dynamics of the fleets (grouping fishing trips into métiers), as well as adding the economic component to evaluate the profitability of fishing trips, climatic conditions, and oceanographic processes in the region (rainfall or upwellings). Several questions have arisen, since this is a sequential fishery: will there be independent variables for each fleet? and will the indices generated be proportional to abundance? Nevertheless, there has been a debate on how to deal with the behavior of fishermen and fishing patterns. One possible solution could be through the synergistic interaction of the different components involved.

In short, the large amount of data series of the present study provides robustness to the results obtained in the modeling of the red grouper CPUE, the abundance indices generated can be used in assessment and management work.

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Figure 1

Behavior of historical catches of the red grouper *Epinephelus morio* in the Campeche Bank, Mexico.

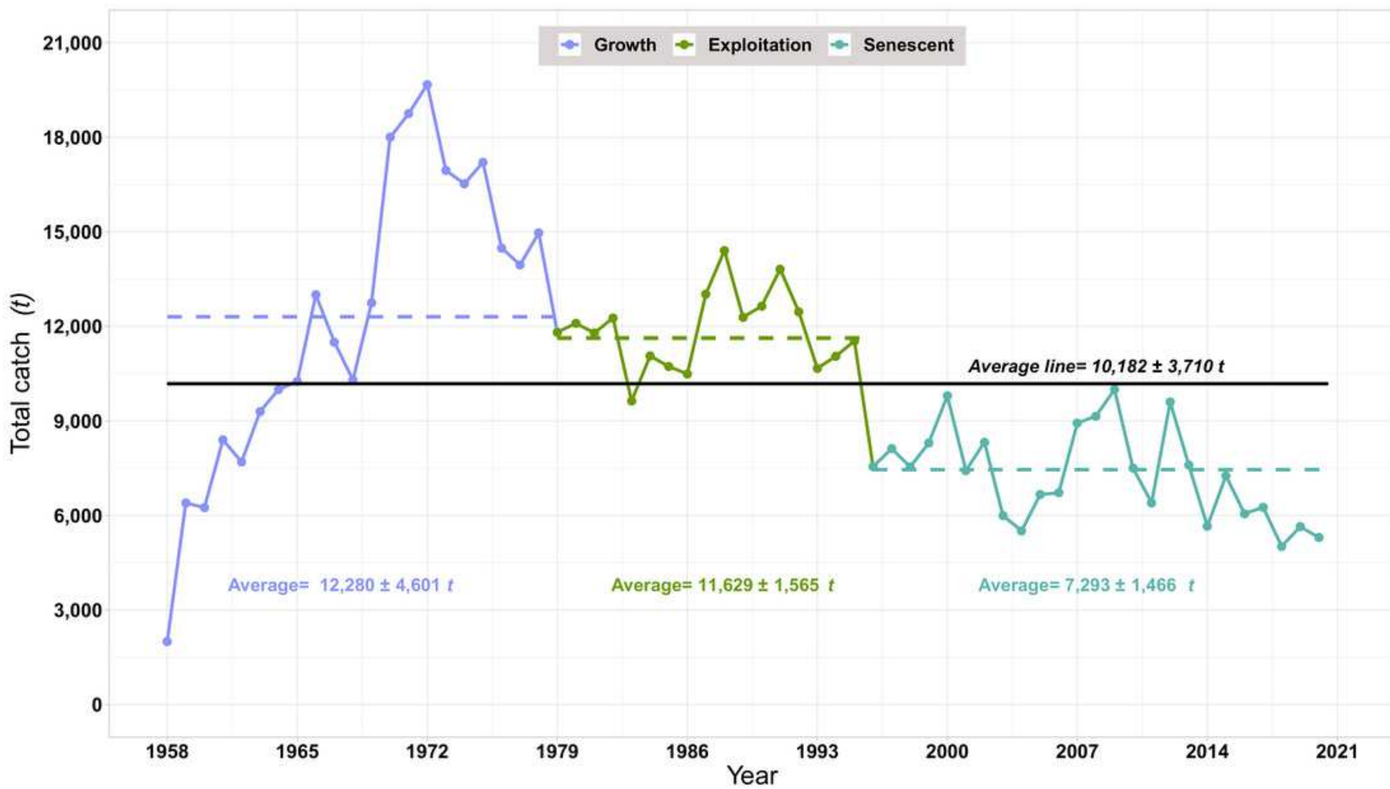


Figure 2

Fishing area for the catch of red grouper in the southeastern Gulf of Mexico.

The spatial component for the small-scale fleet was addressed by the place of origin of the boats, and in the semi-industrial fleet, the fishing zones proposed by the Instituto Nacional de Pesca were used. Dotted lines indicate the 40 m isobath and 200 m common operating range of the small-scale and semi-industrial fleets, respectively

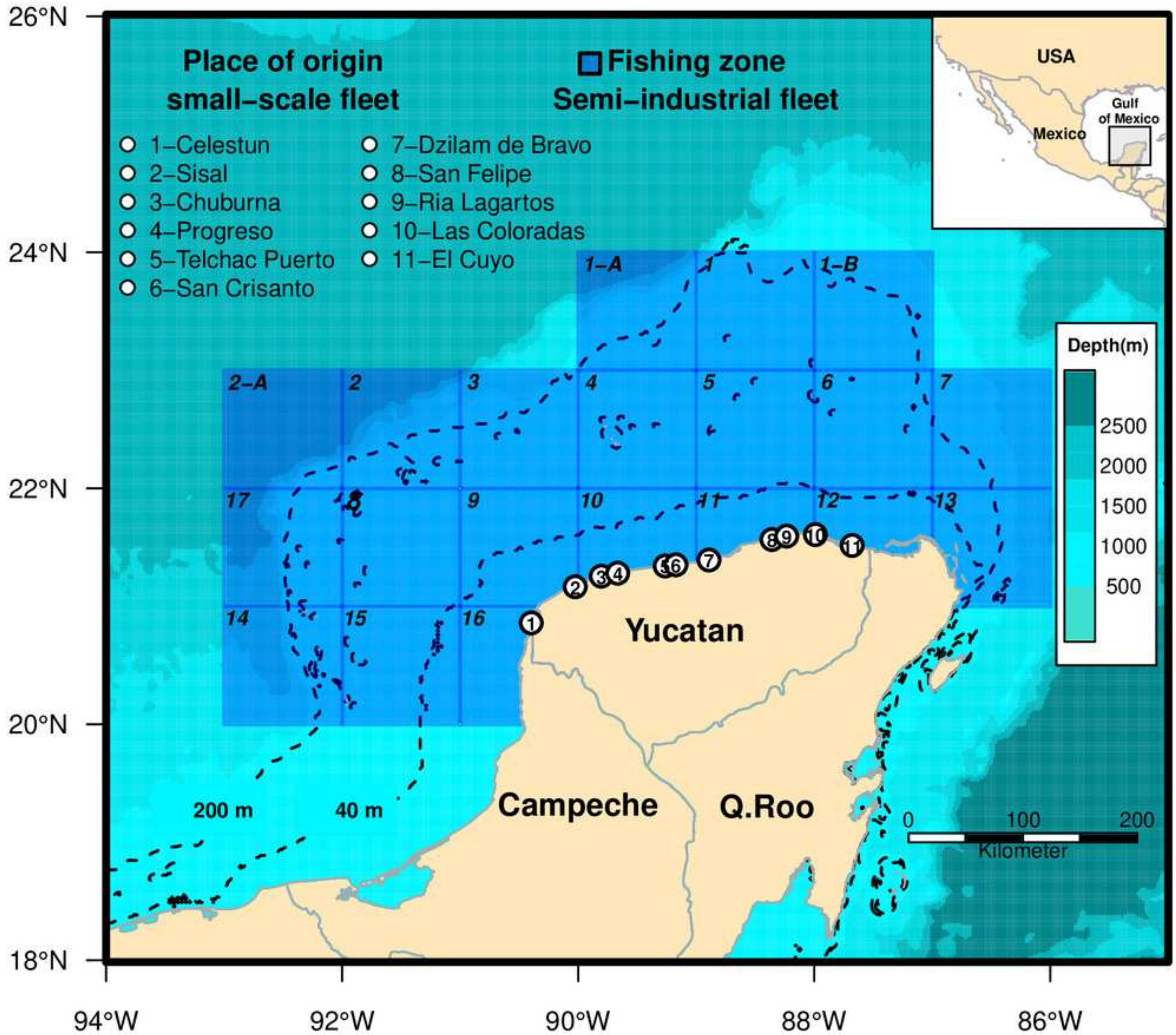

Place of origin
small-scale fleet
1–Celestun
2–Sisal
3–Chuburna
4–Progreso
5–Telchac Puerto
6–San Crisanto
7–Dzilam de Bravo
8–San Felipe
9–Ria Lagartos
10–Las Coloradas
11–El Cuyo
Fishing zone
Semi-industrial fleet
USA
Mexico
Gulf of Mexico
Depth(m)
2500
2000
1500
1000
500
1-A
1
1-B
2-A
2
3
4
5
6
7
17
9
10
11
12
13
14
15
16
Yucatan
Campeche
Q.Roo
200 m
40 m
0
100
200
Kilometer
26°N
24°N
22°N
20°N
18°N
94°W
92°W
90°W
88°W
86°W

Figure 3

Effects of environmental, temporal, spatial, and operational components on the catch per unit effort of red grouper recorded by the semi-industrial for the best GAM.

The solid black lines indicate the median catch per unit effort values, and the blue shaded edges show the 95% confidence intervals.

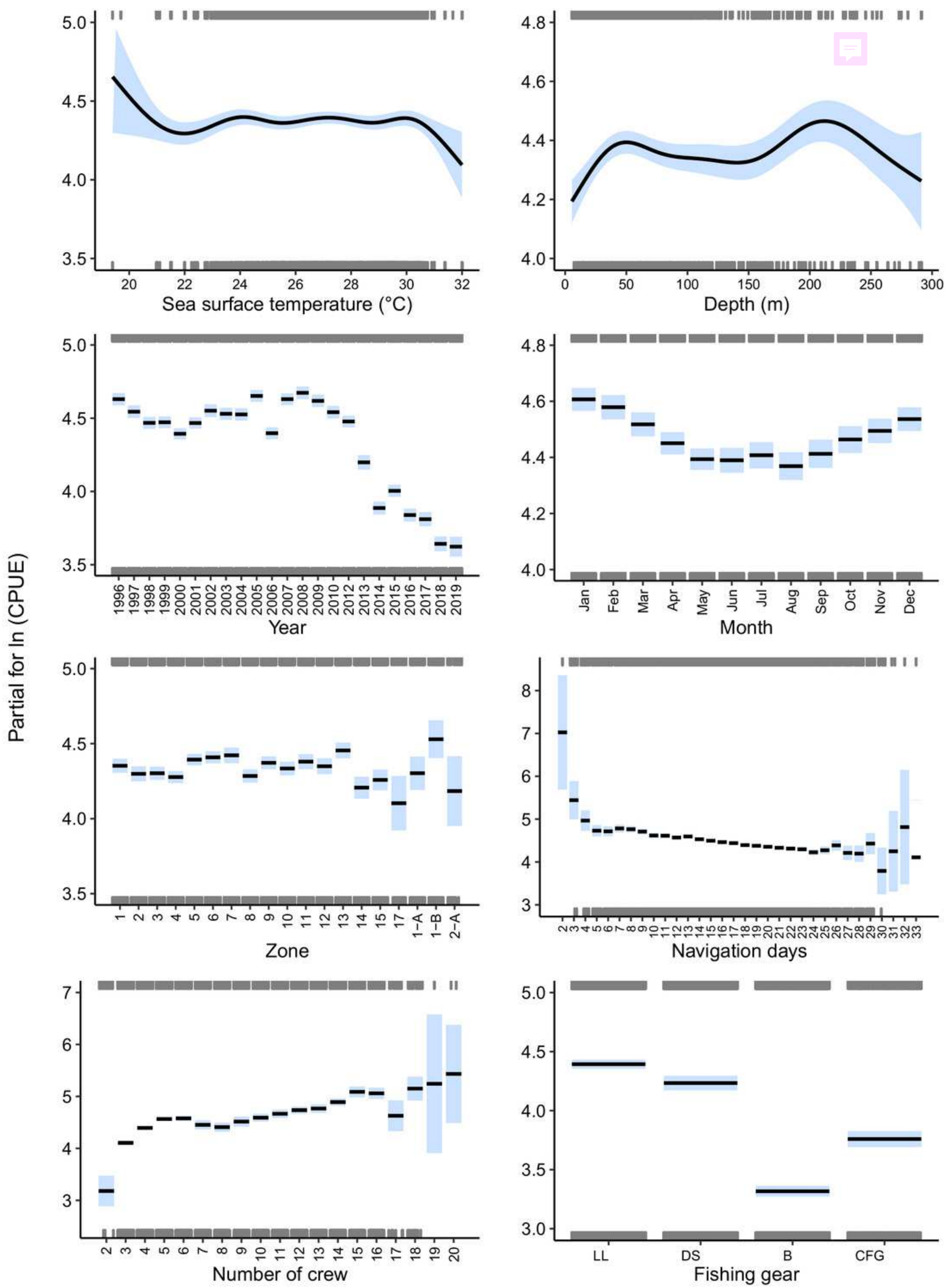
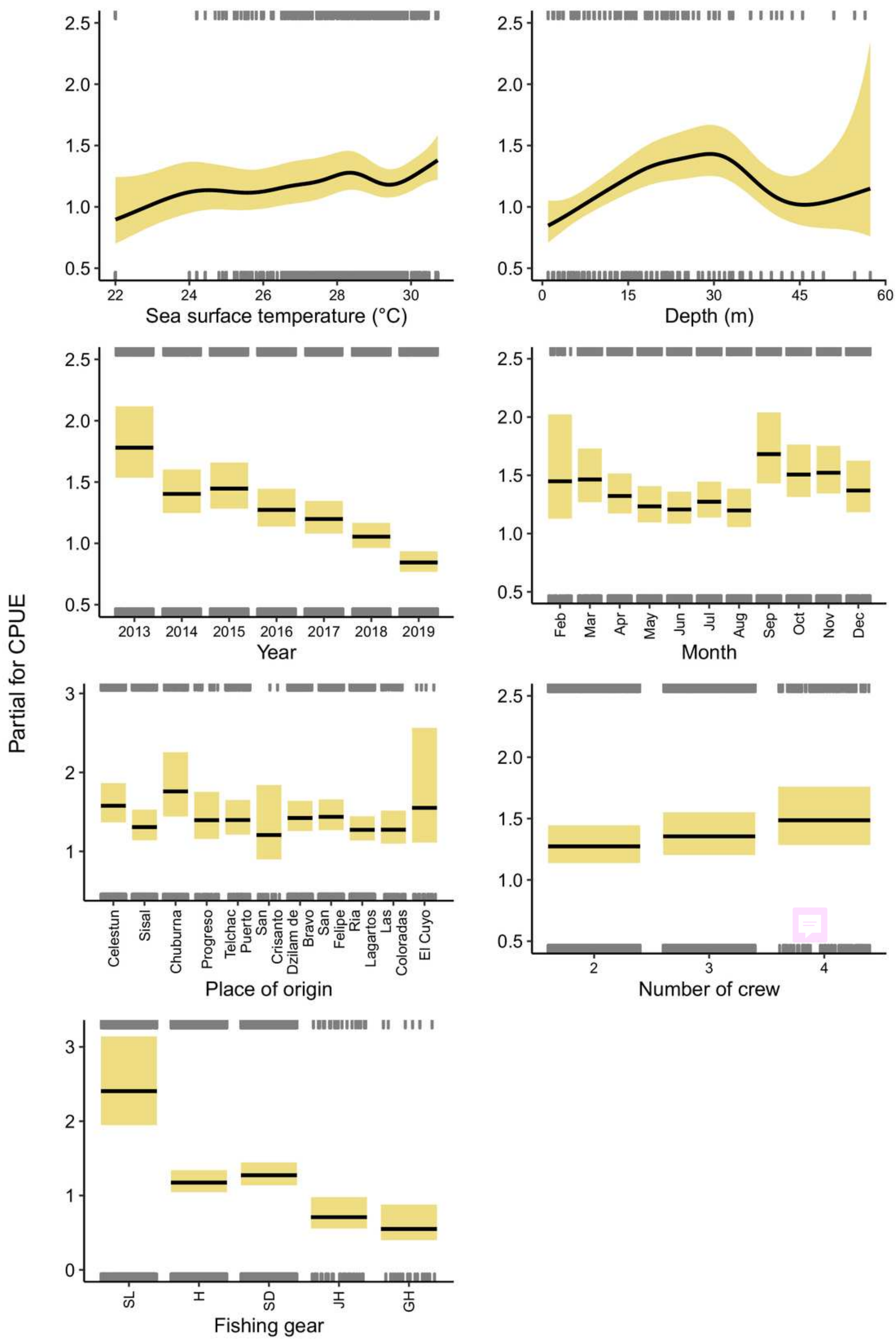

Partial for ln (CPUE)
Sea surface temperature (°C)
Depth (m)
Year
Month
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Zone
Navigation days
Number of crew
Fishing gear
LL
DS
B
CFG

Figure 4

Effects of environmental, temporal, spatial, and operational components on the catch per unit effort of red grouper recorded by the small-scale fleet for the best GAM.

The solid black lines indicate the median catch per unit effort values, and the golden shaded edges show the 95% confidence intervals.



Partial for CPUE
2.5
2.0
1.5
1.0
0.5
22
24
26
28
30
Sea surface temperature (°C)
0
15
30
45
60
Depth (m)
2013
2014
2015
2016
2017
2018
2019
Year
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
3
2
1
Celestun
Sisal
Chuburna
Progreso
Telchac Puerto
San Crisanto
Dzilam de Bravo
San Felipe
Ria Lagartos
Las Coloradas
El Cuyo
Place of origin
2
3
4
Number of crew
0
SL
H
SD
JH
GH
Fishing gear

Figure 5

Comparison between nominal catch per unit effort and fitted catch per unit effort by year and month of red grouper recorded by the semi-industrial fleet in the southeastern Gulf of Mexico.

Symbols indicating significance: ns $p > 0.05$, * $p < 0.05$, ** $p < 0.01$. *** $p < 0.001$ and **** $p < 0.0001$

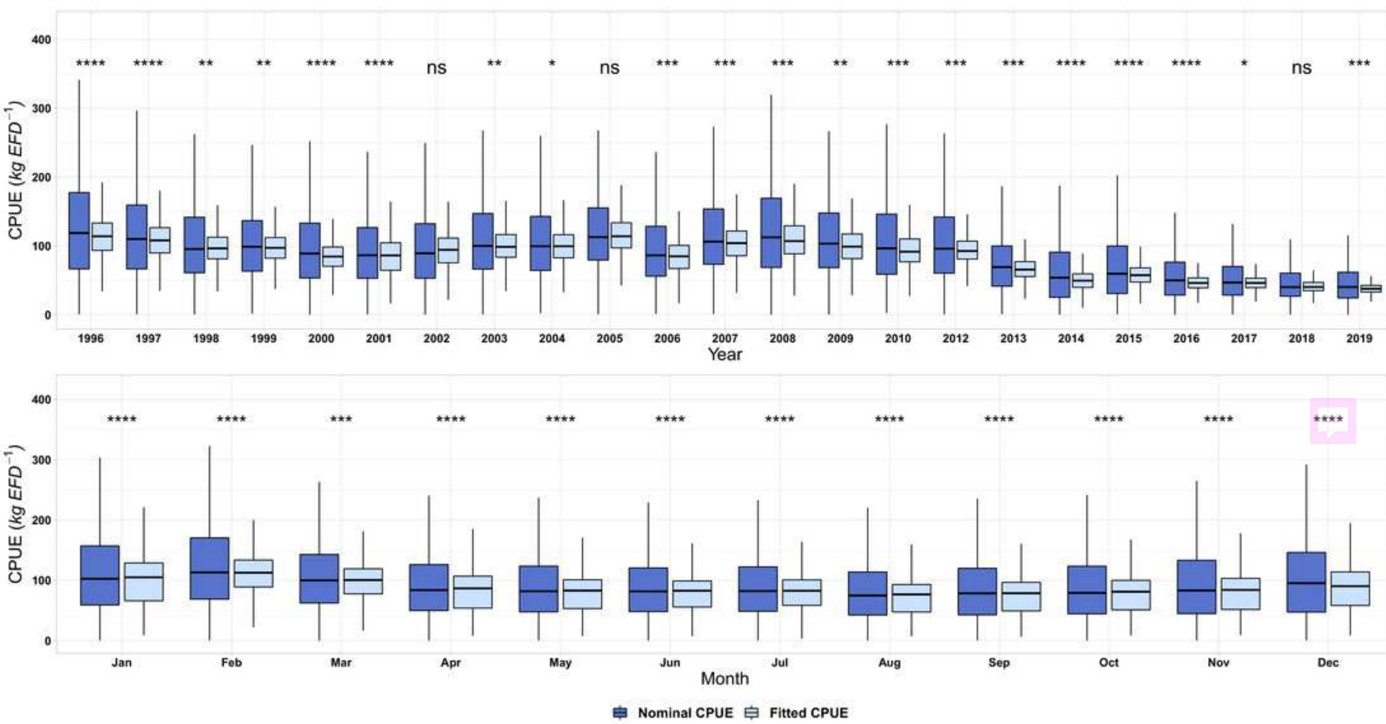


Figure 6

Comparison between nominal catch per unit effort and fitted catch per unit effort by year and month of red grouper recorded by the small-scale fleet in the southeastern Gulf of Mexico

Symbols indicating significance: ns $p > 0.05$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ and **** $p < 0.0001$.

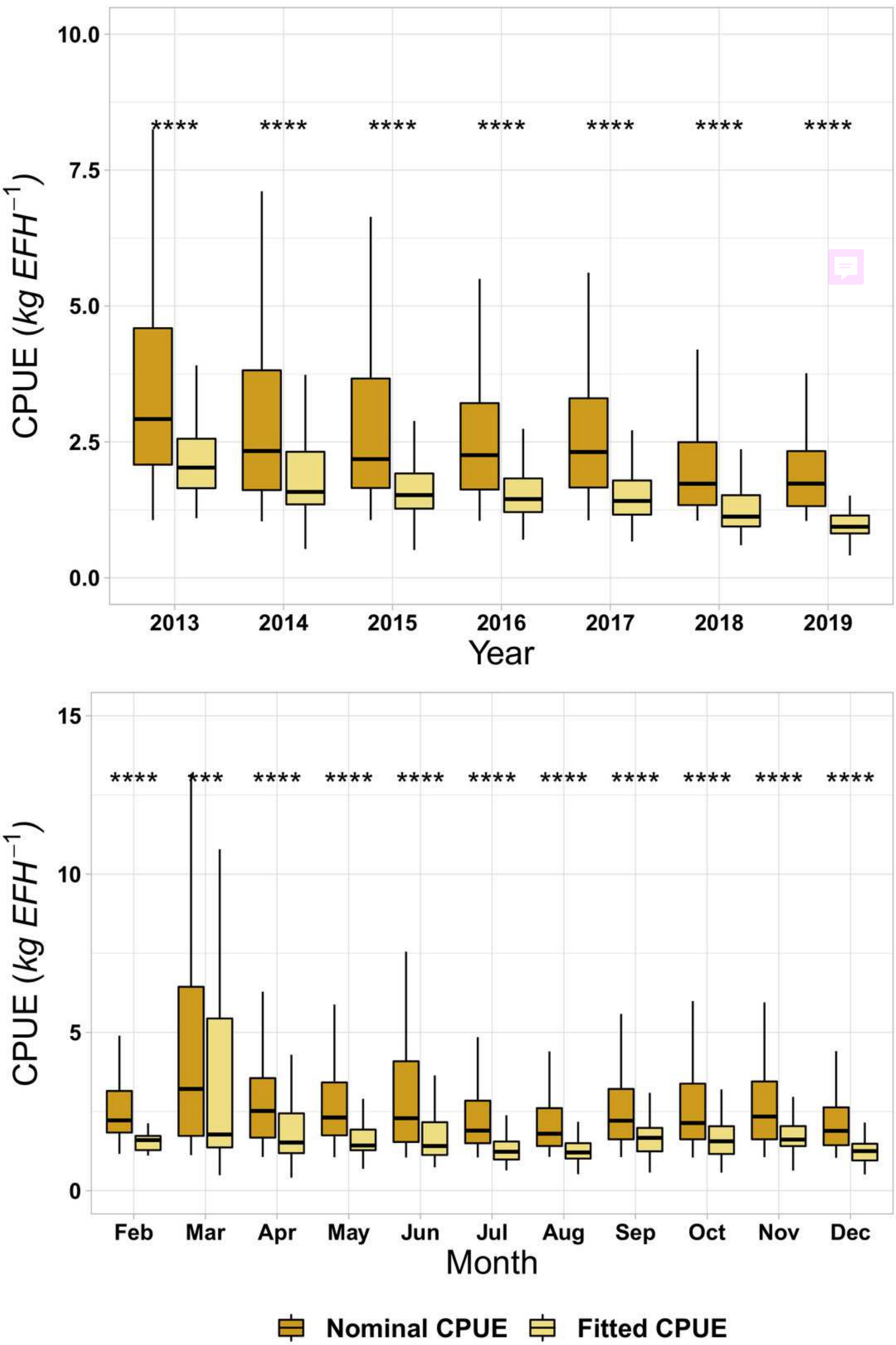

10.0
7.5
5.0
2.5
0.0
CPUE (kg EFH⁻¹)
****
2013
2014
2015
2016
2017
2018
2019
Year
15
10
5
0
CPUE (kg EFH⁻¹)
***
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
Nominal CPUE
Fitted CPUE

Table 1 (on next page)

Classification of variables into components for modeling the catch per unit effort of red grouper in the SGM.

Table 1:

Classification of variables into components for modeling the catch per unit effort of red grouper in the SGM.

Component	Variable	Domain	Importance
Environmental	Sea surface temperature	Celsius degrees (°C)	Most models used to assess fish populations have inferred that changes in abundance are due to fishing pressure, ignoring a natural decline due to environmental changes (Hilborn & Mangel, 2013). Identifying the environmental factors that contribute to CPUE variation is key to incorporating this component into evaluation models (Bigelow, Boggs & He, 1999)
	Deep	Meters (m)	
Temporal	Year	Semi-industrial fleet :1996—2019 Small- Scale fleet:2013—2019	The objective of CPUE standardization is to obtain an accurate annual index for use in stock assessment models (Hinton & Maunder, 2004). Fishermen in the SGM modify their effort
	Month	Semi-industrial fleet: January—December	

		Small- Scale fleet: February—December	according to the fishing season and market conditions (Salas, Torres-Irineo & Coronado, 2019)
Spatial	Zone	Semi-industrial fleet :1—17	Catchability varies spatially due to changes in fishery composition and resource abundance (Maunder & Punt, 2004; Monroy-García et al., 2019) so identifying where fishing occurs and the concentration of effort is key to regulating the fishery (e.g. no-take zones)
	Place of origin	Small- Scale fleet: Celestun—El Cuyo	
Operative	Navigation days	Semi-industrial fleet: Days	Vessel skippers and fishermen modify their fishing trip based on their experience with the objective of maximizing their income, alternating fishing gear, changing target species, reducing fishing time and the number of crew members (Murillo-Posada, Salas & Velázquez-Abunader, 2019; Salas, Torres-
	Number of crew	Semi-industrial fleet: Numbers	
	Fishing gear	Semi-industrial fleet: Bicycle (B), longline (LL), Dinghy and shortline (DS), Combined (C)	

	Small- Scale fleet: Short longline (SL), Headlines (H), Scuba diving (SD), Jimba and handlines (JH), Gillnets and handlines (GH)	Irineo & Coronado, 2019)

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Table 2 (on next page)

Results of the best generalized additive model that explain the effects of the components on catch per unit of effort for red grouper caught by the semi-industrial fleet.

Column heading abbreviations are as follows: degrees of freedom for parametric terms (df), effective degrees of freedom (edf), reference degrees of freedom (rdf) for smooth terms, statistics of the *F* (*F*) model and *s* denotes smooth terms.

Table 2. Results of the best generalized additive model that explain the effects of the components on catch per unit of effort for red grouper caught by the semi-industrial fleet. Column heading abbreviations are as follows: degrees of freedom for parametric terms (df), effective degrees of freedom (edf), reference degrees of freedom (rdf) for smooth terms, statistics of the *F* (*F*) model and *s* denotes smooth terms.

Component	Variable	df	edf	rdf	*F*
Environmental	*s* (Sea surface temperature)		8.46	8.91	2.84
	s (Depth)		6.89	7.89	8.85
Temporal	Year	22			293.67
	Month	11			28.37
Spatial	Zone	18			14.30
Operative	Navigation days	31			31.50
	Number of crew	18			118.70
	Fishing gear	3			2557.93

Table 3 (on next page)

(on next page)

Results of the best generalized additive model that explain the effects of the components on catch per unit of effort for red grouper caught by the small-scale fleet.

Column heading abbreviations are as follows: degrees of freedom for parametric terms (df), effective degrees of freedom (edf), reference degrees of freedom (rdf) for smooth terms, statistics of the *F* (*F*) model and *s* denotes smooth terms.

Table 3. Results of the best generalized additive model that explain the effects of the components on catch per unit of effort for red grouper caught by the small-scale fleet. Column heading abbreviations are as follows: degrees of freedom for parametric terms (df), effective degrees of freedom (edf), reference degrees of freedom (rdf) for smooth terms, statistics of the *F* (*F*) model and *s* denotes smooth terms.

Component	Variable	df	edf	rdf	*F*
Environmental	*s* (Sea surface temperature)		6.56	7.68	2.41
	s (Depth)		5.96	7.01	12.32
Temporal	Year	6			34.23
	Month	10			7.74
Spatial	Place of origin	10			3.43
Operational	Number of crew	2			6.83
	Fishing gear	4			85.12