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EXPLORATORY STOCK ASSESSMENT OF DORADO (*CORYPHAENA HIPPURUS*) IN THE SOUTHEASTERN PACIFIC OCEAN

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[1] Order subject to changes

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SUMMARY

Dorado (*Coryphaena hippurus*) has a wide distribution throughout the tropical and subtropical waters of the world's oceans. It is one of the most important species caught in the artisanal fisheries of the coastal nations of the eastern Pacific Ocean (EPO), ranging from Chile in the south to Mexico in the north. Available fisheries statistics indicate that the EPO is the dominant region in global production of dorado. The species has been thought of as highly resilient to overfishing due to its high productivity in all the oceans of the world. However, stock assessments are needed to obtain a better picture of the stock status of the species and develop reference points for management. Coastal Member States of the IATTC have requested collaborative research and guidance from IATTC staff on dorado regional research, in particular on stock assessment research. Two IATTC Technical Meetings on Dorado have been conducted to date, in Ecuador and Peru. A large and diverse amount of fishery and biological data for dorado available from IATTC Member States was identified, stock structure assumptions were discussed, as were the methodologies and indicators of stock status to use.

This study presents an exploratory stock assessment for dorado in the southeastern Pacific Ocean. The geographical extent of the assessment is the "core region" of the dorado stock in the EPO. In this region, dorado are mainly subject to targeted artisanal longline fisheries in Peru and Ecuador, but the species is also caught incidentally (as bycatch) by the tuna purse-seine fisheries. The assessment is implemented in Stock Synthesis with a monthly time step during 2007-2014, fits to length-composition data from Peru and purse-seine bycatch (sexes combined) and Ecuador (sex-specific) and CPUE for Ecuador. The monthly time step allows depletion caused by catch and measured by the CPUE to inform estimates of absolute abundance. Catches are those from Peru and Ecuador, and the purse-seine bycatch.

The assessment produces a good fit to Ecuadorean CPUE and size-composition data. Although the fit to size-composition data is good, residual patterns for some months in the Ecuadorean fishery suggest that more work is needed to add processes (*e.g.* estimate growth internally, cohort-specific growth, alternative growth curves) that could explain the lack of fit. Although the assessment results contribute

to the knowledge about the population dynamics of dorado and its history of exploitation in the EPO, the IATTC staff is unable to draw conclusions about stock status, because no reference points, target or limit, have been defined for dorado in the EPO. Nonetheless, some management quantities are presented and discussed for consideration. Recent catches are near MSY estimates from the stock assessment. However, YPR analyses show that the yield curve is very flat, and the fishing mortality required to achieve MSY is poorly defined. Also, a complementary study presents an exploratory management strategy evaluation (MSE) for dorado in the southern EPO. Overall, this study shows that Stock Synthesis is a promising tool for conducting stock assessments of this species in the EPO. More research is needed to refine the model, the data used, and to prioritize collection of new data for the assessment of dorado. Analyses including data from these fisheries and expanding the spatial extent of this assessment could be considered in the future.

1. INTRODUCTION

1.1. General background

Dorado (*Coryphaena hippurus*) Linnaeus, 1758, is an epipelagic and primarily oceanic species with a wide distribution throughout the tropical and subtropical waters of the world's oceans (Palko *et al.* 1982). Also known as *mahi mahi*, *dolphinfish, doradilla*, *lampuga*, *palometa*, and *perico*, it is one of the most important species caught in the artisanal fisheries of the coastal nations of the eastern Pacific Ocean (EPO). The species is thought to be highly resilient to overfishing due to its high productivity in all the oceans of the world (Palko *et al.* 1982). In the EPO in particular, dorado show high rates of growth during a very short lifespan (about three years), early maturity (50% maturity at 0.5-1 years of age), high fecundity, and the capacity to spawn throughout the year in some areas (Martínez-Ortiz and Zúñiga-Flores 2012).

In the EPO, dorado is subject to exploitation by fleets of nearly all coastal nations, from Chile in the south to Mexico in the north, and even occasionally in the southwestern waters of the United States, at the northernmost distribution of the resource (Dapp *et al.* 2013; Lasso and Zapata 1999; Martínez-Ortiz and Zúñiga-Flores 2012; Norton 1999; Solano-Sare *et al.* 2008). The available fisheries statistics indicate that the EPO is the dominant region in global production of dorado, with between 47 and 70% of the total world catches during 2001-2012 (Aires-da-Silva *et al*. 2014). It is estimated that the average total annual catch of dorado in the EPO was about 71,000 metric tons (t) during 2008-2012 (Figure 1.1).

1.2. The IATTC and dorado

Despite the importance of the fishery for dorado in the EPO, there is great uncertainty about the status of the stock (SFP 2013). A stock assessment was attempted in 1991, applying a length-based virtual population analysis to Ecuadorian data only (Patterson and Martínez 1991), but the results of that work are outdated. The exploitation of dorado has evolved greatly since the 1990s, with new fisheries emerging and becoming dominant in terms of catch volume (e.g. artisanal fisheries in Peru, which took between 57 and 81% of the total estimated removals of dorado in the EPO during 2001-2012; Aires-da-Silva et al. 2014).

The high value of dorado exports has also resulted in a growing interest in the process of product certification and ecolabeling for some fisheries. This added to the existing demand for a stock assessment of dorado, since most fishery certifications require comprehensive stock assessments and a management system in place, including reference points (target and limit) and harvest control rules. These are difficult to determine without conventional stock assessments, or at least an understanding of the stock and fishery dynamics at the level needed to conduct a stock assessment.

The Antigua Convention establishes that one of the functions of the Inter-American Tropical Tuna

Commission (IATTC) is to "adopt appropriate measures to avoid, reduce and minimize … impacts on associated or dependent species." Dorado is caught incidentally in the purse-seine fishery for tunas in the EPO (Martínez-Rincon et al. 2009), although in very small quantities (<5%) compared to the total volume of commercial catches in the EPO (Aires-da-Silva et al. 2014). In this context, some coastal Member States of the IATTC have requested collaborative research and guidance from IATTC staff on regional dorado research, in particular on stock assessments (Aires-da-Silva et al. 2014). Following this request, two IATTC technical meetings on dorado were held. The first meeting, held in Manta, Ecuador, in 2014, helped to establish the collaborative research forum that is necessary to work on dorado at the large regional scale of the EPO. Also, a large and diverse amount of fishery and biological data for dorado available from IATTC member countries was identified. The second meeting was held in Lima, Peru, in 2015, and led to great progress on two important questions that need to be addressed for regional management of dorado in the EPO: stock structure assumptions, and which methodologies and indicators of stock status to use.

1.3. Conceptual life-history model for dorado in the EPO

One important outcome of the 2nd meeting on dorado was the elaboration by regional experts of a conceptual life-history model for dorado in the EPO. The genetic studies available are preliminary, but they indicate high genetic variability within the EPO, and most indicate the need for increased sample sizes and improved spatio-temporal sampling. At this point, there is no clear evidence that there is more than one population of dorado in the EPO, but some information suggests that there may be coastal and oceanic components. If that is the case, the coastal (or "more resident") component would be more available towards the coast slightly north of the equator, while the oceanic component migrates to the coastal areas of the EPO around October-November (Figure 2).

As noted by Martínez-Ortiz *et al*. (2015), the rapid spatio-temporal dynamics of dorado off the coasts of Peru and Ecuador should be taken into consideration, to better account for important biological/ecological (recruitment, movement) and fishing (catchability, availability) processes in the stock assessment model. At the start of the dorado fishing season (around October-November in Ecuador), dorado become vulnerable to longline fishing gear in oceanic waters off Peru and Ecuador between 2°S and 10°S from 90°W to 105°W (Figure 2.b). These subtropical waters, with moderate (20-25°C) sea-surface temperatures (SSTs), are located south of the Equatorial Front and west of the cold (16-20°C) water mass associated with upwelling and the Humboldt Current system off Peru. Following the seasonal dynamics of this current system, this cool water mass contracts during the year, and by February-March it is confined to coastal Peruvian waters. This contraction is accompanied by an eastward expansion of the "fringe" of subtropical waters, with moderate SSTs, and dorado become highly vulnerable to fisheries closer to the mainland coasts of Peru and Ecuador through February. By February-March, and as SSTs rise, there is little habitat below 25°C available in the equatorial and tropical Pacific. This coincides with the end of the dorado fishing season in the equatorial region.

1.4. Objectives of the assessment

This report presents an exploratory stock assessment of dorado in the EPO south of the Equator (South EPO), which builds on the discussions at the two IATTC technical meetings and the resulting datasets and knowledge. During the second meeting, it was decided that an exploratory stock assessment should start by focusing on the fishery data available from the "core region" of the dorado stock in the EPO. In this region, dorado are exploited mainly by targeted artisanal longline fisheries from Peru and Ecuador, but are also caught incidentally (as bycatch) by the tuna purse-seine fisheries, and together these three fisheries account for about 90% of the total catch of dorado in the EPO (Aires-da-Silva *et al*. 2014). Furthermore, they are the only fisheries for which moderately long time series of fishery data (*e.g.* catch and effort data, standardized catch per unit effort (CPUE), and catch composition data) are available for stock assessment analysis. Fisheries in other EPO coastal States also catch dorado, but in much lesser amounts. Some of these States (Chile and Costa Rica, for instance) have recently begun data-collection programs for dorado; including data from these fisheries and expanding the spatial extent of this assessment could be considered in the future.

The main objective of this assessment work is to explore the potential usefulness of the Stock Synthesis modelling platform for assessing dorado in the EPO. Although the assessment results contribute to the understanding of the population dynamics of dorado and its history of exploitation in the EPO, the IATTC staff is unable to draw conclusions about stock status, because no reference points, target or limit, have been defined for dorado in the EPO. Nonetheless, some management quantities are presented and discussed for consideration. Also, a complementary study presents an exploratory management strategy evaluation (MSE) for dorado in the EPO (Valero *et al*. 2016).

2. DATA

The fisheries exploiting dorado in EPO, as well as their fishery data used in the assessment, are described below. After considering the quality of the different data sources available, it was decided that the stock assessment should cover 2007-2014, since the data sources available for this period are considered quite reliable. The data are shown in Figure 3 by type, fishery, and years included in the model. Also presented below are data sources collected before this period, although they were not used in the assessment.

2.1. Definitions of the fisheries

In the South EPO, dorado are mainly subject to targeted artisanal longline fisheries by Peru and Ecuador, but the species is also caught incidentally (as bycatch) by the tuna purse-seine fisheries. These three fisheries are defined separately in this stock assessment (Table 2.1). No fishery definitions based on spatial considerations are defined except as implicit in the spatial distribution of the Ecuadorian and Peruvian fisheries. The different data sets that describe the dorado catches taken by these fisheries are described below.

2.2. Catch

The time series of historic catches of dorado obtained for the stock assessment from Peruvian, Ecuadorian and IATTC sources are described below. No information on dorado discards is available, therefore in this report the term ‘catch’ refers to retained catch, and thus observed landings and unloadings.

2.2.1. Peru

Dorado is exploited by artisanal fisheries in coastal and oceanic waters off Peru. Availability of the resource is highly seasonal, usually occurring from September to March, and is associated with warm SSTs (21-30 ˚C). During these months, dorado accounts for about 90% of the total volume of landings by the Peruvian artisanal fishery (Solano-Sare *et al.* 2008). Some landing records exist going back to the late 1980s (IMARPE), but the major development of the Peruvian fishery occurred in the early 2000s, following the increased availability of dorado in 1998 that coincided with the strong El Niño event of that year. Although Peru has the greatest catches of dorado in the EPO, it is second to Ecuador in terms of exports (filleted and fresh) to the United States. Information from various sources indicates that most of the Peruvian catch is consumed domestically.

The Instituto del Mar de Perú (IMARPE) provided official catch landings data, collected by the Statistics

Office of the Ministry of Production (PRODUCE), for dorado taken by the Peruvian artisanal fisheries[2] during 2000-2014. Only annual statistics are available for the 2000-2005 period, but after that they are available by month. Using this combination of annual and monthly data, an attempt was made to construct a historical monthly time series of dorado catches for Peru during the 2000-2014 period (Figure 4.a). Monthly estimates for 2000-2005 were obtained by applying to the annual data the average monthly proportions of the catches available for 2006-2015.

2.2.2. Ecuador

Dorado is exploited by Ecuadorian artisanal fisheries, mainly the multi-species longline fishery which shifts target among large pelagic fish species, including dorado, tuna, billfishes, and sharks. This fishery began gradually in the mid-1970s, but underwent a great expansion during the 1990s and 2000s. The traditional fishing areas, which were initially within 40 nautical miles (nm) of the coast, have expanded gradually over the years to as far as 1,400 nm from the mainland coast west of the Galapagos Islands, establishing what is now known as the "oceanic-artisanal fishery" in Ecuador. Like in Peru, there is a great seasonality in these fisheries: the longline fishery targeting dorado operates mainly during October-February, with peak catches in December and January. Dorado accounts for more than 65% of the estimated landings of large pelagic fish species by artisanal fisheries in Ecuador, and 35 to 40% of the exports of pelagic fish to the United States (Martínez-Ortiz and Zúñiga-Flores 2012). The longline fishery for tuna-billfish-shark (TBS) species takes place all year round. However, catches of TBS species decline greatly during the dorado season because longline vessels change their gear in order to target dorado, using the smaller "doradero" hooks. Martínez-Ortiz *et al*. (2015) provide an extensive description of the Ecuadorian artisanal fishery for large pelagics, including species composition and spatio-temporal dynamics.

An attempt was made to construct a historical monthly time series of dorado catches taken by Ecuadorian fisheries during the 1987-2015 period (Figure 4.b). For the most recent years (2008-2015), catch statistics were extracted from the databases of Ecuador's artisanal fishery landings monitoring system (*Sistema de Control y Monitoreo*; SCM), operated by the Undersecretariat of Fisheries Resources (SRP(Martínez-Ortiz *et al.* 2015). Catch estimates for the early period were obtained from fishery statistics published by the National Fisheries Institute (INP).

2.2.3. Bycatch from tuna purse seine fisheries

Dorado are caught as bycatch in the tuna purse-seine fisheries in the EPO. There are three types of purse-seine sets for tuna (on tunas associated with dolphins, associated with floating objects, and unassociated tunas); dorado are caught predominantly in floating-object sets (xxx%). In 1993, IATTC observers on large (IATTC size-class 6; carrying capacity greater than 363 t) purse-seine tuna vessels began to collect data on bycatches of dorado (Figure 4.c). Data on bycatches by smaller (size classes 1-5) are not available, so they were estimated by applying the catch-per-set rates of Class-6 vessels to sets by the smaller vessels (xxx% of the total number of purse-seine sets).

2.2.4. Other fisheries

There are other sources of fishing mortality for dorado in the EPO that were discussed at the IATTC Technical Meetings on Dorado. In the South EPO, the Peruvian and Ecuadorian fisheries are clearly the dominant sources of the dorado removals, and these data are included in this assessment. However, there are some additional reliable dorado data from Chilean fisheries which could be added in future

[2] Instituto Nacional de Pesca Ecuador (1999) Estadísticas de los Desembarques Pesqueros en el Ecuador 1985-1997. Departamento Procesamiento de Datos división de Biología y Evaluación de Recursos Pesqueros. Marín de López C, Ormaza-Gonzalez *F* y Arriaga-Ochoa L (eds). INP. 152 pp.

improvements of this assessment. The distant-water longline fleets targeting tuna and billfishes also have bycatches of dorado. IATTC Resolution C-11-08 established a scientific observer program for longline vessels over 20 meters length overall which would cover at least 5% of the fishing effort (defined as effective days fishing, excluding transit days) by such vessels, starting in 2013. Therefore, additional reliable data on dorado bycatches by these fleets may become available in the future.

2.3. Indices of abundance

CPUE data from the Peruvian and Ecuadorian longline artisanal fisheries were used to produce a set of candidate indices of relative abundance. The real changes in dorado abundance assumed to be represented in CPUE data may be confounded with changes over time in fishing practices and/or spatio-temporal effects. "Catch-effort (or catch) standardization", which needs to be accounted for to remove biases and produce a reliable index of abundance (Maunder and Punt, 2004). Generalized Additive Models (GAMs) were used for catch-effort standardization of the CPUE data for dorado; the results are summarized below, and presented in detail in Appendix A.

2.3.1. Peru

A GAM for the dorado CPUE in weight that assumes a Gamma error distribution was used to standardize the Peruvian CPUE data. The explanatory variables included in the GAM were year, month, and fish-carrying capacity of the vessel. Information on geographical location (latitude and longitude) is not available in the Peruvian trip records. An attempt was made to account for spatial effects on the CPUE by producing separate indices of abundance for three main fishing regions, based on port of landing: North (Paita); Central (Chimbote-Pucusana); and South (Ilo). Since CPUE data after 2010 may be of better quality than those for previous years, standardized CPUEs were computed separately for two time blocks (2003-2010 and 2011-2014; Figure A.1). Model diagnostics for the GAM produced for the different regions and time blocks of the Peruvian fishery are shown in Figures A.2-A.7.

2.3.2. Ecuador

GAMs were used to develop a standardized CPUE index for the Ecuadorian longline fishery targeting dorado. Several different GAMs were explored for the catch data: a negative binomial (NB) GAM for counts of fish (taking effort into consideration) (Figure A.8), and two different GAMs for the CPUE in weight, one based on a Gamma distribution with log link and the other based on a lognormal distribution (Figure A.9). The NB GAM fitted to the count data had the following form for the right side of the model equation:

= year-month effect + 2-D spatial smooth surface + linear term for log(effort)

where effort is in number of hooks and the spatial smooth surface is a function of the latitude and longitude of the fishing location. The two GAMs for CPUE in weight had the same form for the right side of the model equation:

= year-month effect + 2D spatial smooth surface.

For the CPUE models, a small constant (a value slightly lower than the lowest non-zero CPUE value) was added to the CPUE values before fitting the models, because 1.6% of trips that used dorado hooks had no catch of dorado; delta-*F* or zero-inflated models were not considered at this point because the percentage of zero-value observations is small. After reviewing the model diagnostics (Figures A.11-13), and assuming that the weight data are more accurate than the count data, the Gamma model was selected. Judging by the generalized cross-validation score, the Gamma distribution was a better fit to the CPUE data than the lognormal distribution, but not by percent deviance explained or adjusted R^2. However, diagnostic plots for the Gamma model looked slightly better than for the lognormal model, and the Gamma distribution has the advantage that it does not require a bias correction to obtain the back-transformed CPUE predictions. Nonetheless, all three models appeared to suffer from a similar problem: they overestimated at lower values and underestimated at the highest values. However, this is not surprising, given the variance formulations for all three distributions. In future research, other distributions will be explored, including a right-truncated distribution (which would de-emphasize the very largest catches) and mixture distributions to try to better capture the largest catches without affecting the fit to smaller catches. These data, both counts and CPUE (weight), are too overdispersed for the NB/Gamma/lognormal distributions, given the available predictors. It is noted that the slope of the linear term for log(effort) in the NB model was different from 1.0 (estimated slope = 0.455, s.e. = 0.0338; a slope estimate of ≈1.0 would correspond to log(effort) as an offset). The standardized indices computed from these three models were a) data-weighted for the NB GAM; and b) area-weighted for the Gamma and lognormal GAMs.

T here are differences in the standardized indices obtained from different GAMs (Appendix A). As described above, the standardized CPUE derived from the Gamma model was chosen as the best available index of relative abundance for calibrating the stock assessment model for dorado (Figure 5a). The CPUE mainly reflects the decay of a cohort of dorado over time year after year.

2.4. Size-composition data

Size[3]-composition data from the dorado catches were obtained from Peruvian, Ecuadorian, and IATTC sources. These data are typically considered to inform the stock assesment model about the selectivity of the different fisheries and cohort strength. The size-composition data from different fisheries are described below.

2.4.1. Peru

Dorado size-composition data, collected by IMARPE at the principal ports where Peruvian artisanal fisheries unload their catches, are available (2004-2014), but not separated by sex. Sampling was mainly opportunistic since it depends upon the availability of dorado and the logistical access of port samplers to the catches. Length frequencies of dorado were taken in fork length to the next-lowest centimeter. For this stock assessment, only the size-composition data for which monthly information is available are used (2007-2014; Figure 6.a).

2.4.2. Ecuador

Dorado size-composition data from Ecuadorian artisanal fisheries were collected at the ports of Esmeraldas, San Pablo de Manta, and Anconcito, mainly by SRP samplers, who record fork length, total weight, and sex (Martínez-Ortiz and Zúñiga-Flores 2012). Some size data collected by fishery observers are also available. For this assessment, only monthly size-composition data, by sex, from artisanal fisheries targeting dorado were used (Figure 6.b).

2.4.3. Tuna purse-seine fishery

IATTC observers estimate the size composition of dorado catches by classifying the fish into three size categories (0-30 cm, 31-60 cm, > 60 cm) (Figure 6.c). Although there are concerns about the reliability of these estimates, they were included in the assessment model as an attempt to obtain an approximation of the selectivity of dorado by the tuna purse-seine fishery.

[3] ‘size’ is usually, but not necessarily, synonymous with ‘length’

3. ASSUMPTIONS AND PARAMETERS

3.1. Biological information

Defining the biological parameters is a first important step in the construction of any age-structured stock assessment model. The biological assumptions defined in the dorado stock assessment model are described below.

3.1.1. Growth

The research of Goicochea *et al*. (2012) was adopted as the best available study to define the age and growth parameters for dorado. This study relies on an age determination technique based on the interpretation of microincrements in otoliths collected from dorado caught in northern Peruvian waters. The growth curves estimated in this study for females and males are assumed in the stock assessment model (Figure 7.a).

Another important component of growth used in age-structured statistical catch-at-length models is the variation in length-at-age. Information on the variability of the length-at-age can be obtained from age-at-length data, which is available from Goicochea *et al*. (2012). Unfortunately, the dorado samples were not collected randomly, but rather to cover a range of sizes to provide information on mean length-at-age. Therefore, the otolith data is not the best data source to provide a good measure of variation of length-at-age. The parameters that define the variation of the length-at-age were estimated from inspection of identifiable cohorts in the size composition data. These estimates were fixed in the stock assessment model (Figure 7.b)

The length-weight relationships determined by Zúñiga-Flores (2014), were used to convert lengths to weights in the current stock assessment (Figure 7). The study presents length-weight relationships obtained from females and males sampled in different ports of Ecuador. For this assessment, the relationships estimated for the ports of Santa Rosa and Anconcito were used. These ports are closer to the main southern fishing grounds exploited by the Ecuadorian fleet, but most importantly closer to the grounds exploited by Peruvian artisanal fisheries where the majority of the removals take place.

3.1.2. Natural mortality (*M*)

Estimates of M for dorado have been produced using indirect methods (Martínez-Ortiz and Zúñiga-Flores, 2012; Zúñiga-Flores, 2014). However, these estimates vary greatly (0.43-2.5 yr^{-1}) depending on the methodology used. An M value of 1 yr^{-1} is considered reasonable to use in the dorado stock assessment. For a virgin (F = 0) or heavily exploited population (F=2), M=1 allows for some survivorship beyond age 1 year (Figure 9).

3.1.3. Recruitment and reproduction

The dorado maturity ogive estimated by Zúñiga-Flores (2014) was used in the assessment. Recruitment is assumed to be independent of the spawning stock size because dorado is a highly fecund pelagic spawner.

4. MODEL STRUCTURE CONFIGURATIONS

The Stock Synthesis model (SS - Version 3.24f; Methot and Wetzel 2013) was used to assess the status of dorado in the South EPO. It consists of a catch-at-length, age-structured, integrated (fitted to many different types of data) statistical stock assessment model. The model is fitted to the observed data (indices of relative abundance and size compositions) by finding a set of population dynamics and fishing parameters that maximize a penalized likelihood, given the amount of catch taken by each fishery. Many aspects of the underlying assumptions of the model are described in Section 3. The underlying concept of the model is that monthly declines in the CPUE are explained by the catch and therefore provide information on absolute abundance as assumed in standard depletion estimators (Maunder *et al*. 2015).

The following parameters are assumed to be known for the current stock assessment of dorado in the South EPO:

1. Mean length-at-age and the variability of the length at age (Figure 6.b);
2. The length-weight relationship (Figure 7);
3. Natural mortality rate (M=1 yr^{-1} for both sexes);
4. The sex ratio of age-0 fish (post-larvae) (0.5)
5. Length-specific maturity curve (Figure 8);
6. The steepness of the stock-recruitment relationship (h=1).
7. The CPUE time series of the Ecuadorian artisanal fishery was chosen as the most reliable index of abundance to calibrate the stock assessment model. For this reason, its coefficient of variation (CVs) was fixed at 0.2.
8. Female selectivity curves for Peruvian and Ecuadorian fisheries which catch larger dorado are assumed to be asymptotic. Male are allowed to have a lower selectivity than females and to have dome-shape selectivity. The purse-seine bycatch fishery selectivity was assumed to be asymptotic.

The following parameters have been estimated in the current stock assessment of dorado from the South EPO:

1. Recruitment occurring in the months of December and January of every year from 2007 to 2013 (includes estimation of virgin - or average - recruitment and monthly temporal recruitment anomalies). An early recruitment deviate in 2006 is also estimated.
2. Catchability coefficients for the Ecuadorian CPUE time series which is used as the main index of abundance. There is the perception that the availability of dorado is strongly linked to environmental conditions which are very dynamic off Ecuador and Peru where most of the dorado catches are taken. This may affect catchability of the fishing fleets on a yearly basis. Therefore, catchability is assumed to be time-varying, with one catchability parameter estimated for each fishing year (which mainly applies to a single cohort).
3. Parameters defining the selectivity curves for the three fisheries defined in the model. Since length composition from dorado caught by the Ecuadorian fisheries are available for females and males, selectivity curves are estimated for both sexes separately. For Peru, there is no information on the sex composition of the catch (sexes pooled in the size composition data) so selectivity of the males is fixed at the offset between males and females as estimated for the Ecuadorean data. (note that the male selectivity for Peru was fixed based on a previous model)
4. Initial population size and age structure. The starting conditions of the assessment cannot be considered as unfished because there is a history of catch prior to what is modelled in the assessment. Stock Synthesis allows for estimating an initial fishing mortality so the model takes into account catches before the model starts. One initial fishing mortality parameter (for Peru which dominates the catches) is estimated. This is not designed to describe any particular process in the dynamics of the fishery, or that we are assigning all early catch to Peru, it just provides a way to parsimoniously start the model away from a fished condition.

An important decision that needs to be made in integrated statistical stock assessment models is the relative weighting assigned to the different data components. The “Francis approach” is taken which argues that abundance information should primarily come from the indices of abundance (CPUE) and not from composition data (Francis, 2011). Following this rationale, the size compositions of the different fisheries were down-weighted so that the Ecuadorian CPUE is the main dataset driving the population dynamics and defining absolute scale (R_0) in the model. The following multiplicative weighting factors, λ (lambda) were applied to the likelihoods of the composition data: 0.05 for Peru, 0.5 for Ecuador, 0.005 for the tuna purse-seine fishery. While higher weighting is given to the Ecuadorian sex-composition data, lower weighting is given to the IATTC size-class composition data.

There is uncertainty in the results of the current stock assessment. This uncertainty arises because the observed data do not perfectly represent the population of dorado in the South EPO. Also, the stock assessment model may not perfectly represent the dynamics of the dorado population or of the fisheries that operate in the EPO (model uncertainty). Uncertainty is expressed as approximate confidence intervals and CVs. The confidence intervals and CVs have been estimated under the assumption that the stock assessment model does perfectly represent the dynamics of the system. Since it is unlikely that this assumption is satisfied, these values may underestimate the amount of uncertainty in the results of the current assessment. The model structure uncertainty is investigated in several sensitivity analyses.

The following summarizes the important aspects of the base case assessment (1) and the three sensitivity analyses (2-4):

1. **Base case assessment**: steepness of the stock-recruitment relationship = 1 (no relationship between stock and recruitment); the mean length-at-age, and the parameters that define the variability of the length-at-age, are fixed; fitted to CPUE time series for Ecuadorian artisanal fishery; asymptotic size-based selectivities for females caught by the Ecuadorian and Peruvian fisheries; down-weighted size composition data for all fisheries (The following multiplicative weighting factors, λ (lambda) were applied: 0.05 for Peru, 0.5 for Ecuador, 0.005 for the tuna purse-seine fishery.

2. **Sensitivity to alternative natural mortality (*M*) values.**

   A range of *M* values between 0.1 yr^{-1} and 1.6 yr^{-1} were used as alternatives to the *M* of 1 yr^{-1} assumed in the base case. The range of alternatives is partially based on the large range of reported *M* values for dorado from *M* of 0.43 yr^{-1} (Zúñiga, 2014) to 2.5 yr^{-1} (Hoening method applied to data from Zúñiga, 2009).

3. **Sensitivity to time varying catchability**

   The base case model estimates time varying catchability for Ecuadorean CPUE. An alternative case with catchability estimated as a single parameter with no time varying deviates was conducted.

4. **Sensitivity to alternative selectivity curves.**

   The base case assumes that the selectivity functional form is asymptotic. We allowed for selectivity to be dome-shaped in the Peruvean fishery, where selectivity is allowed to be lower for larger fish.

5. RESULTS

5.1. Base case model

5.1.1. Model fit

The model produces a reasonably good fit to the Ecuadorian CPUE which was chosen as the main index of abundance to calibrate stock assessment model (Figure 11.a). For all years, the model is able to capture the CPUE decline which is mainly measuring the monthly decay of a single cohort under natural mortality and fishery exploitation. In general, the model captures the high CPUE values at the start of the fishing season (around September), and follow its rapid decline as the season progresses and tappers off around April. However, the quality of the model fit varies among years, particularly at the start and end of the fishing season (Figure 11.b). In some years, the model is unable to capture the high CPUE values at the start of the season (*e.g.* 2011 and 2013). Likewise, the model is unable to fit the lower CPUE values at the end of the season for most years. This may be caused to a model misspecification that needs to be resolved in the future. For example, rapid changes in availability as the dorado is moving in and out of the fishing ground (Martínez-Ortiz *et al.* 2015) or different timing of recruitment. Improvements could be made in the future by using time varying selectivity options in Stock Synthesis.

As explained above, the CPUE available from Peruvian fisheries were not considered reliable for including in the stock assessment model at this stage. Nonetheless, these data were included in the stock assessment model, so that comparisons can be made between trends in these data and the model relative abundance predictions obtained from fitting to the Ecuadorian CPUE alone. It is quite remarkable that CPUE trends observed in the three fishing regions exploited by Peruvian fisheries in the late period (2011-2014) are reasonably consistent with the model fit to the Ecuadorian CPUE (Figure 11c). This is not surprising considering that both fisheries are exploiting the same dorado stock and overlap in space, at least at some point during the fishing season. It also adds strength to the belief that dorado data collection from Peruvian artisanal fisheries has improved after 2010. Such improvements should continue, in particular, obtaining georeferenced data for the catch and effort records from the fishing trips (latitude and longitude positions). This will allow space to be explicitly dealt with in the CPUE standardization rather than separating by principal ports of landing (proxy for geographic area of operation).

The model fit to the size composition data of the Peruvian fishery aggregated for all years is good (Figure 12a). The model fits to the monthly size-composition data from the Peruvian and Ecuadorian artisanal fisheries for dorado, as well as the size-class composition data from the dorado bycatches of tuna purse-seiners are shown in Appendix B. The model provides a very good fit to monthly length-composition data from Peru (Figure B.1). In general, the modal peaks for each cohort predicted by the model correspond very well with those observed in the data. This indicates consistency with the mean length at age predicted by the growth curve assumed in the model, which was derived from dorado caught by the Peruvian fishery (Goicochea *et al.* 2012). The variability of the length-at-age as predicated by the model is very consistent with that observed in the data, particularly for the larger fish that are caught later in the season. However, the variability of the length-at-age estimated by the model are not consistent with the proportions observed for smaller fish (*e.g.* July-October 2007; Figure B.1).

The model fit to the size composition data of the Ecuadorean fishery aggregated for all years is good (Figure 12b) for both sexes. The model provides reasonably good fits to the monthly size composition data for Ecuador for most months, particularly for the months were most of the cach is taken (September to February), some years however there are missfits to the main modes in the data. In addition, the model provides poor fits for other months, particularly between April and August (Figure

B3). This could be the result to several processes. First, the model does not estimate growth which is fixed at growth estimates from dorado caught by the Peruvian fishery (Goicochea *et al.* 2012), althought there is information on size and age from Ecuador it was not included in the assessment since the ages were estimated by different methodologies (based on scales) and there was no information on comparisson between methods. Estimating growth inside the model could improve the fits to the model. Second, there could be intracohort growth differences that are unnacounted for in the model. Third, the poor fits either at the begginning or at the end of the fishing season could be a result of changing availability or selectivity when the fish are starting to become available to the fishery or become dispersed at the end of the fishing season. There could be other processes or a combination of processes responsible for this misfits. However, the fact that fits are good when aggregated for all years (Figure 12b) for both sexes, and also good for the months were month of the catch is taken is assuring that the model is removing fish at sizes consistent with the data.

The dorado selectivity curves by different fisheries are shown on Figure 11.

5.1.2. Recruitment and biomass

The base case estimates for the dorado annual recruitment in the South EPO during 2007-2014 are shown Figure 14. There is inter-annual recruitment variability. Although the parameter that defines recruitment variability (sigmaR) is fixed in the assessment (sigmaR = 0.6), the root mean squared error (Rmse) of the estimated recruitment deviations is very similar (Rmse: 0.56). Recruitment deviates were unconstrained (no penalties on their deviation) suggesting that the assumed recruitment variability is similar to that supported by the data. Without catch and size composition data for 2015 being available for the assessment, it is not possible to reliably estimate recruitment in 2014 which begins to occurs at the end of the year (December and January, as defined in the model). For this reason, the 2014 recruitment is estimated at average conditions (virgin recruitment, R_0).

There are pronounced seasonal fluctuations of the dorado biomass on a yearly basis in the South EPO (Figure 15). On average annual terms, the summary biomass (1+ year old fish) peaks late in the calendar year (September-December), and rapidly declines to its lower values around May-June of the following year. This generally represents the total weight of a cohort, which increases initially as growth rates are higher than total mortality and then declines as the growth rates decrease and/or the mortality increases. According to the base case, and while measured at the start of the spawning season (November as defined in the model), the summary biomass of dorado has remained quite stable during the historic period of the assessment, averaging at about 90,000 metric tons per year (Figure 15). Likewise, the spawning biomass (measured in November at the start of the spawning season) has remained very stable over the historic period of the assessment (averaging about 18,000 tons per year; Figure 16). The precision of the spawning biomass estimates is very high (average coefficient of variation of 0.1).

5.1.3. Fishing mortality (*F*)

The base case estimates for the fishing mortality rate (*F*) varied from 0.53 to 0.85 during 2007-2014 (Figure 17a). The instantaneous monthly rates of fishing mortality by fishery are shown in Figure 16b.

5.1.4. Model diagnostics

5.1.4.a R_0 profile

A likelihood profile on the average recruitment (R_0) showed that data types diverge on their information about abundance levels (Figure 19). The CPUE data supports lower R_0 than the size composition data, however both CPUE and size composition data have very steep likelihood gradients at values not much lower than the R_0 estimated in the base case (Figure 19). The length composition data supports higher

R_0 values, however there is not much information from lenght composition at large R_0 values, that is the likelihood is very flat. The profile was very unstable, with convergence issues in a number of intermediate values. The divergence in support between CPUE and lenght composition data suggests that some misspecification in the base model is likely and more proccess could be added to the modelling of CPUE (*e.g.* cohort specific catchability) and lenght data (*e.g.* estimating growth, alternative selectivity patterns). However, adding processes with esimable parameters may increase the convergence issues.

5.1.4.b Age-structured production diagnostic

The ASPM produces similar estimates of abundance to the full integrated analysis suggesting that there is information about absolute abundance in the indices of relative abundance and how it is depleted by the catch (Figure 20).. This is expected because the monthly CPUE mainly comprises a single cohort and is akin to a depletion based estimator. The ASPM estimates lower abundance and more variability in abundance. Annual recruitment is estimable in the ASPM since the depletion estimation is essentially applied to each cohort to estimate the initial strength of that cohort. The estimates of biomass are lower, but the variation in biomass is about the same as the full integrated model. These results suggest that the composition data are having some influence on the absolute abundance, but not as much as found for many other assessments of short lived species that are do not have the depletion estimator characteristics of the data and model.

6. MANAGEMENT QUANTITIES

6.1. Base case model

At present, there are no reference points (target and limit) defined for dorado in the EPO. For the tuna stocks, the IATTC evaluates stock status relying on calculations based on spawning biomass and the maximum sustainable yield (MSY). In this exploratory stock assessment, some spawning biomass and MSY-related quantities are presented, and their potential applicability for managing the dorado in the EPO is discussed.

The spawning biomass ratio (the ratio of the current spawning biomass to that of the unfished stock; SBR), described by Watters and Maunder (2001), has been used to define reference points in many fisheries. It has a lower bound of zero. If it is near zero, the population has been severely depleted, and is probably overexploited. If the SBR is one, or slightly less than that, the fishery has probably not reduced the spawning stock. If the SBR is greater than one, it is possible that the stock has entered a regime of increased production.

This SBR defintion of Watters and Maunder (2001) can be considered as *static* quantity since it is related to unfished equilibrium stock status. Hereafter, and to diferentiate with the dynamic SBR concept described below, this static SBR measure is refered to as SBR*s*. SBR*s* for dorado was computed as the ratio of the spawning biomass at a given year to that of the unfished stock, both measured at the start of the spawing season (November). The SBR*s* estimates produced by the base case model are quite stabe over the assesment period, averaging at about 0.20. This value coincides with the base case model estimate for SBR*s* corresponding to the MSY ($\text{SBR}s_{\text{MSY}} = S_{\text{MSY}}/S_{F=0}$).

Various studies (*e.g.* Clark 1991, Francis 1993, Thompson 1993, Mace 1994) suggest that some fish populations are capable of producing the MSY when the SBRs is about 0.3 to 0.5, and that some fish populations are not capable of producing the MSY if the spawning biomass (*S*) during a period of exploitation is less than about 0.2. Unfortunately, the types of population dynamics that characterize tuna stocks and other very highly productive species as dorado have generally not been considered in these studies, and their conclusions are sensitive to assumptions about the relationship between adult biomass and recruitment, natural mortality, and growth rates. The effect of misspecifying the SBR that produces MSY and using MSY-based reference points for management could be evauated by simmulation work simmilar to Valero *et al*. (2016).

A *dynamic* concept of SBR, hereafter refered to as SBR*d* can also be considered for dorado (Wang *et al*. 2009). Specifically, SBR can be computed as the ratio of the spawning biomass at the start of the spawning season with fishing to that without fishing. The dyamic method (SBR*d*) produces higher SBR estimates thant those computed by the static method (SBR*s*) (Figure 21).

MSY is defined as the largest long-term average catch or yield that can be taken from a stock or stock complex with the constant fishing mortality under prevailing ecological and environmental conditions with maintain recruitment at average levels. The base case estimate for the MSY is at 89,211 metric tons which is slightly above the maximum recorded total annual catch around 76,000. However, the fishing mortality needed to obtain MSY is two orders of magnitude greater than the current fishing mortality due to the flat yield curve.

6.1.1. Sensitivity to alternative model configurations

Results from model sensitivity configurations were summarized in figures of time series of quantities of interest (Spawning biomass, SBR, recruitment; Figures 22 to 26 an Table 2 of main quantities of interest.

1. **Sensitivity to alternative natural mortality (*M*) values.**

   The base case model assumes an *M* of 1 yr^{-1}, however the likelihood profile over *M* indicates that the CPUE and the length composition data support lower values of *M* around 0.6 yr^{-1} (Figure 20, top panel) for the length data and around 0.24 yr^{-1} for the CPUE. Although values as low as 0.43 yr^{-1} have been reported for dorado (Zúñiga, 2014), the values supported by the likelihood profile in *M* are suspect for several reasons. On one hand, *M* is notoriously difficult to estimate (Lee *et al*. 2011) even in cases with informative data types (such as age compositions) and exploitation history (long history of exploitation and varying levels of exploitation), none of this applies to dorado. On the other hand, the *M* profile is conditional on the model being properly specified and as discussed before, there is indication from the R0 profile that some level of model misspecification seems still present. Nonetheless we present a figure of the expected MSY at different levels of *M* (Figure 22, bottom panel).

2. **Sensitivity to time varying catchability**

   Estimating catchability as a single parameter with no time varying deviates results in slightly higher recruitment variability (Figure 23) however time series of age-0 recruitment (Figure 24), Spawning biomass (Figure 25) and SBR (Figure 26), and are not markedly different results to the base case.

3. **Sensitivity to alternative selectivity curves.**

   Allowing selectivity of the Peru fishery to be dome-shaped resulted in estimated dome-shape selectivities but no noticeable changes in results compared to the base case model (Figures 23 to 25).

1. YIELD-PER-RECRUIT ANALYSIS

Yield-Per-Recruit (YPR) analysis was carried out using the Stock Synthesis model. The use of SS makes the YPR analysis consistent with the stock assessment assumptions. The YPR analysis was used to investigate the impact of seasonal closures and minimum legal size limits (MLS). To implement the YPR analysis the SS model was first re-run using the fishing mortalities as parameters and checked to ensure that the results were the same as when using the hybrid approach to implement fishing mortality (an efficient method of solving the catch equation). Using the fishing mortalities as parameters approach allowed the fixing of the fishing mortality rates for the YPR analysis and manipulating them to implement the MLS through a knife edge retention curve and also the seasonal closures by changing the fishing mortality to zero for the closed months. We investigated MLS of 80, 90, 100, and 110 cm with zero and 30% mortality rates for the discarded fish under the MLS. The discard mortality rate was arbitrarily chosen for illustrative purposes only. We investigated both delaying the opening of the season and closing the season early. The YPR analysis is conducted using the absolute yield, which is equivalent to MSY because the stock assessment assumes that recruitment is independent of stock size, and all scenarios use the same average recruitment. (note that the area closure analyses were conducted using an old assessment model and therefore cannot be compared to the other YPR analyses, these will be updated when time allows)

The first thing to note about the YPR analysis is that the yield curve is very flat (Figure 27). For this reason, fishing mortality rates required to achieve MSY are poorly defined and not presented further. Analyses based on projections with effort remaining at current levels or implementing management retrospectively might be more useful (see Valero *et al*. 2016). The maximum equilibrium yield could be increased by a moderate amount if a MLS is implemented even in the presence of discard mortality of 30% (Table 3). The discard mortality has a moderate influence on the maximum equilibrium yield. A MLS only causes a small increase in the SBR measured at the time of spawning (November). Seasonal closures have less impact on maximum equilibrium yield, but a larger impact on SBR, than MLS (Table 4). Closures at the start of the fishing season are more beneficial in terms of both maximum equilibrium yield and corresponding SBR.

7. FUTURE DIRECTIONS

The following are a list, not prioritized, of future research needed for stock assessment of dorado in the EPO:

7.1. Growth

Estimate growth inside the model, using not only data on age and size from Peru but also from Ecuador, This would neccesitate a comparisson between different methodologies between Peru (based on fish otholiths) and Ecuador (based on fish scales). Explore potential growth differences between cohorts. A more flexible growth curve may be needed.

7.2. Spatial extent of assessment

Dorado is subject to fishery exploitation by fleets of nearly all coastal nations in the EPO ranging from Chile, in the South, to Mexico, in the North. The current exploratory stock assessment only uses data from Peru and Ecuador. Further work should consider inclussion of data from other fleets from other coastal nations in the southern EPO, for example Chile. Population dynamic analyses could be performed for data north of the Equator for a potential northern EPO stock assessment or an eventual EPO wide assessment of dorado.

7.3. Integration between stock assessment and alternative management strategies

The quality, type and quantity of data varies greatly among the coastal nations that fish dorado in the EPO (IATTC 2014). Although limited data may preclude, in some instances, to conduct an integrated assessment of the kind presented here, emerging properties of the assessment (*e.g.* strong seasonal trends in CPUE, strong seasonal modal progression in sizes, etc) may allow for implementation of simple harvest control rules based on limited data and management strategies based on available or simple to collect data could be tested formally in an integrated way with available stock assessments such as in

Valero *et al*. (2016)

7.4. Data collection

Improve data collection, for example georeferencing of catches in Peru may allow for better CPUE standardization. More basic information such as monthly CPUE and monthly size composition data would be very informative. More information on catch statistics, including removals from recreational fisheries and likely estimates of unreported catches.

7.5. Tagging

Tagging programs would provide invaluable information such as independent estimates of fishing mortality, natural mortality, movement North and South of the Equator, and allow integration of otolith/scale and tagging data on growth.

7.6. Movement in and out of the fishing area and timing of the movement

Significant questions still remain about the process and timing of dorado as they enter and exit the fishing area, which are confounded with fishing mortality. More understanding of them would allow a better conceptual model of proceses at the start and end of the fishing season and provide information on how to parameterize stock asessment prameters (*e.g.* selectivity and catchability)

7.7. Sex ratio differences in the catch

During the 2nd Dorado meeting, participants shared information on dorado sex-ratio by area. A compilation of the available data was presented and discussed with a focus on identifying potential processes behind apparent changes in sex-ratio of dorado. It is not clear so far if the variability in sex ratios are due to biological (*e.g.* sex ratio at birth, differences in rates of natural mortality), fishery (availability or exploitation rates) or sampling processes (*e.g.* potential miss-identification of inmature males and females). The impact of some of these altenatives were explored during model building, and eventually modelled as males being less selected than females and allowing for dome-shaped selectivities of males. However the underlying causes of sex ratio differences are unknown and more research is needed to identify them.

7.8. Availability or recruitment

It is unclear if inter year differences in CPUE are due to mostly changes in availability, changes in recruitment between years or a combination of the two. Similarly, intra-year chnages in catchjability may be due to movemnent in and out of the fishing year or temporal variation in the timing of recruitment or growth. More research is needed also on potential drivers of recruitment or changes in availability, such as potential effects between SST and those processes.

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TABLE 1. Fisheries defined for the stock assessment of dorado in the EPO. LL = longline; PS = purse-seine.

TABLA 1. Pesquerías definidas para la evaluación del dorado en el OPO. LL = palangre; PS = red de cerco.

Fishery/Survey	Name	Gear	Fishing years
Pesquería/Estudio	**Nombre**	**Arte**	**Años pesqueros**
F1	Peru	LL	2007-2014
F2	Ecuador	LL	2007-2014
F3	PSbycatch_south5N	PS	2007-2014
S1	Peru_N-early	LL	2007-2010
S2	Peru_N-late	LL	2008-2014
S3	Peru_C-early	LL	2007-2010
S4	Peru_C-late	LL	2008-2014
S5	Peru_S-early	LL	2007-2010
S6	Peru_S-late	LL	2008-2014

TABLE 2. Model summaries for main sensitivities configurations to the base case

	Base	Dome	*M*_0.43	*M*_1.6	Qnotv
S_0 (t)	90,045	89,952	205,001	62,015	85,577
B_0 (t)	254,687	254,429	545,880	192,791	242,067
S_{MSY} (t)	17,987	17,893	15,336	22,351	17,196
MSY (t)	89,211	89,010	79,502	100,530	84,490
S_{2014}/S_0	0.22	0.22	0.08	0.38	0.23
S_{MSY}/S_0	0.20	0.20	0.07	0.36	0.20
S_{2014}/S_{MSY}	1.10	1.11	1.00	1.07	1.16

TABLE 3. Results of the YPR analysis using different MLSs.

Size limit (cm)	Discard mortality rate	MSY	%baseMSY	SBR
None	0	89770	100	0.18
80	0	105791	118	0.19
80	0.3	99241	111	0.18
90	0	115300	128	0.20
90	0.3	101948	114	0.19
100	0	116348	130	0.21
100	0.3	98942	110	0.19
110	0	108835	121	0.21
110	0.3	94924	106	0.19

TABLE 4. Results of the YPR analysis using different months of closure. The Months are those defined for the fishing year (need to change to calendar year). (note that the area closure analyses were conducted using an old assessment model and therefore cannot be compared to the other YPR analyses, these will be updated when time allows).

Closure	MSY	%baseMSY	SBR
None	72326	100	0.17
1-5	75138	104	0.25
1-6	76882	106	0.25
1-7	78169	108	0.24
1-8	77756	108	0.22
1-9	74653	103	0.19
8-12	71647	99	0.15
9-12	72285	100	0.16
10-12	72540	100	0.17

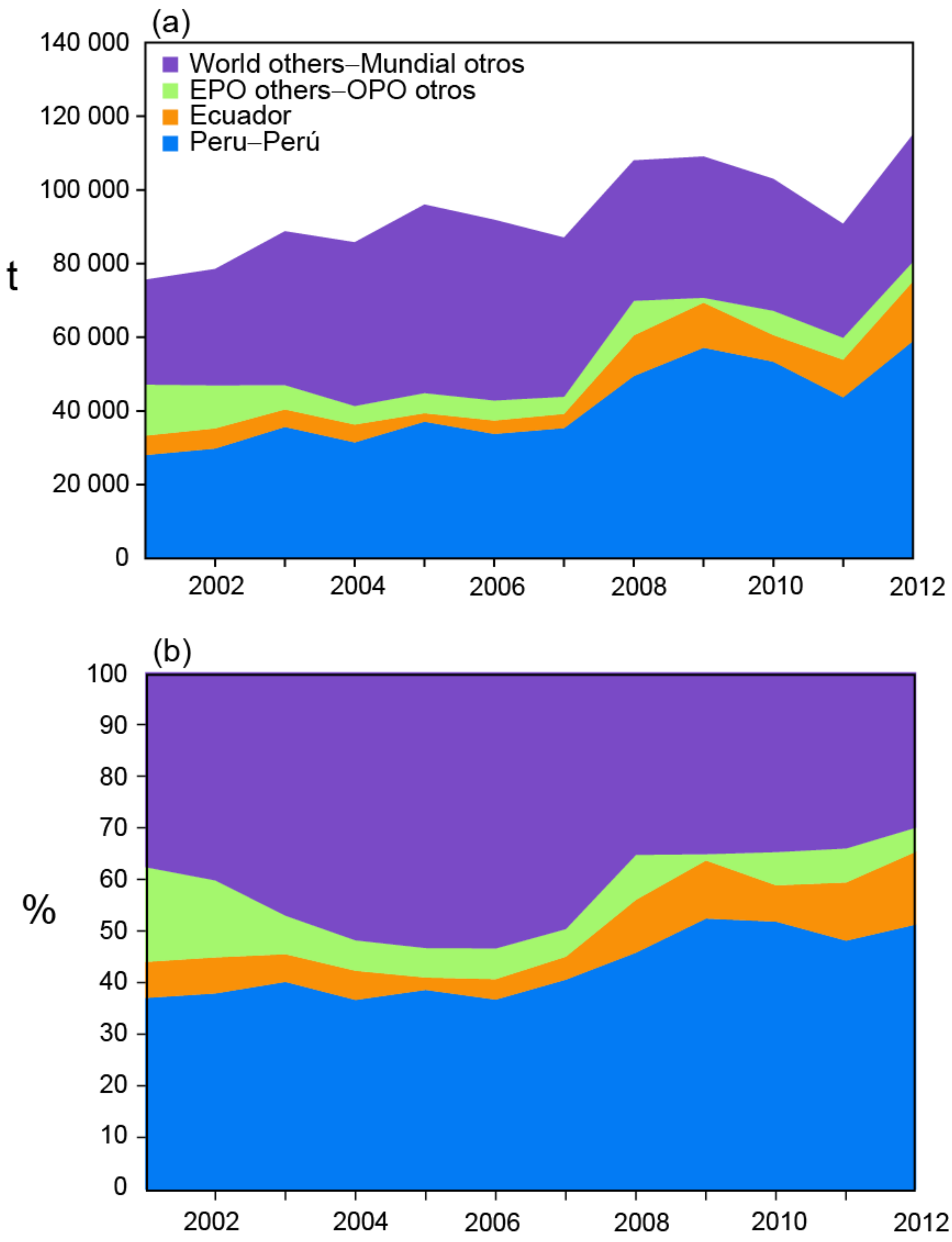


FIGURE 1. World catches of dorado, 2001-2012, by weight (a) and percentage (b). Source: Aires-da-Silva et al. (2014).See text for sources of data. Catch statistics were compiled from the following sources: 1) FAO FishStat database, 2) US import trade records (United States International Trade Commission, USITC), and 3) statistics reported by EPO coastal nations.

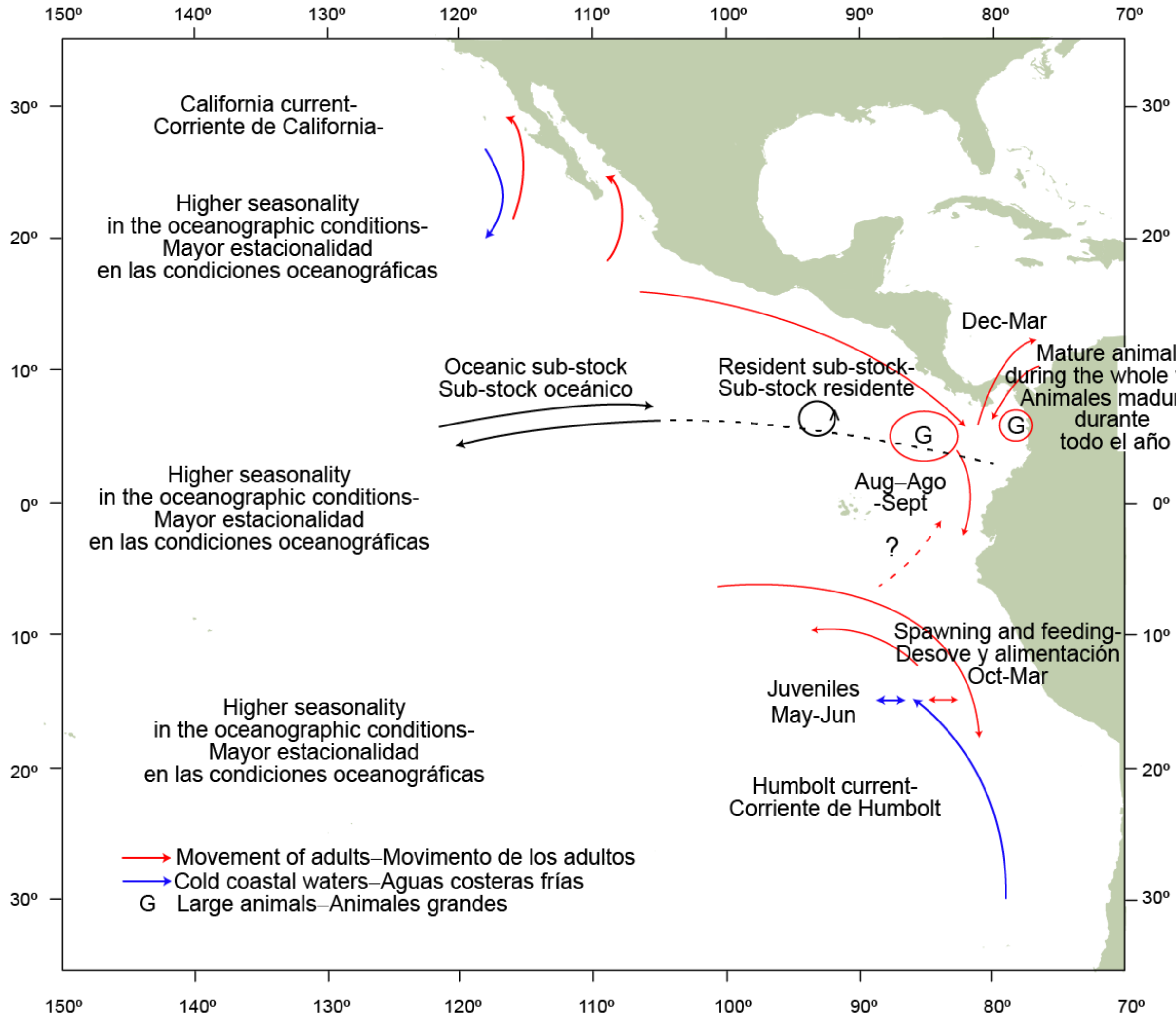


FIGURE 2a. Conceptualized model for dorado's movement and spatial distribution related to their life-cycle based on discussions during the 2nd Meeting on Dorado in Lima, Peru in 2015.

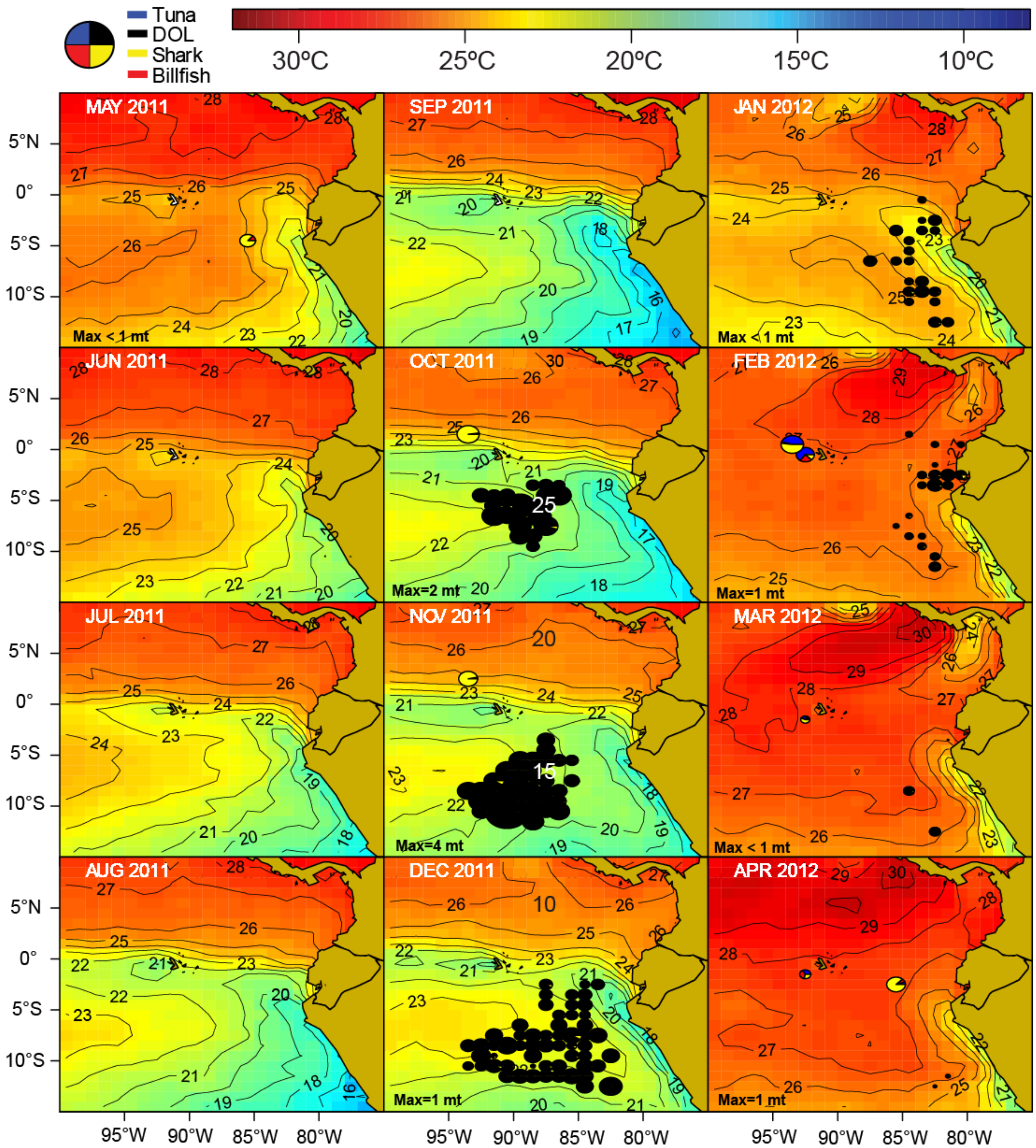


FIGURE 2b. Spatio-temporal distribution of the catches by the Ecuadorian artisanal longline fishery targeting dolphifih (*C. hippurus*, DOL) for fishing year 2011 – 2012 (from Marinez-Ortiz et al, 2015).

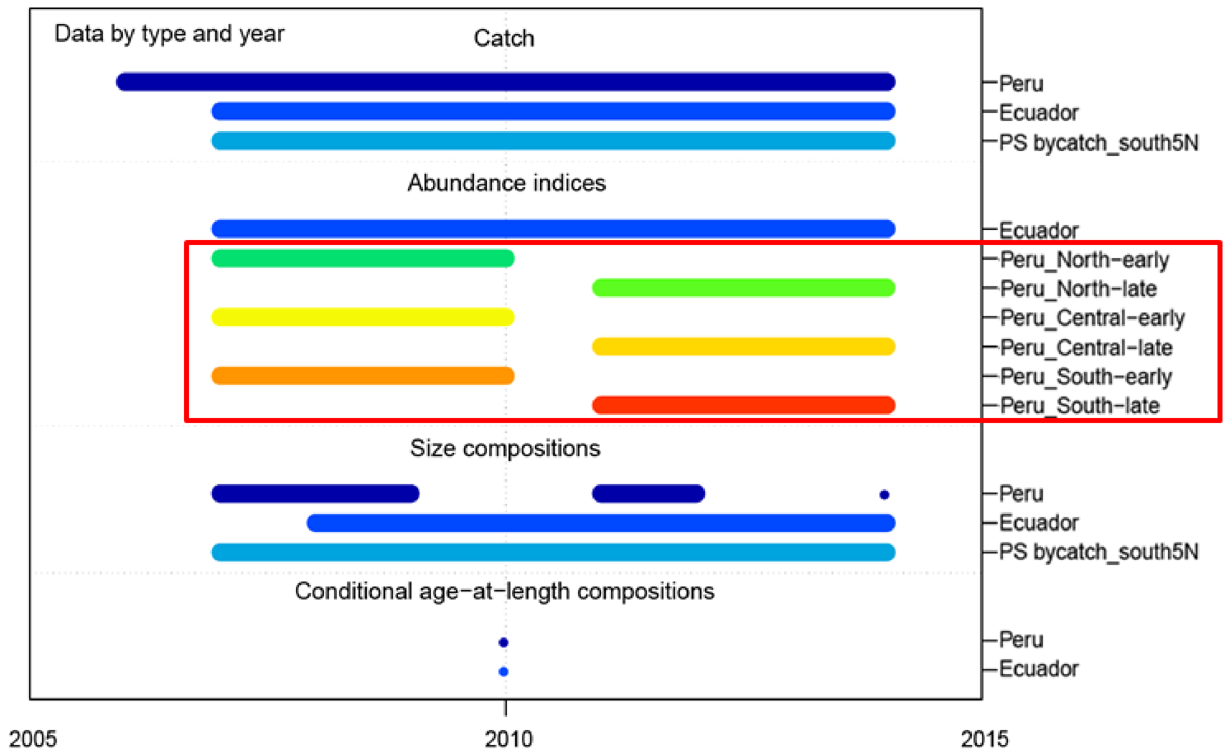


FIGURE 3. Data type by fishery and year. The abundance indices inside the red square are not usedin the model estimation, they are included only for comparative purposes.

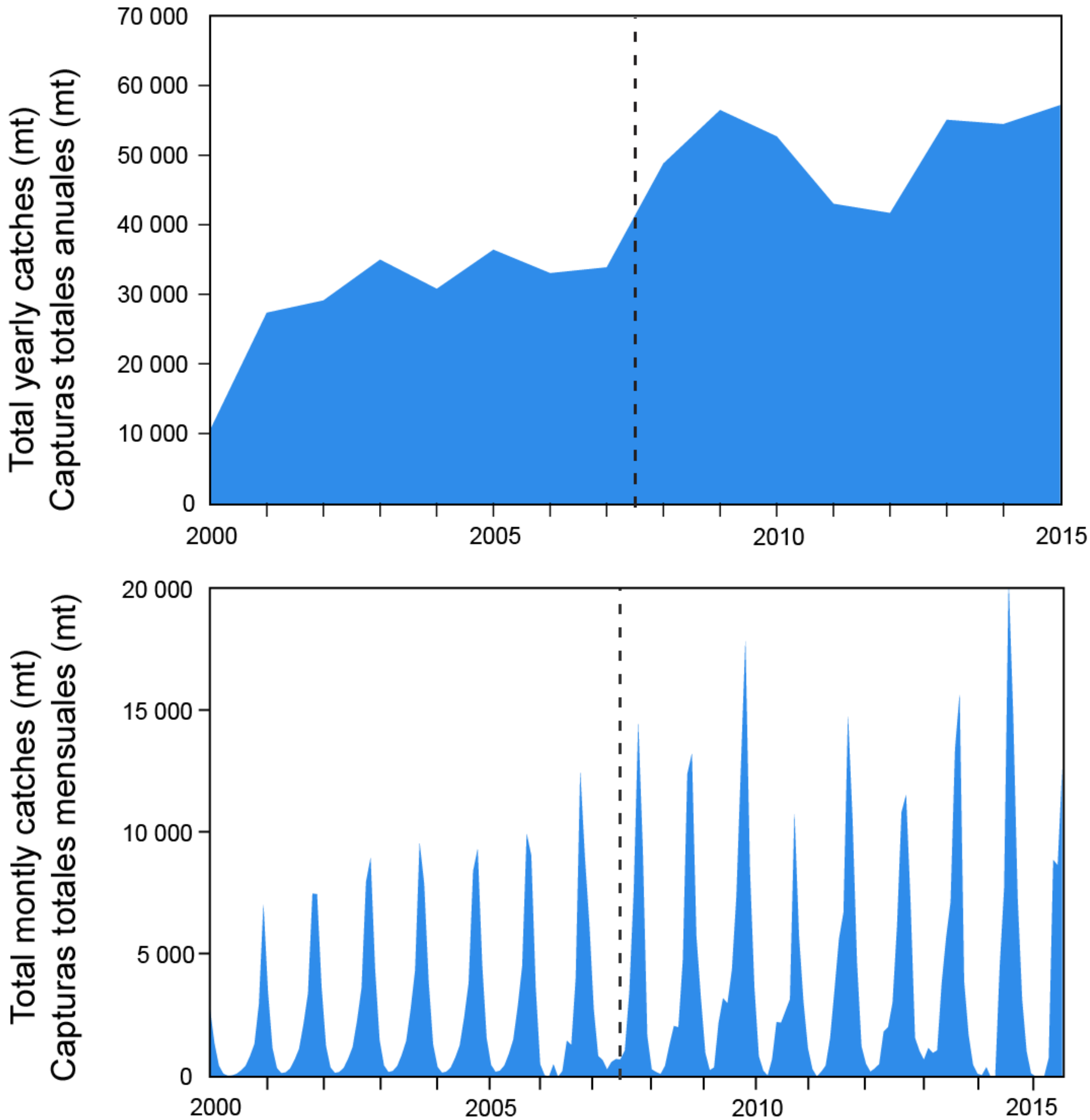


FIGURE 4a. Total catches (Top panel: annual, Bottom panel: monthly) of dorado by Peruvian artisanal fisheries. Monthly catch records for the early period 2000-2005 were not available. Monthly estimates were obtained by multiplying yearly catches by mean monthly catch proportion factors available for the later period (2006-2015, see **FIGURE** 4.f)

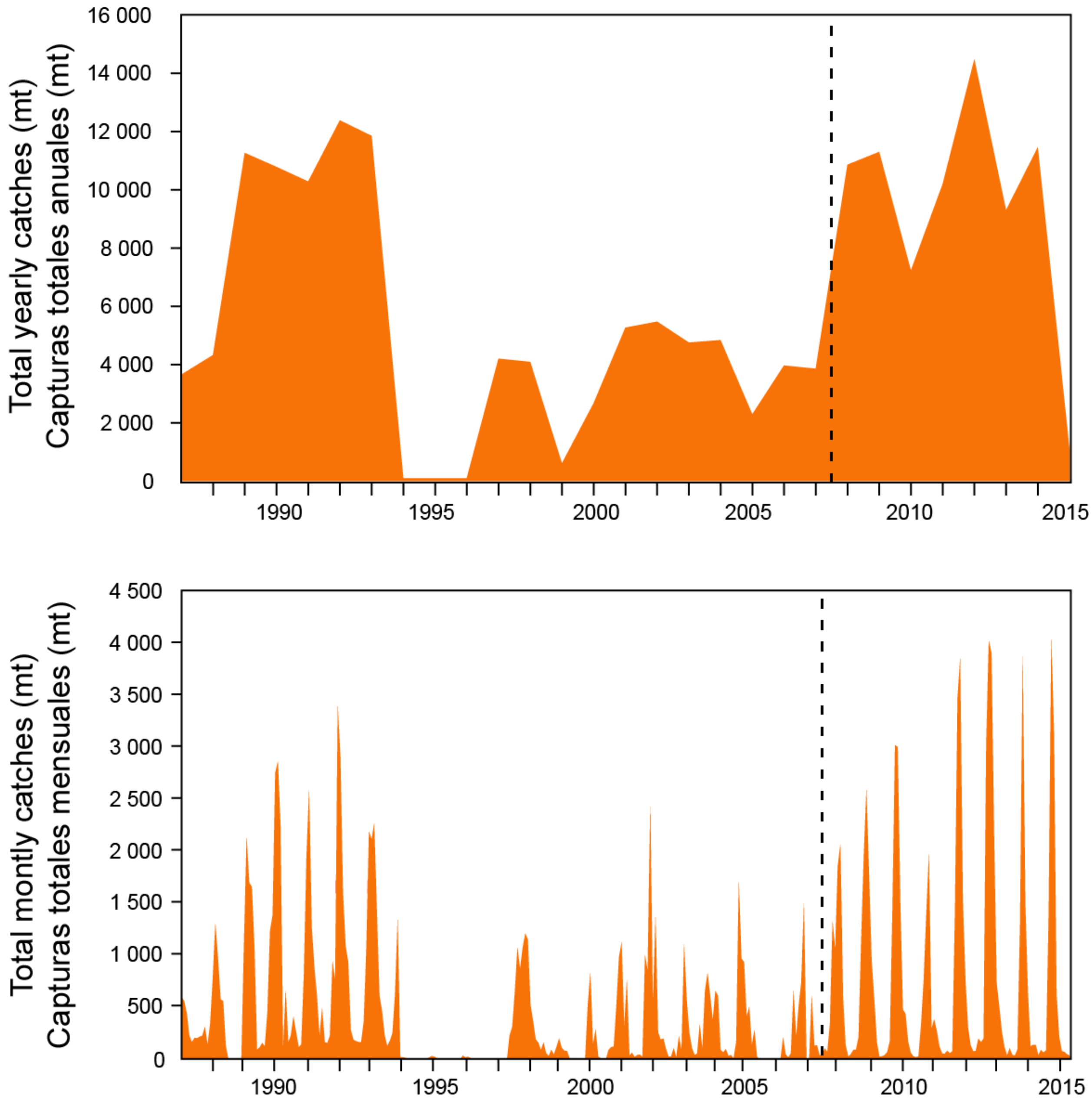


FIGURE 4b. Total catches (Top panel: annual, Bottom panel: monthly) of dorado by Ecuadorian artisanal fisheries. a) annual catches; b) monthly catches.

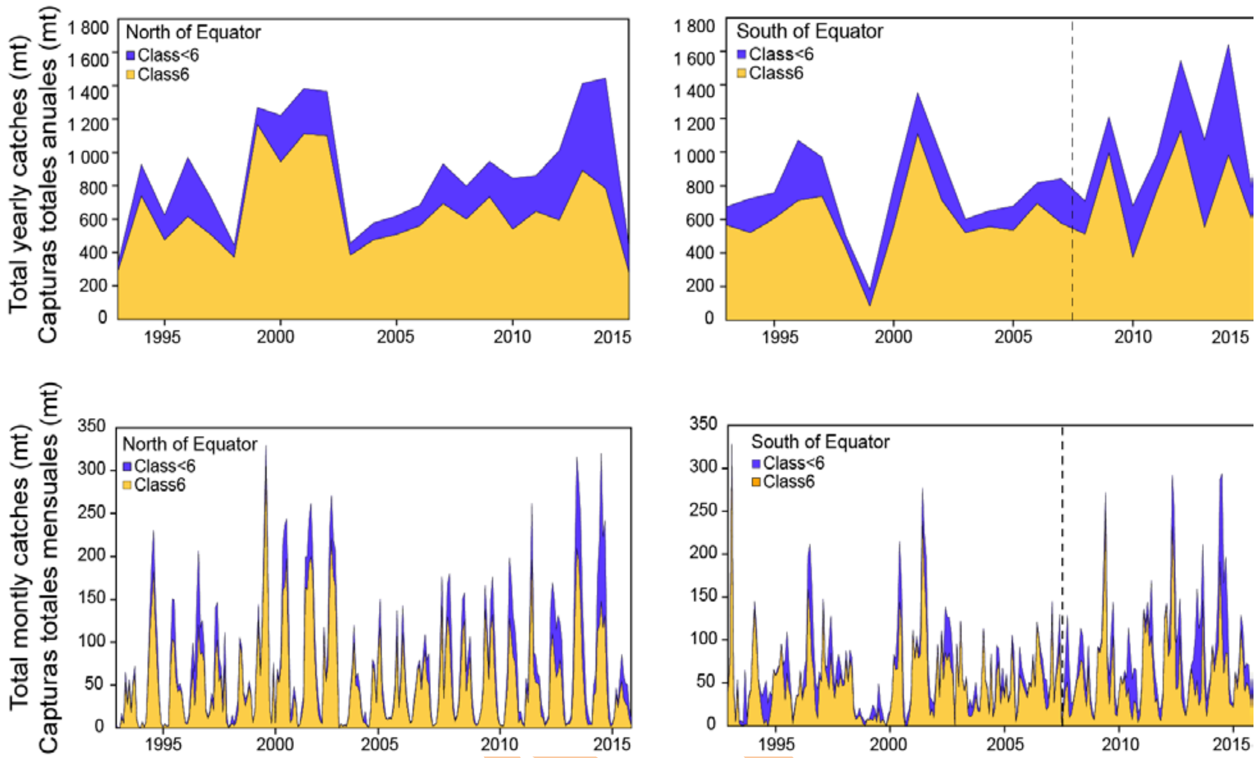


FIGURE 4c. Total bycatches (Top annual, Bottom monthly) of dorado by tuna purse-seine fisheries. Top: north of the Ecuador; bottom: south of the Ecuador. Estimates are available for larger (class-6) and smaller (class 1-5) purse seiners. See section 2.2.3 for detail on the estimation method.

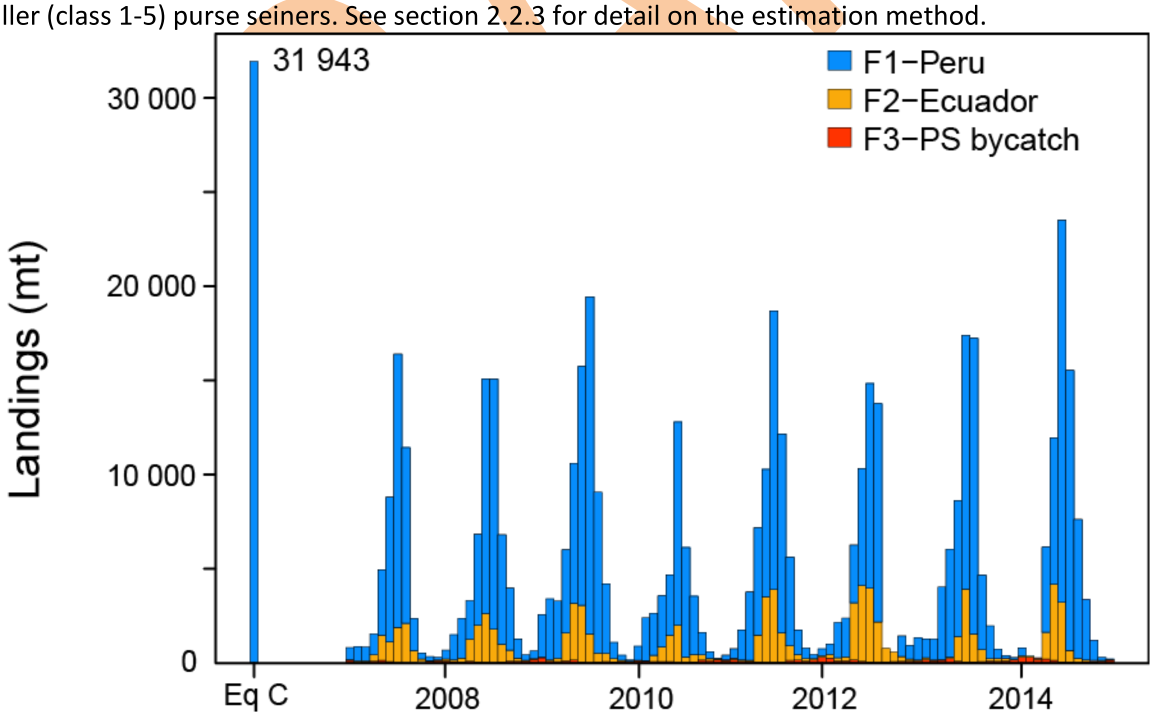


FIGURE 4d. Total monthly landings of dorado by fishery in the South EPO.

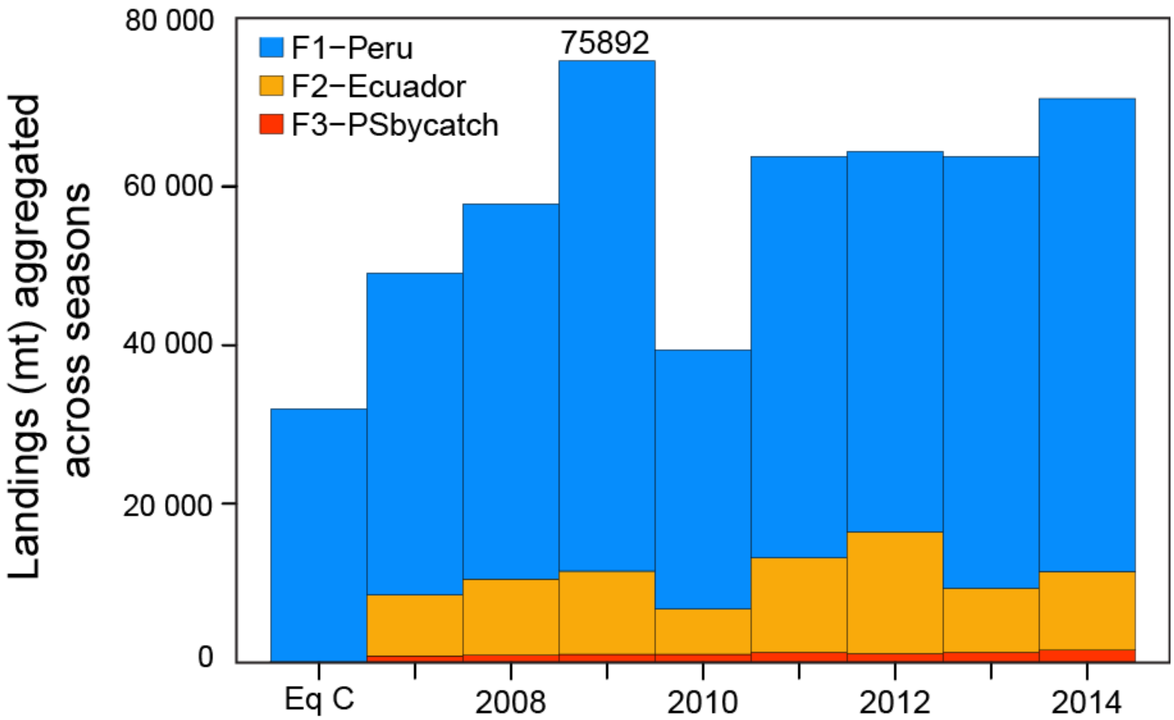


FIGURE 4e. Total annual landings of dorado by fishery in the South EPO.

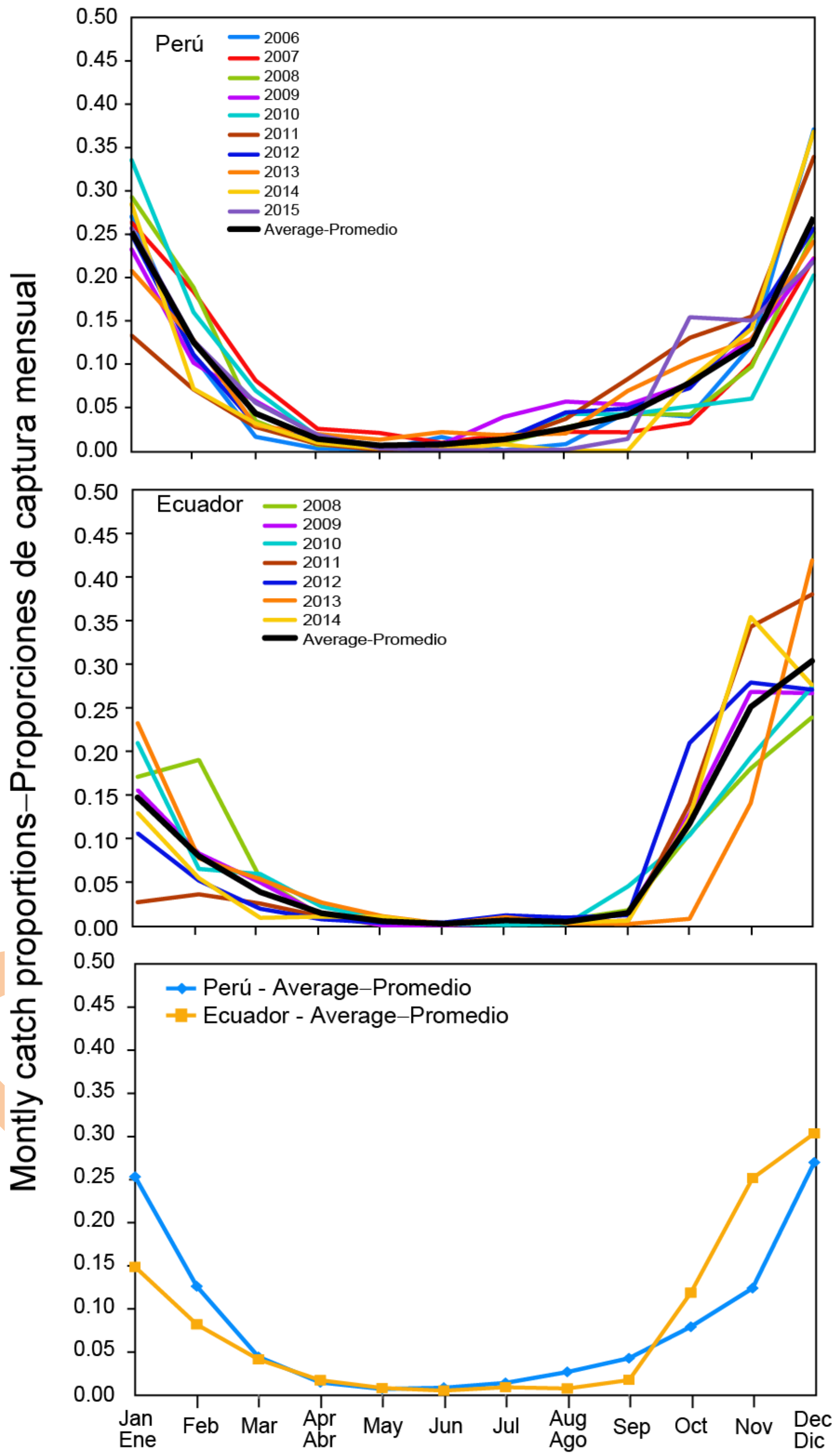


FIGURE 4f. Dorado monthly catch proportions for artisanal fisheries by Peru (2006-2015) and Ecuador (2000-2014).

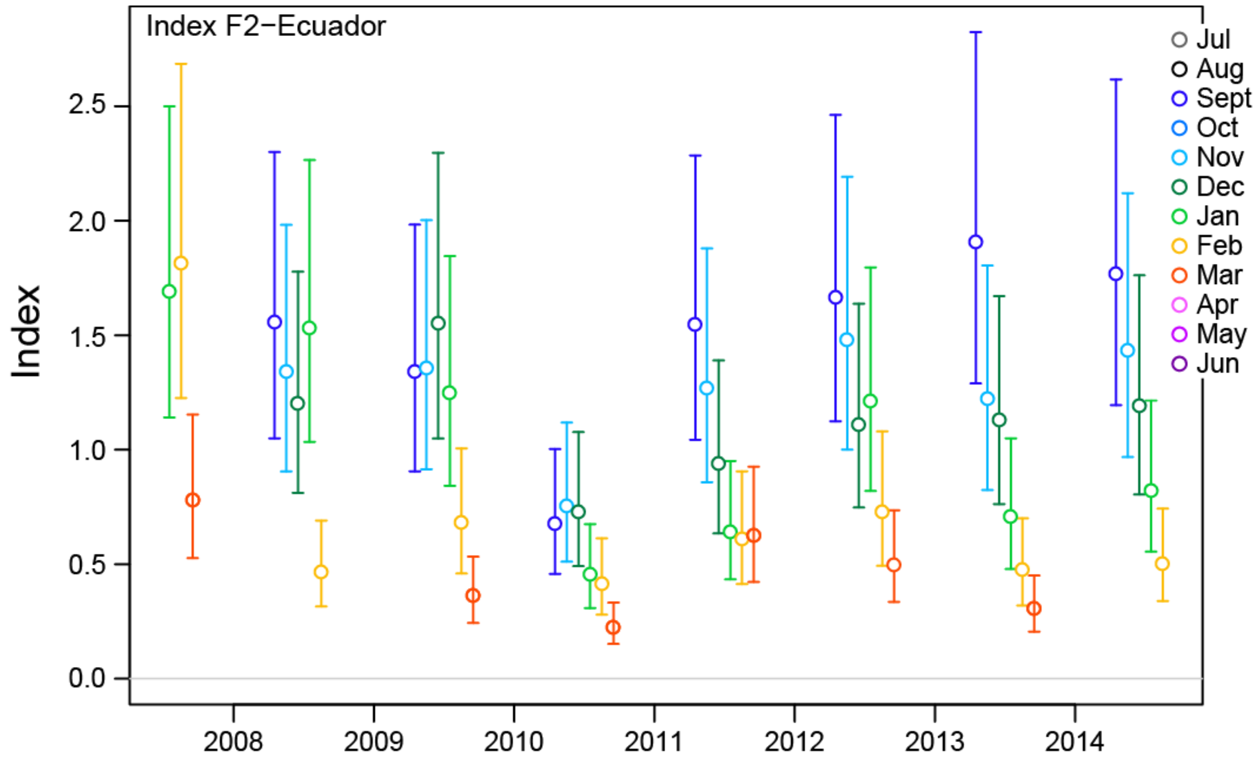


FIGURE 5a. Dorado standardized CPUE from Ecuadorian artisanal fisheries. The vertical lines represent the fixed confidence intervals (± 2 standard deviations) around the CPUE values.

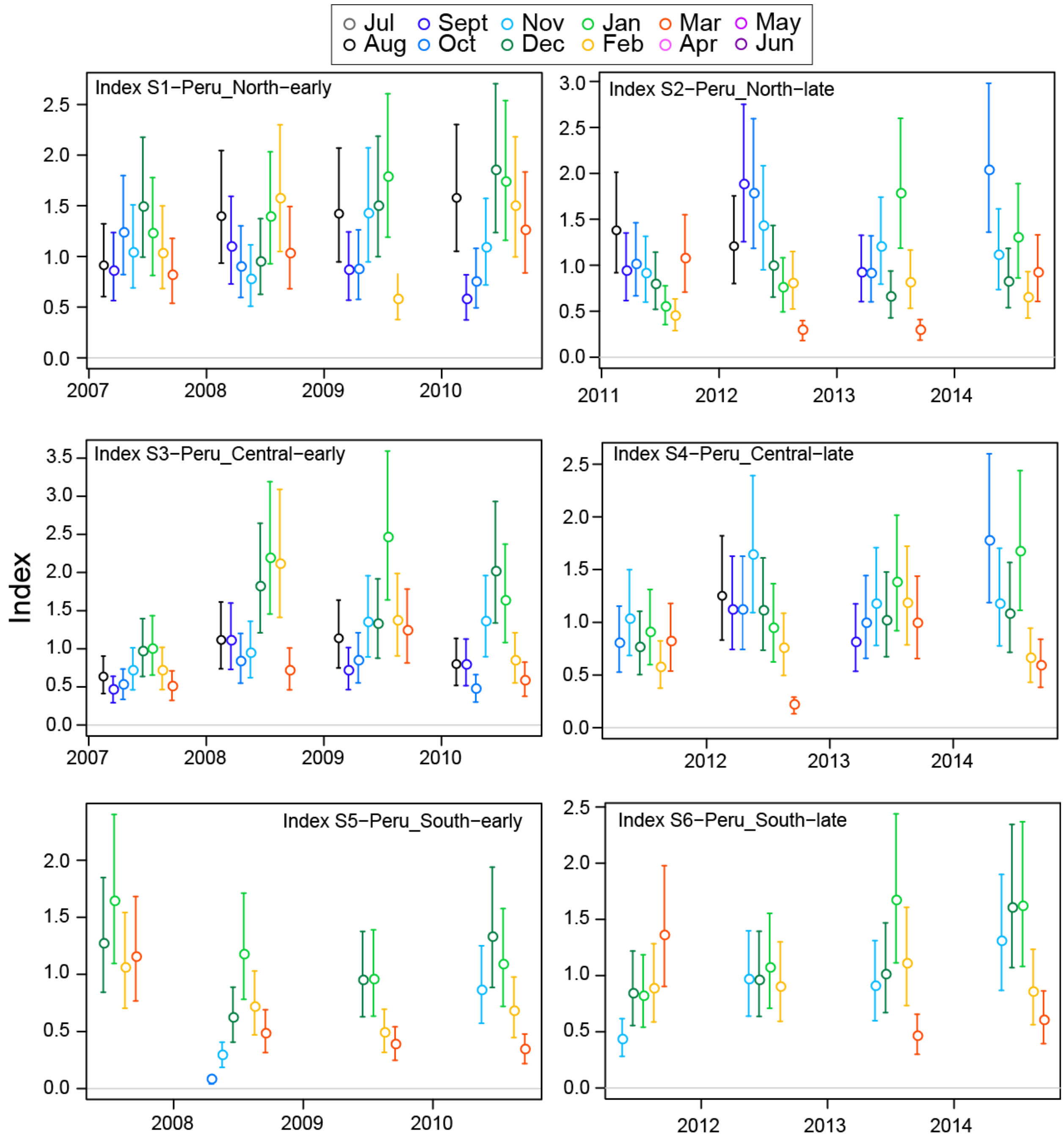


FIGURE 5b. Dorado standardized CPUE from Peruvian artisanal fisheries. The vertical lines represent the fixed confidence intervals (± 2 standard deviations) around the CPUE values.

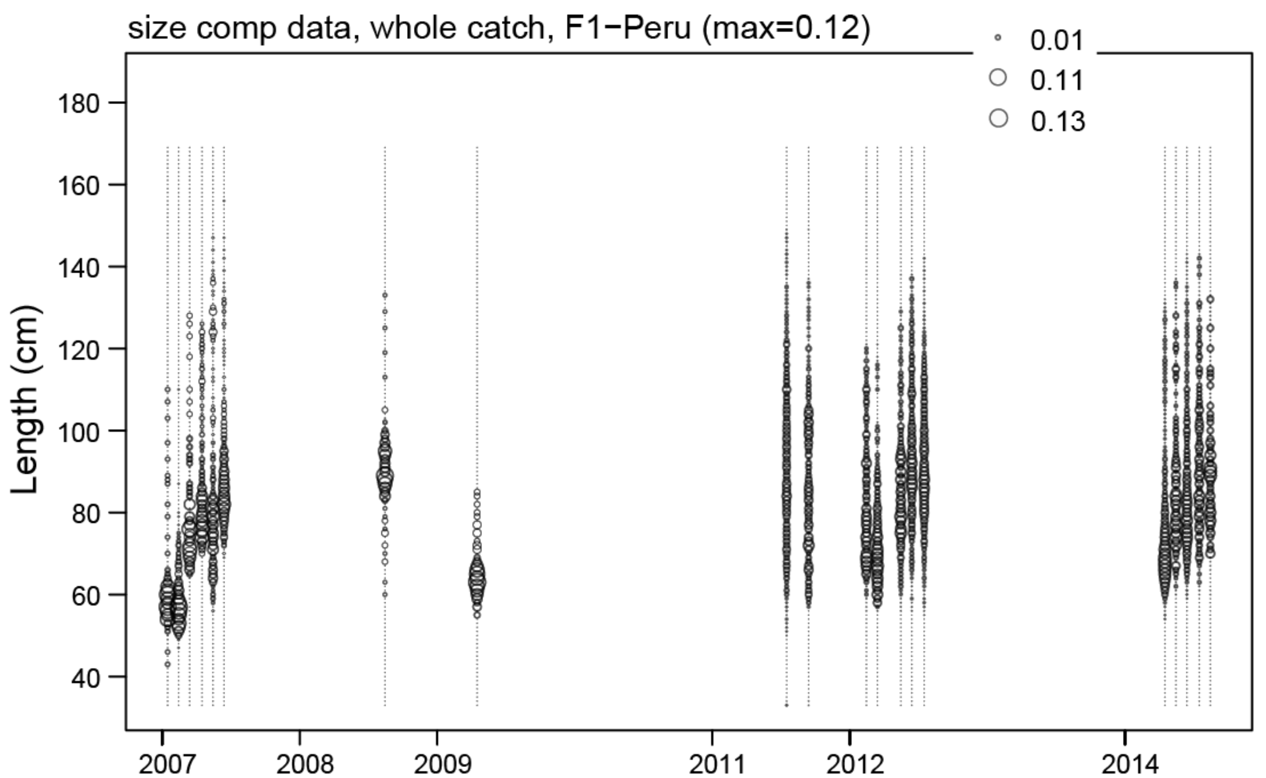


FIGURE 6a. Dorado size composition data from Peruvian fisheries.

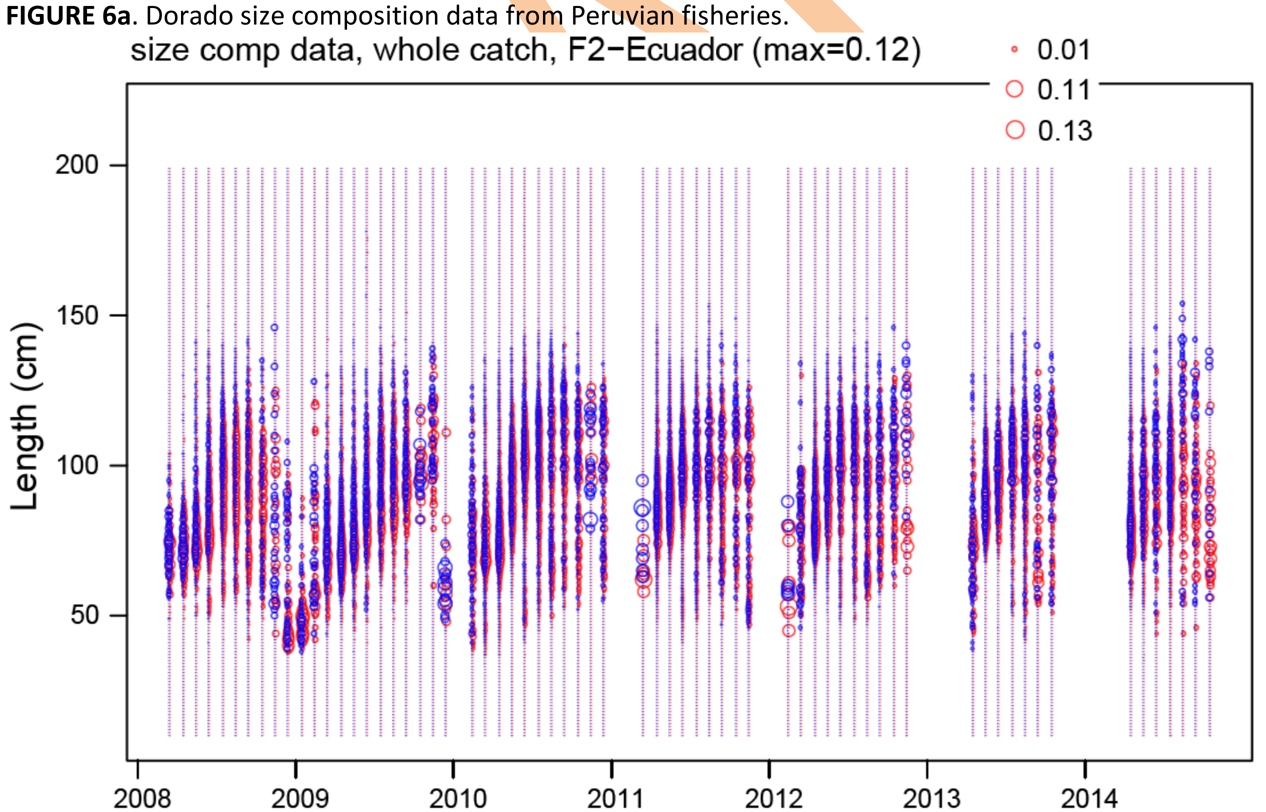


FIGURE 6b. Dorado size composition data from Ecuadorian fisheries.

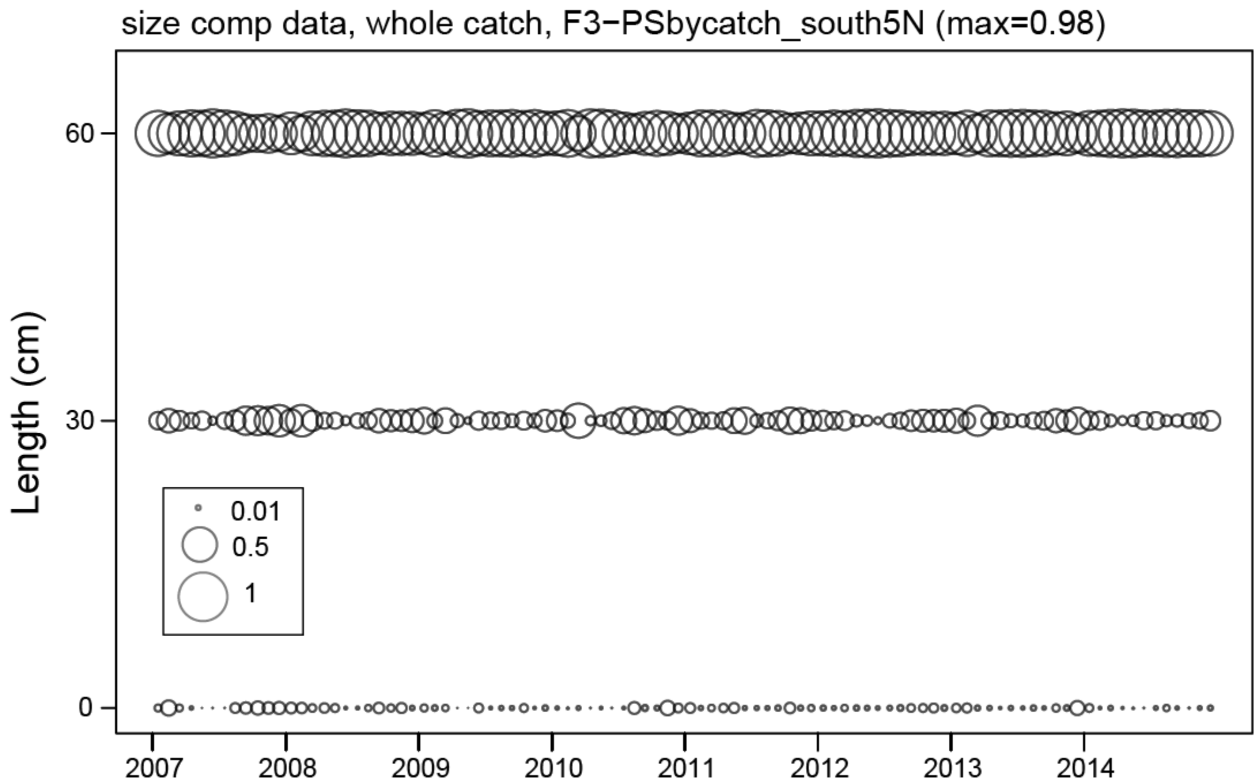


FIGURE 6c. Dorado size composition data from tuna purse-seine fisheries.

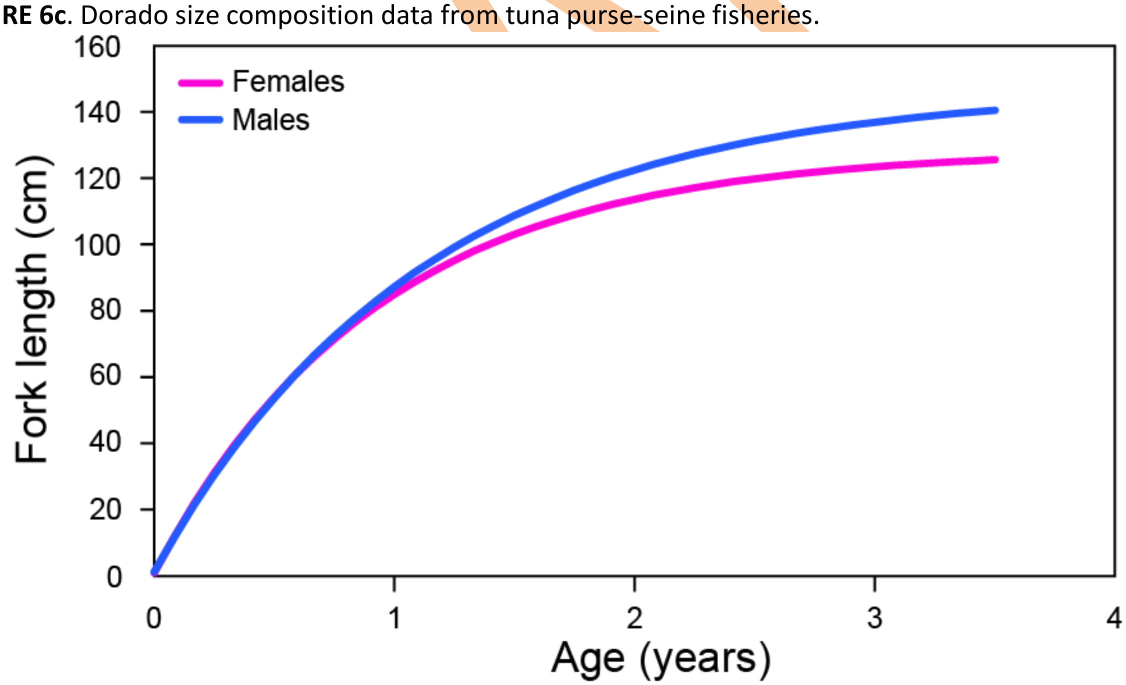


FIGURE 7a. Von Bertalanffy Growth Function for males and females from Goicochea *et al* (2012).

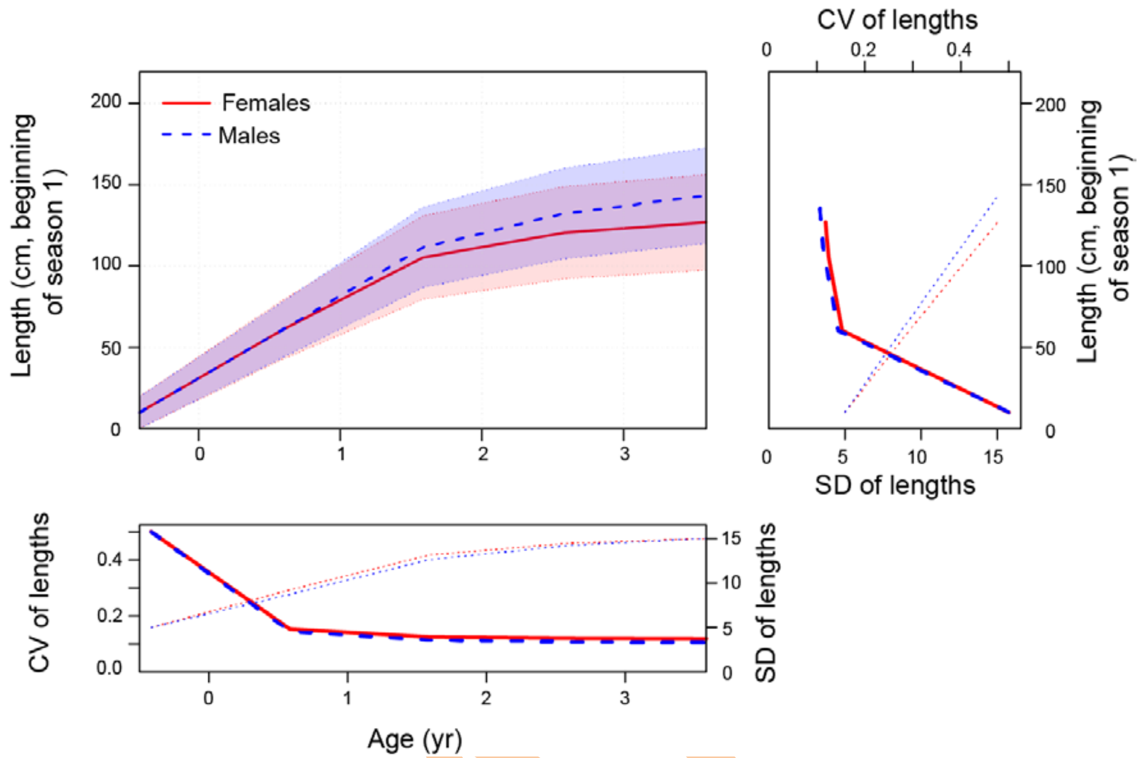


FIGURE 7.b. Growth curve for females and males Goicochea *et al.* (2012). Estimated values of the variability of the length at age.

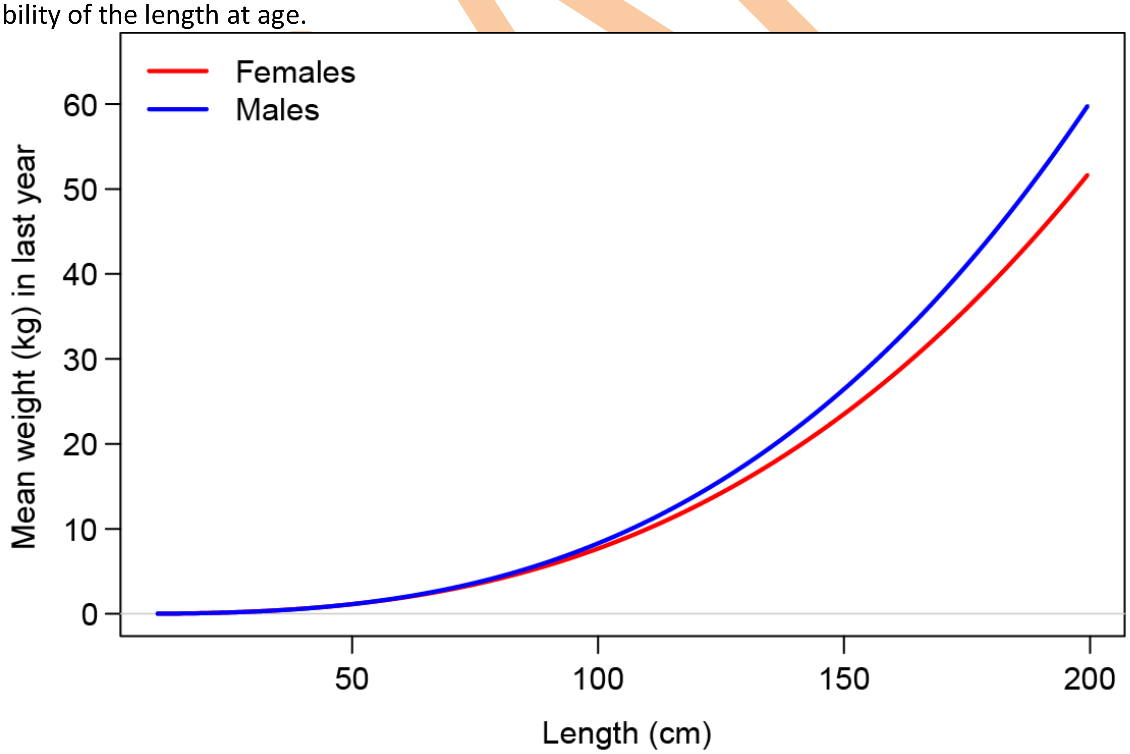
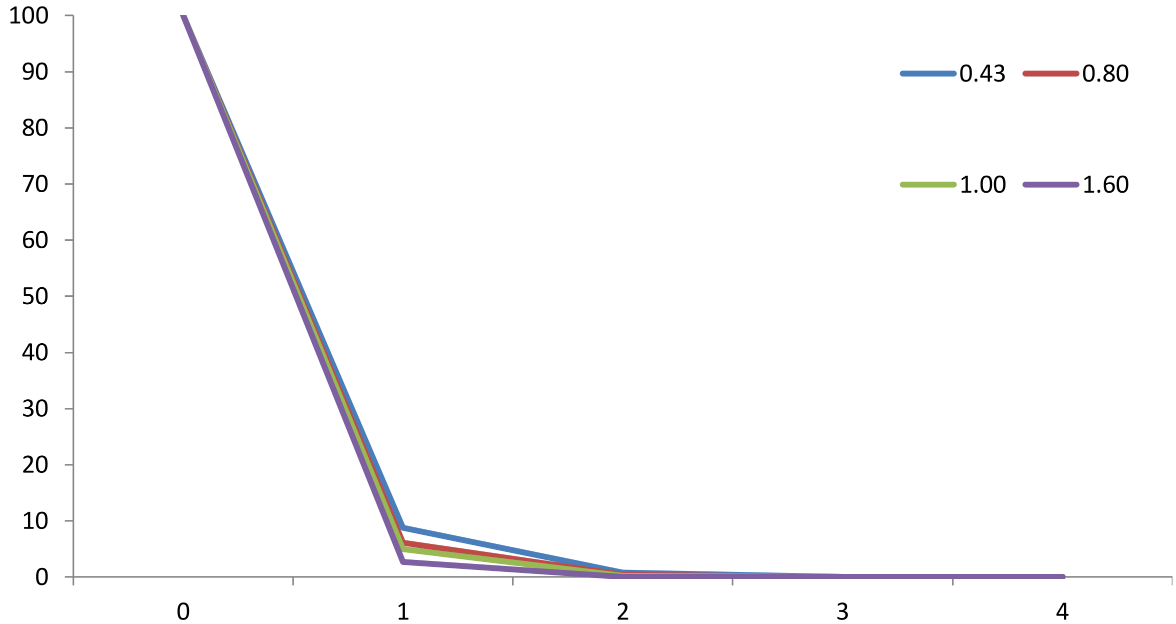


FIGURE 8. Dorado length weight relationship, Zúñiga-Flores (2014).



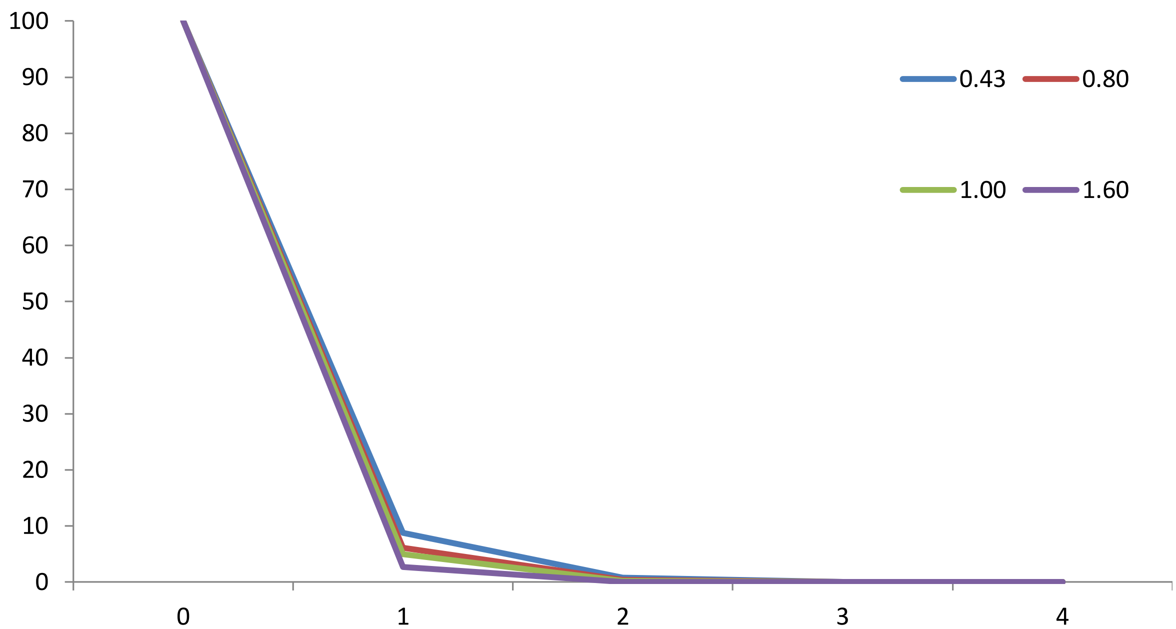
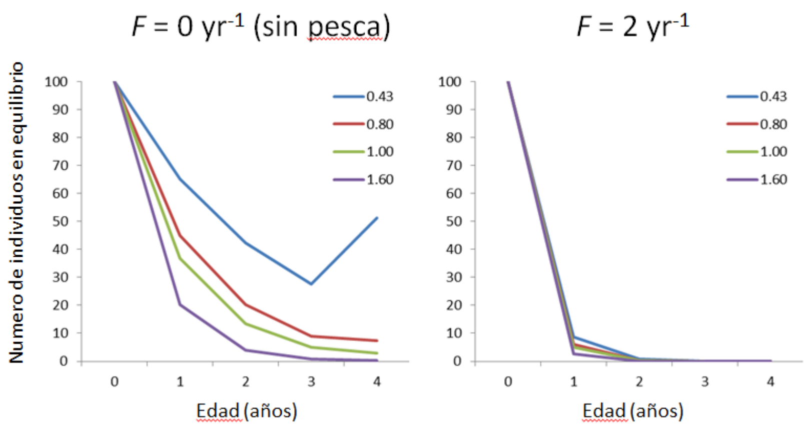


FIGURE 9. Survivorship of a cohort over time (in years) under different M values. Top : no fishing mortality (F = 0); Bottom: under exploitation with F = 1 yr^{-1}



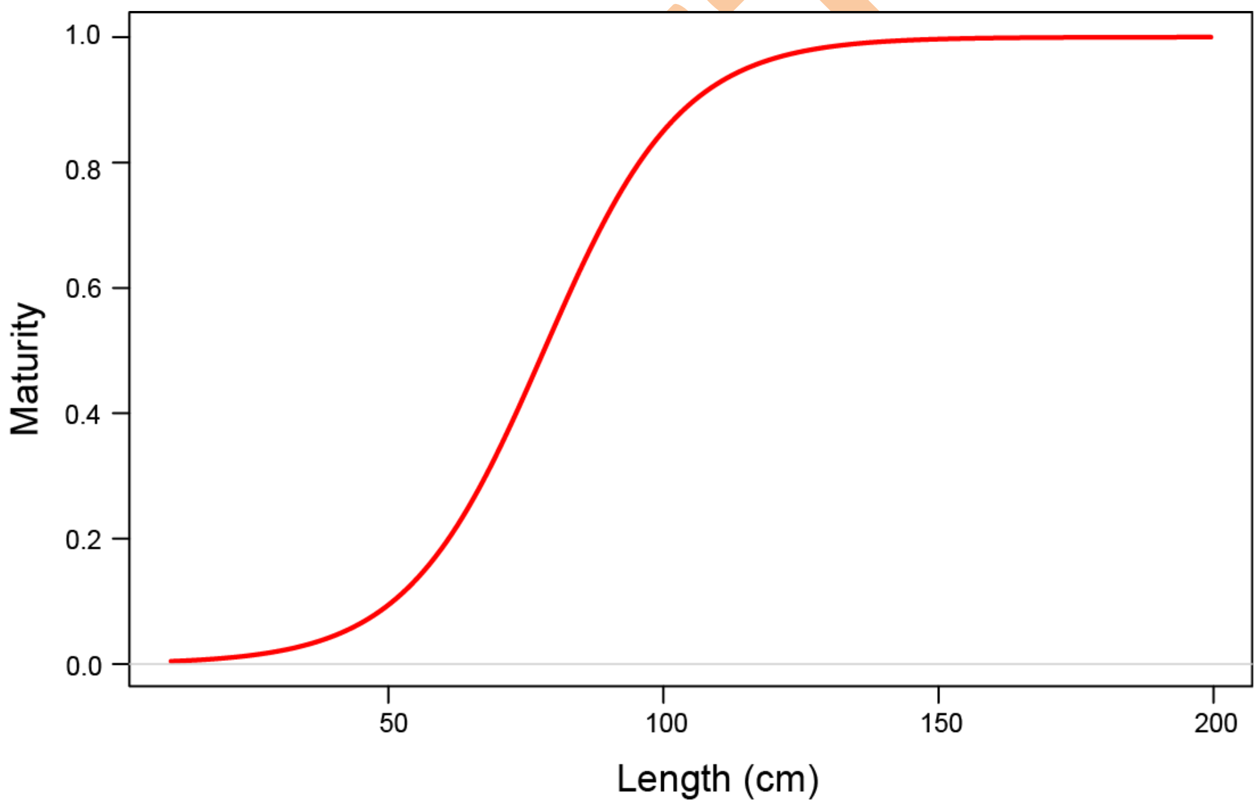


FIGURE 10. Maturity ogive for female dorado, Zúñiga-Flores (2014).

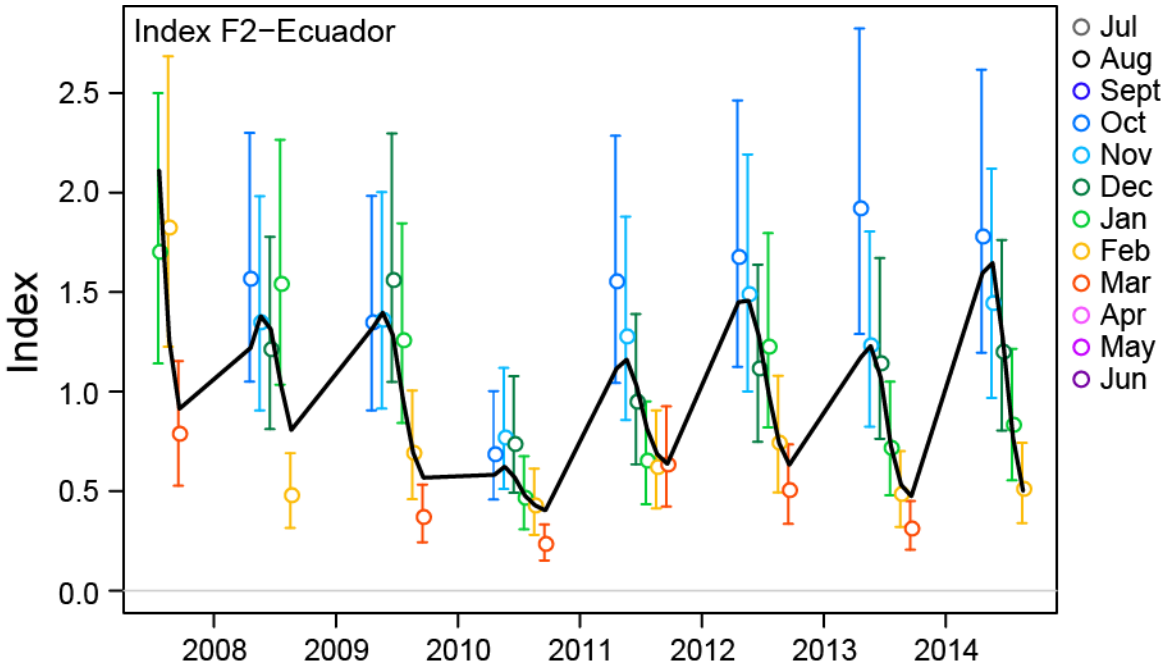


FIGURE 11a. Base-case model fit to the standardized CPUE data from the Ecuadorian artisanal fishery. The vertical lines represent the fixed confidence intervals (± 2 standard deviations) around the CPUE values.

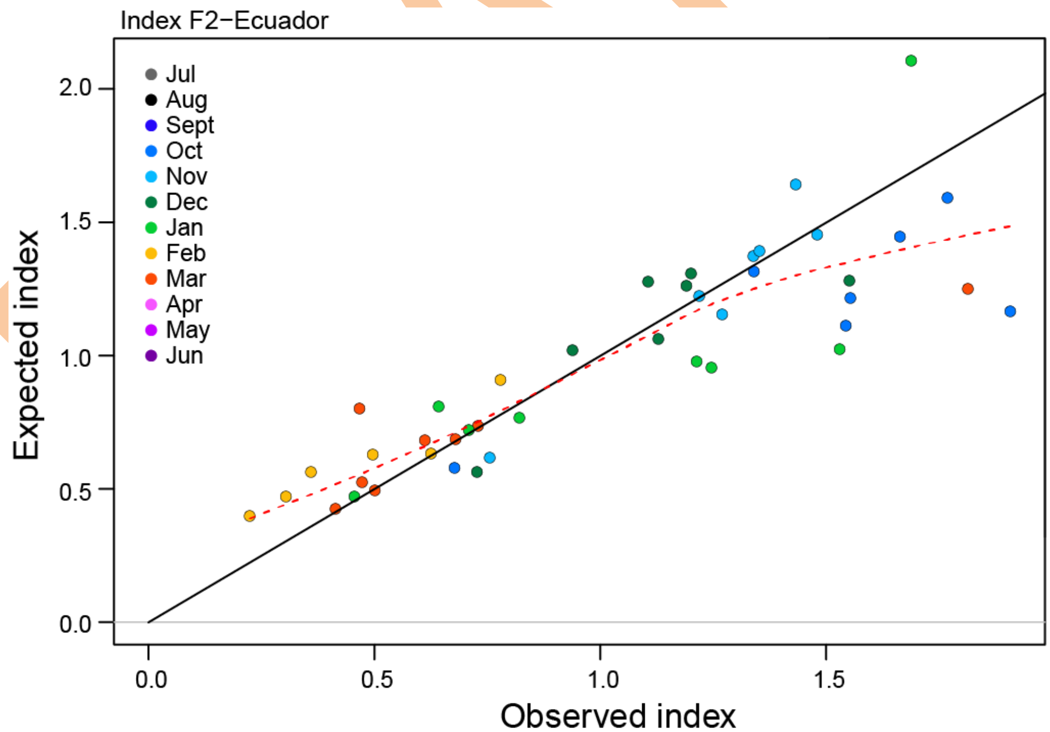


FIGURE 11b. Observed versus expected CPUE values from the Ecuadorian artisanal fishery. The black solid line marks a 1:1 relationship. The red dashed line is a loss smoother over the points.

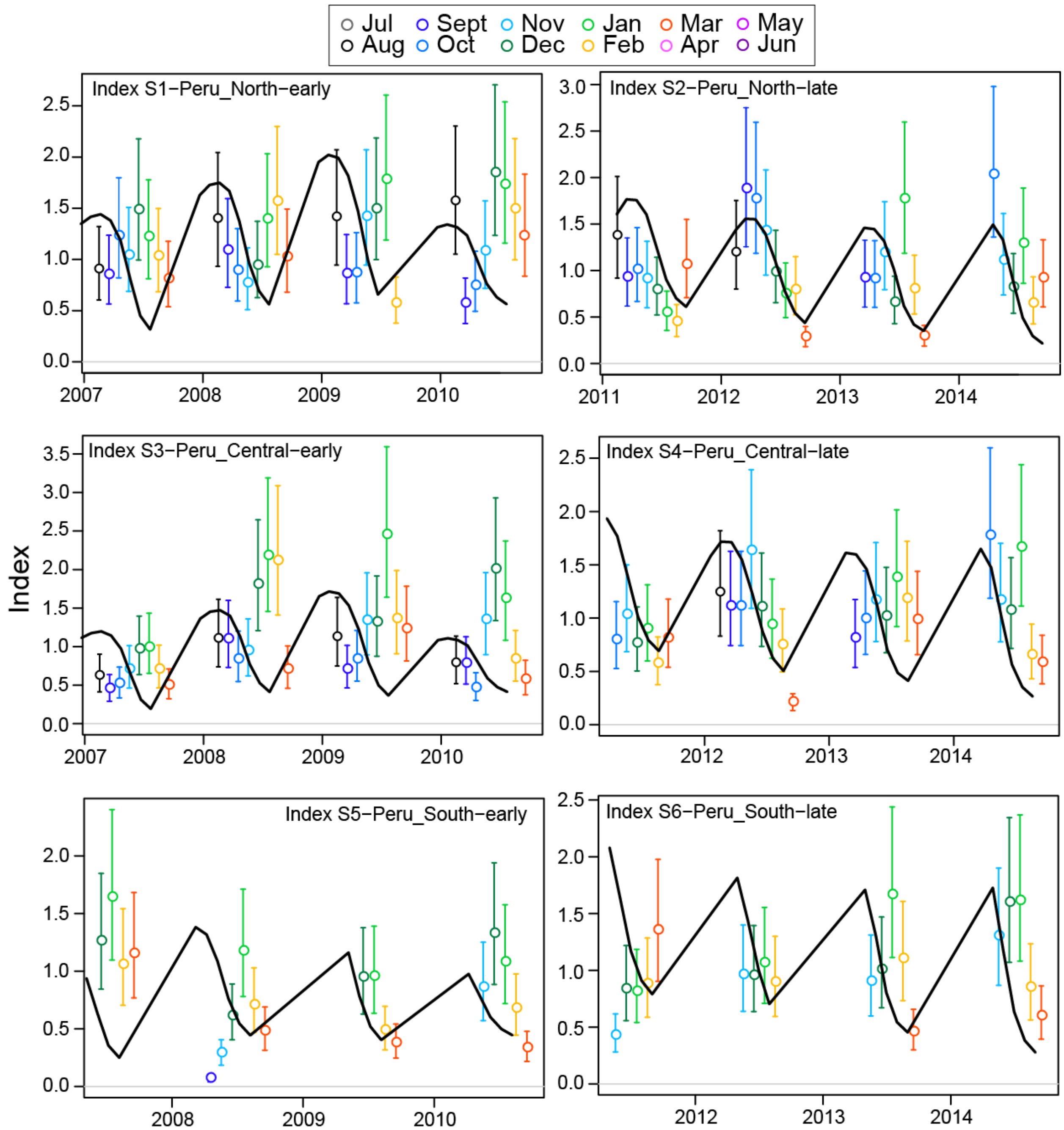


FIGURE 11c. Model fit to the standardized CPUE data from Peruvian artisanal fisheries operating in three regions: Northern (Paita), Central (Chimbote-Pecusana) and Southern (Ilo) regions. The CPUE indices are separate into an early and late periods cut at 2010, after which there we improvements in the Peruvian data collection.

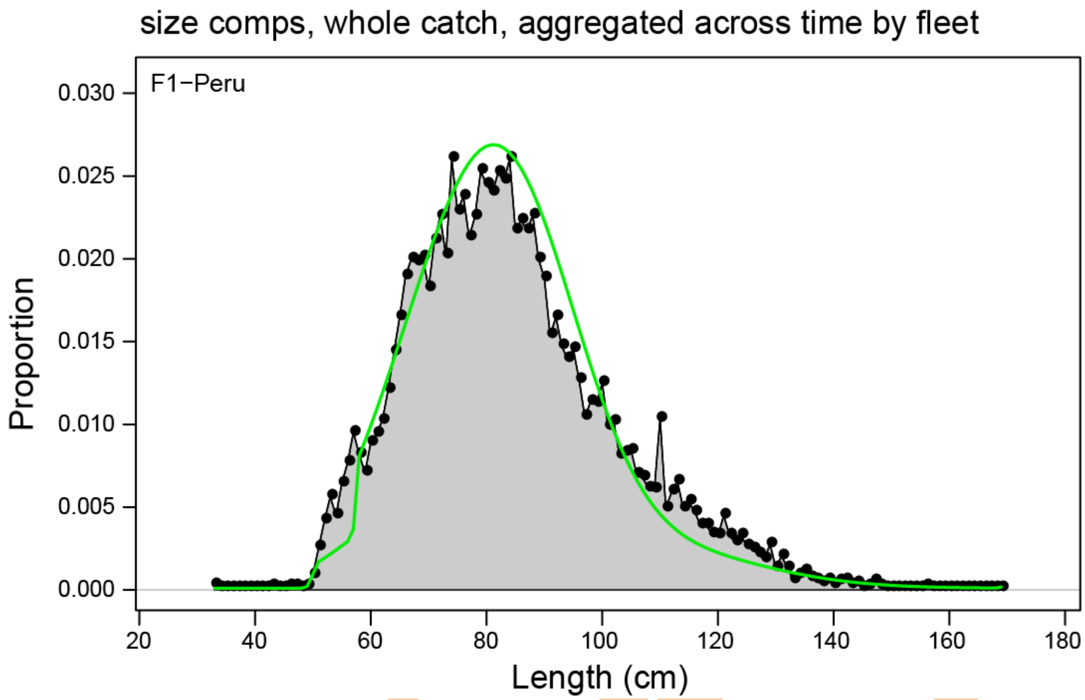


FIGURE **12a**. Average observed (dots) and predicted (curves) length composition of the catches taken by the Peruvian artisanal fishery (F1) for sexes combined.

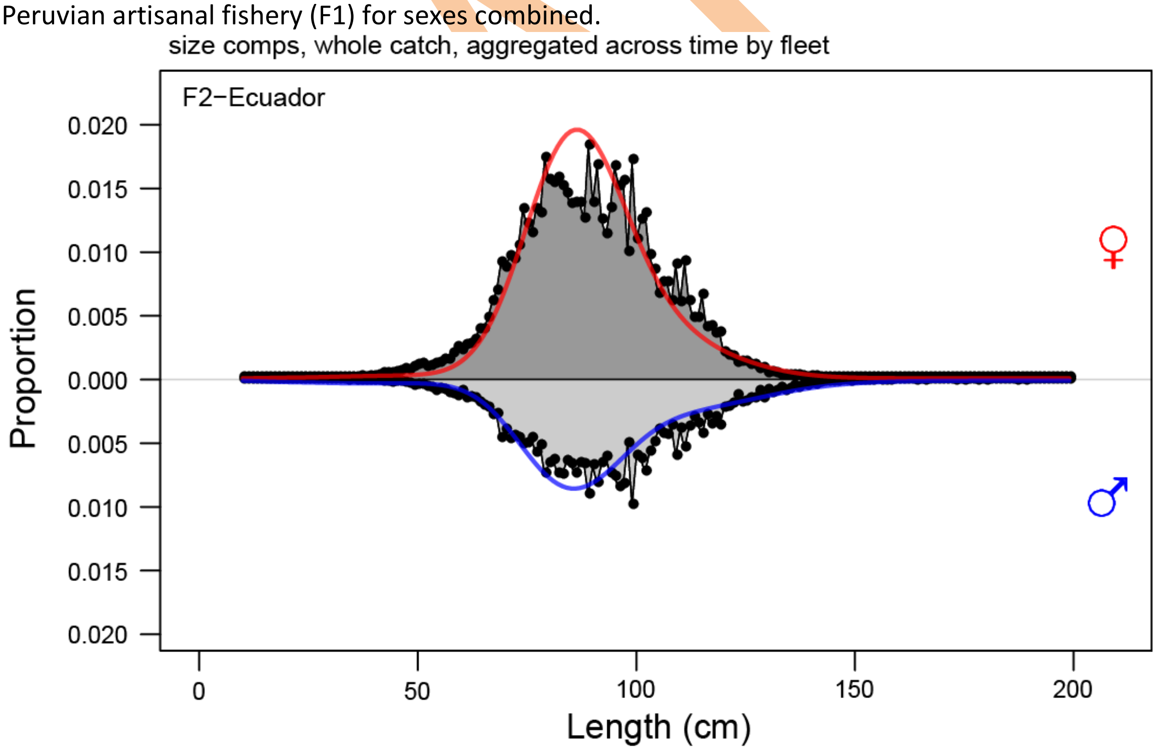


FIGURE 12b. Average observed (dots) and predicted (curves) length composition of the catches taken by the Ecuadorian artisanal fishery (F2), for females (top) and males (bottom).

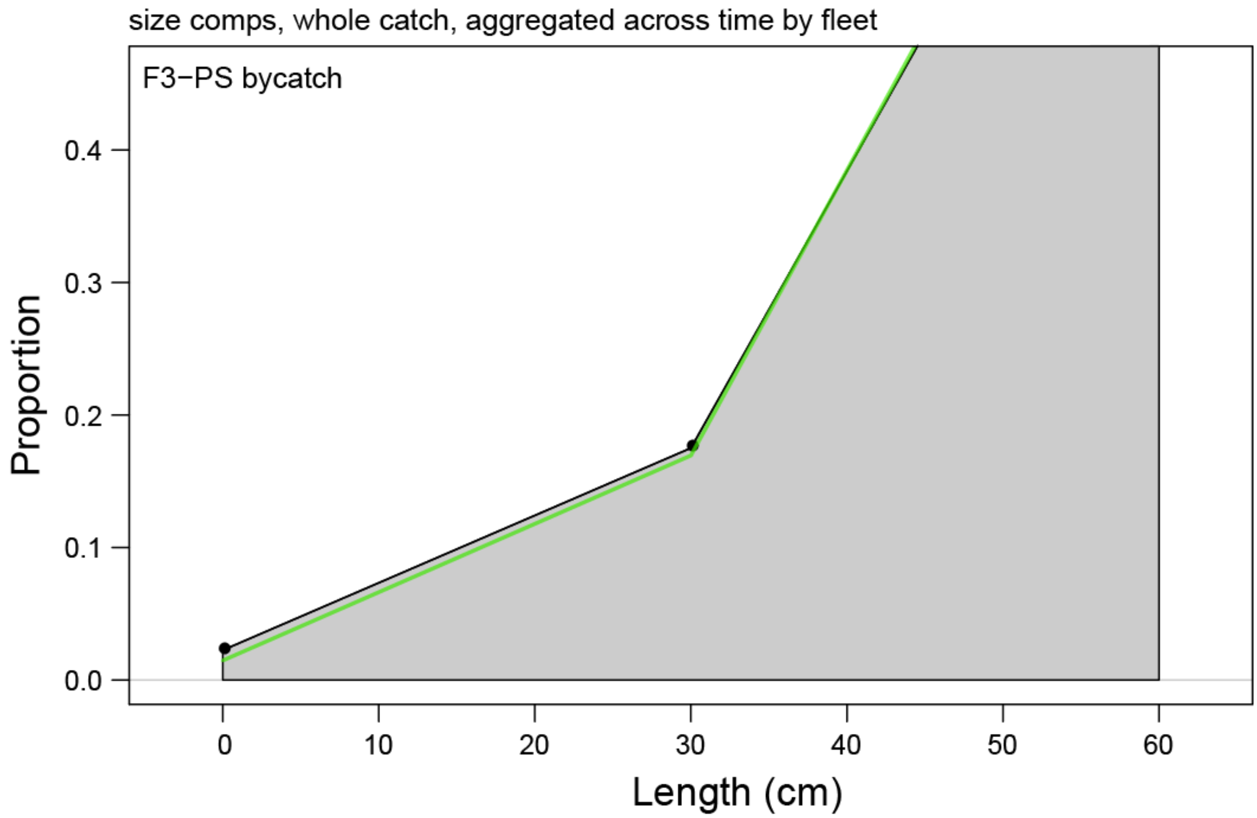


FIGURE 12c. Average observed (dots) and predicted (curves) length-class composition of the dorado bycatches taken by tuna purse-seine fishery (F3).

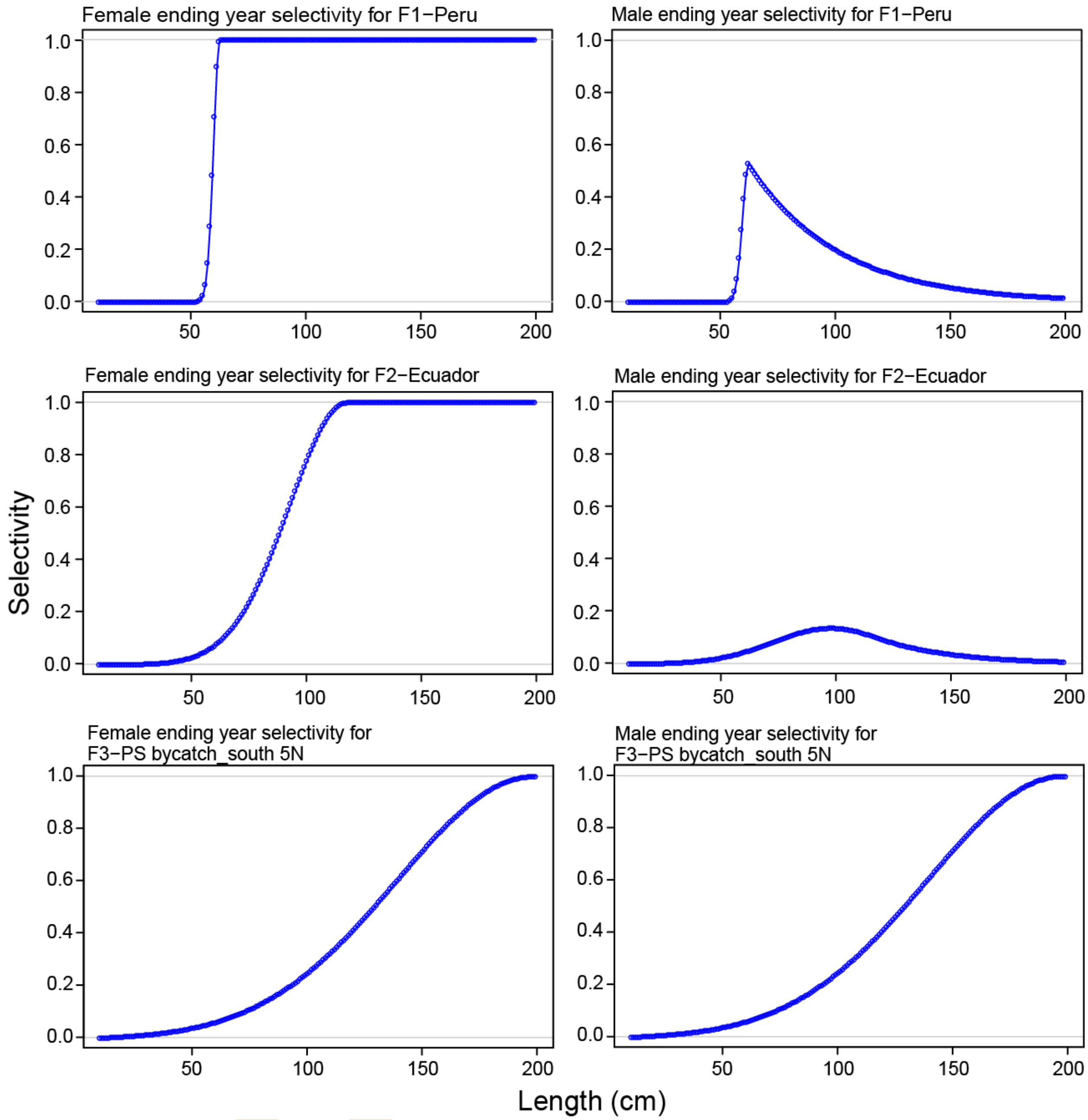


FIGURE 13. Size selectivity curves for the dorado fisheries. Left – females, Right – males

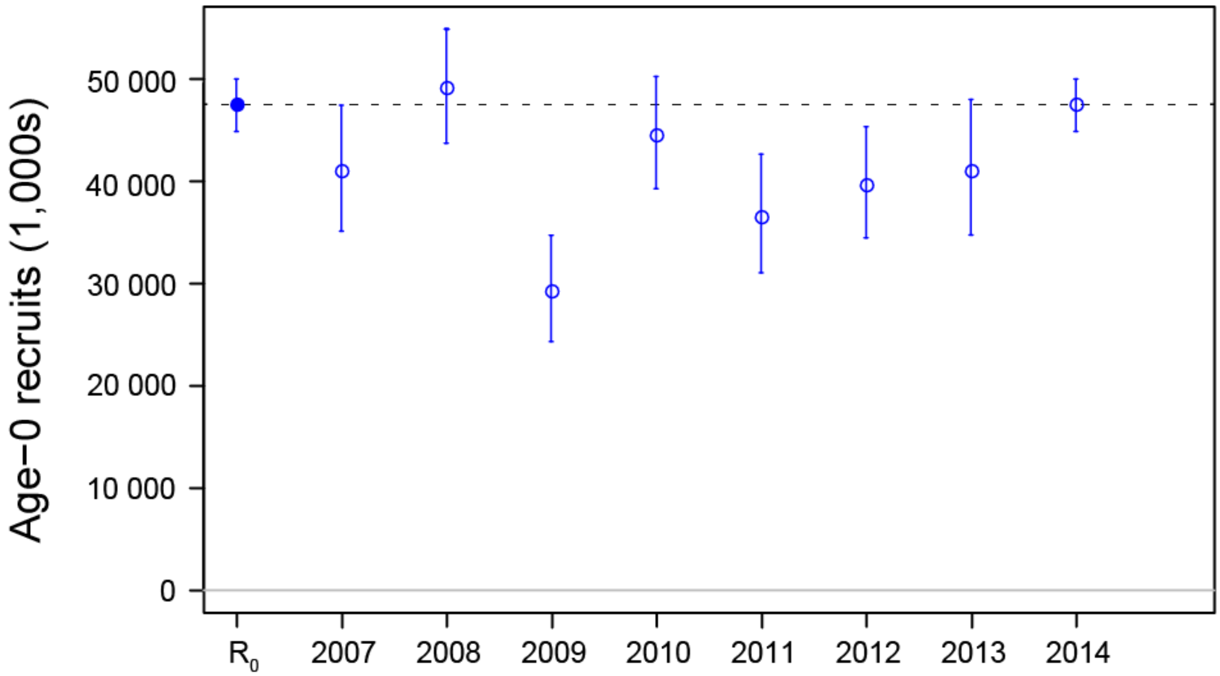


FIGURE 14. Estimates of the annual recruitment of dorado in the south EPO. The vertical lines represent the 95% confidence intervals around the recruitment estimates (open circles). The solid blue circle represents the estimate of the virgin recruitment (R0). In Stock Synthesis, age-0 recruitment is defined as post-larvae fish.

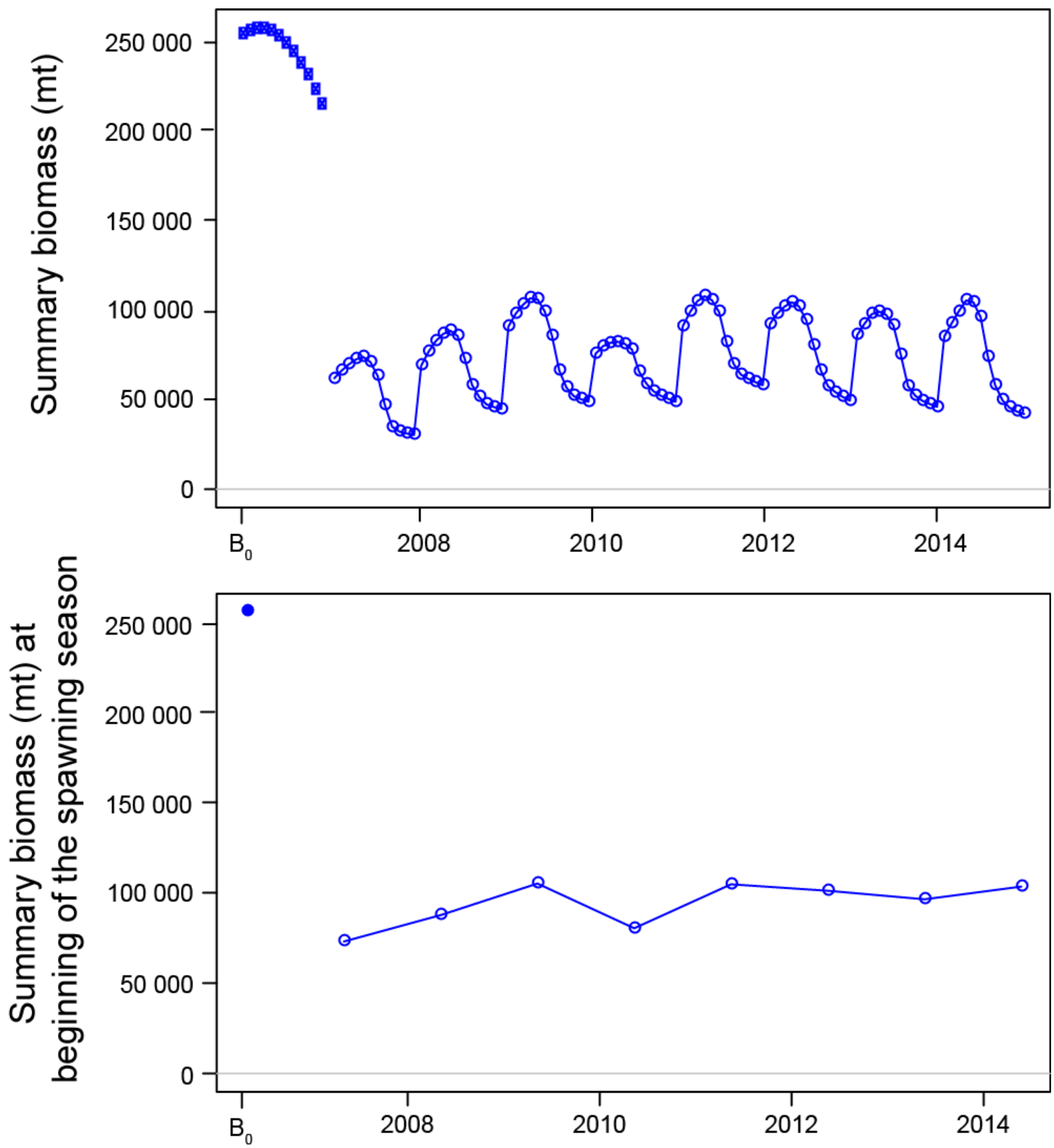


FIGURE 15. Estimates of the biomass of dorado 1+month old (summary biomass) in the south EPO. a) summary biomass at the start of each month, b) summary biomass at the beginning of the spawning season (defined as the month of November in the assessment model), the blue dot represents the estimate of the virgin summary biomass (B0) at the beginning of the spawning season.

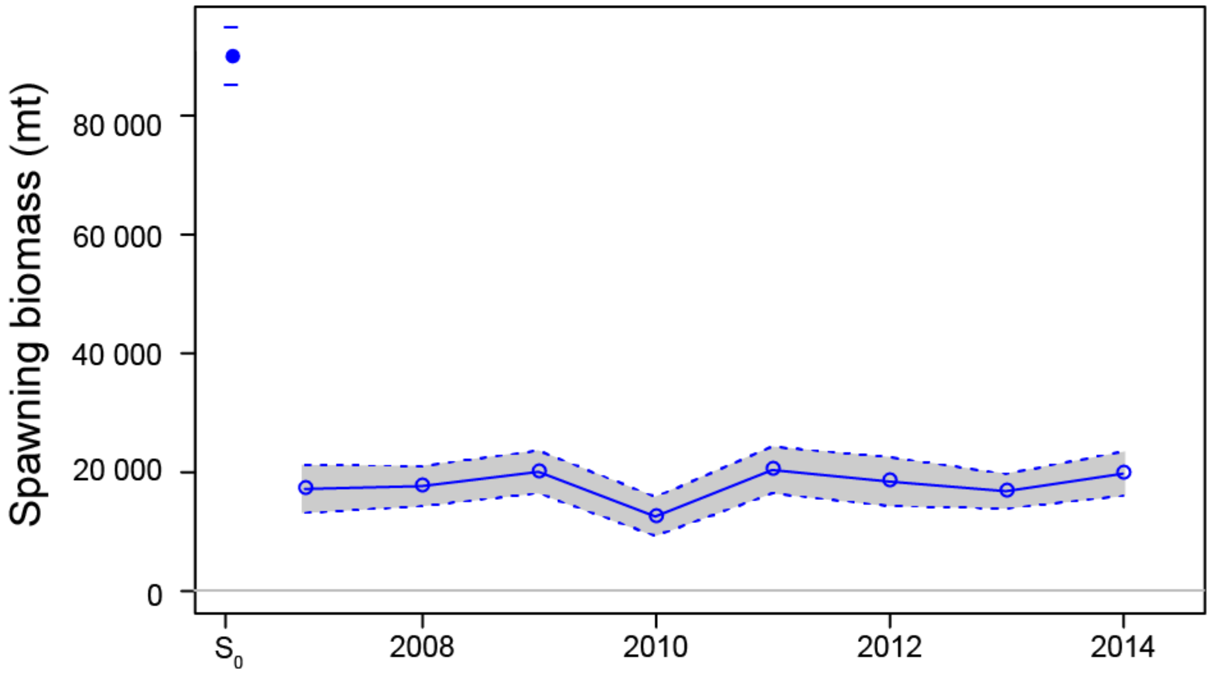


FIGURE 16. Estimates of the spawning biomass of dorado in the south EPO at the beginning of the spawning season (defined as the month of November in the assessment model model). The line connects illustrates the maximum likelihood estimates (open circles). The shaded area indicates the approximate 95 percent confidence intervals around these estimates.

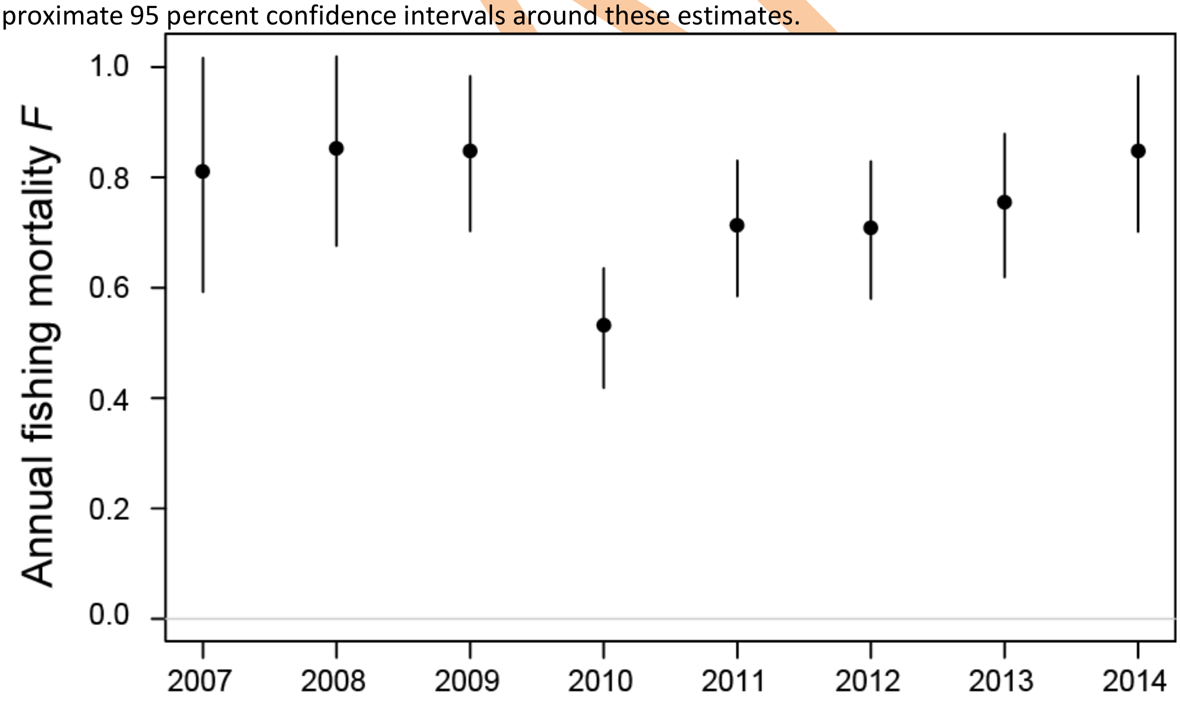


FIGURE 17a. Annual fishing mortality (*F*), by all fisheries, for dorado recruited to the fisheries of the south EPO.

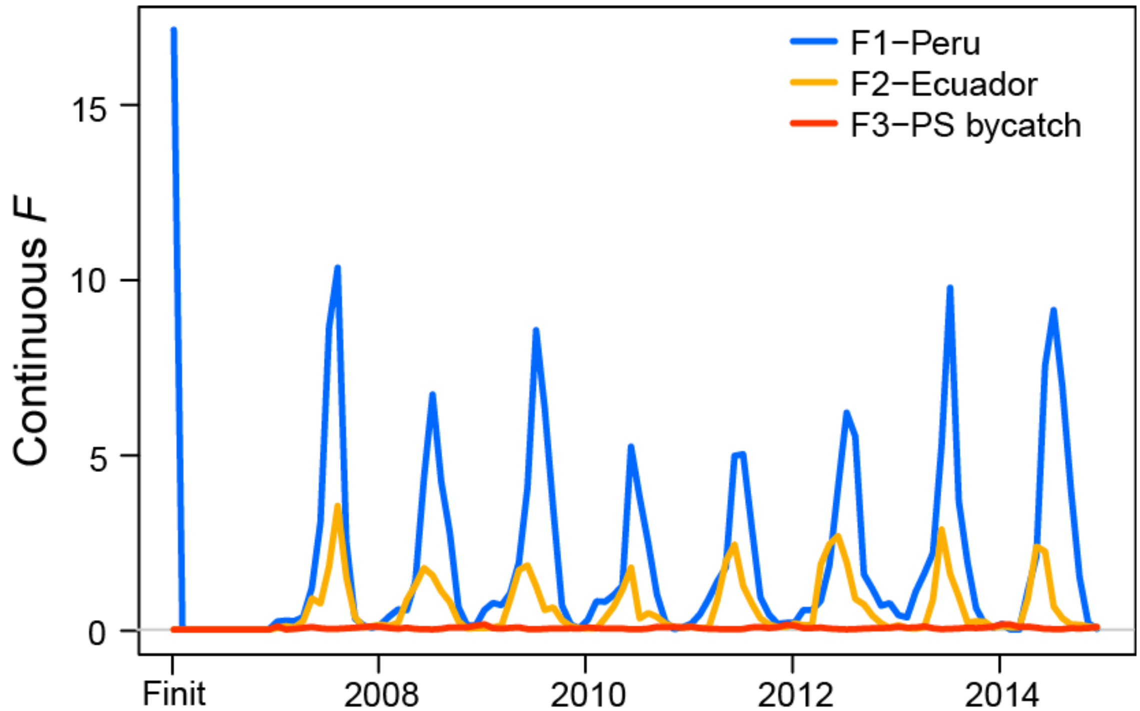


FIGURE 17b. Annualized (x 12) monthly instantaneous fishing mortality (F), by fishery, for dorado recruited to the fisheries of the south EPO.

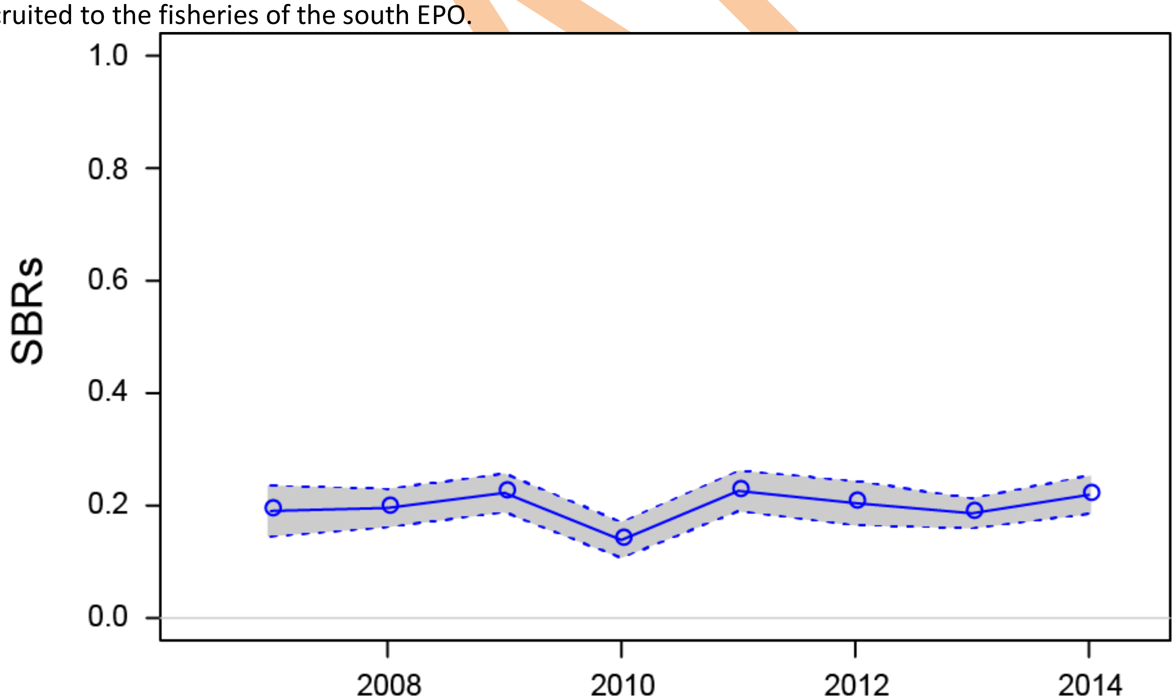


FIGURE 18. Estimates spawning biomass ratios (SBRs) of dorado recruited to the fisheries of the south EPO. The line connects illustrates the maximum likelihood estimates (open circles). The shaded area indicates the approximate 95 percent confidence intervals around these estimates.

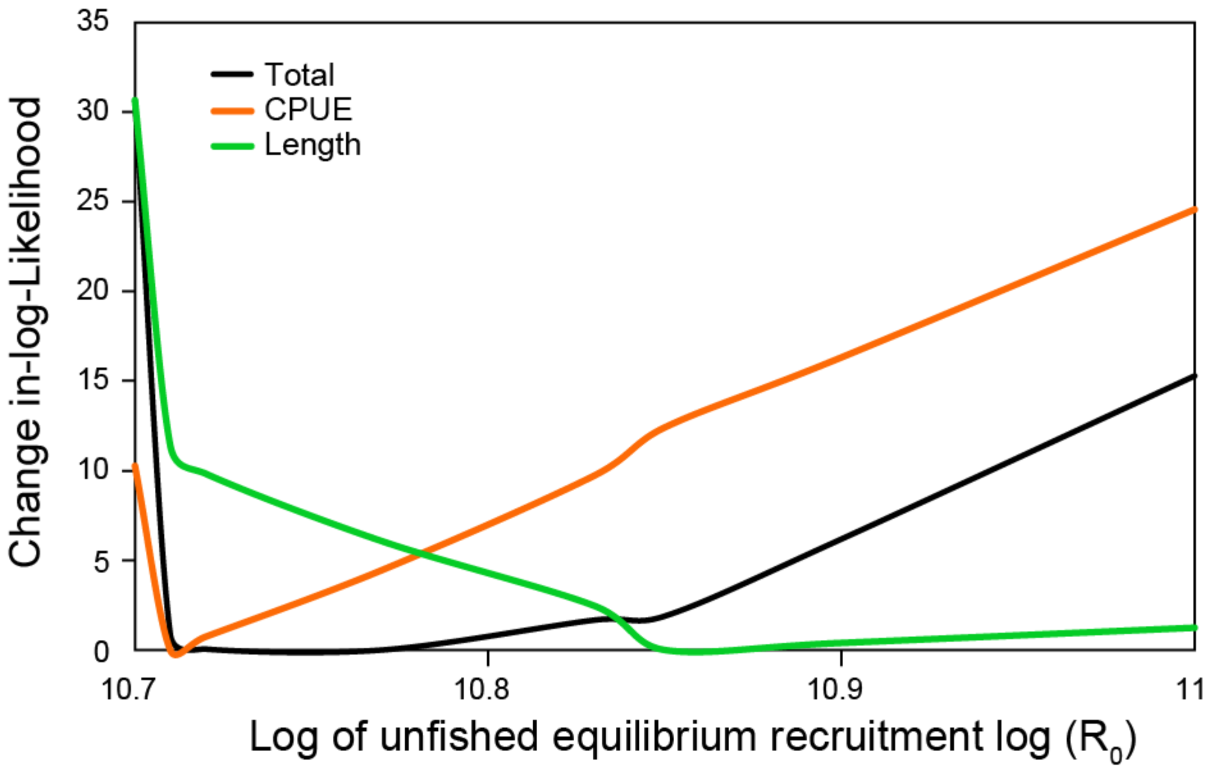


FIGURE 19. Likelihood profile on the average recruitment under no fish conditions (R_0) for the total likelihood (Total), Ecuadorean CPUE (CPUE) and length composition data (Length).

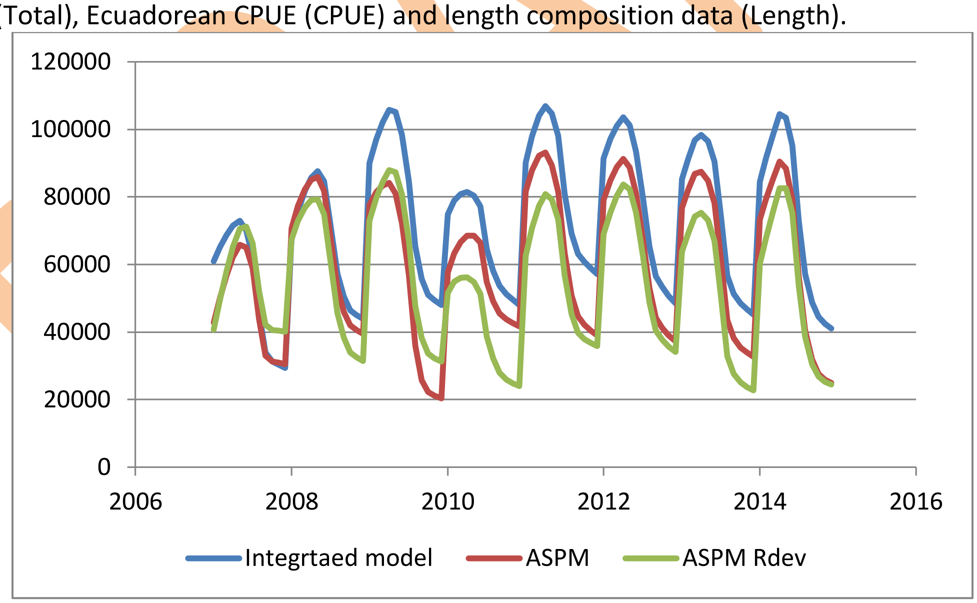


FIGURE 20. Age-structured production model (ASPM) diagnostic.

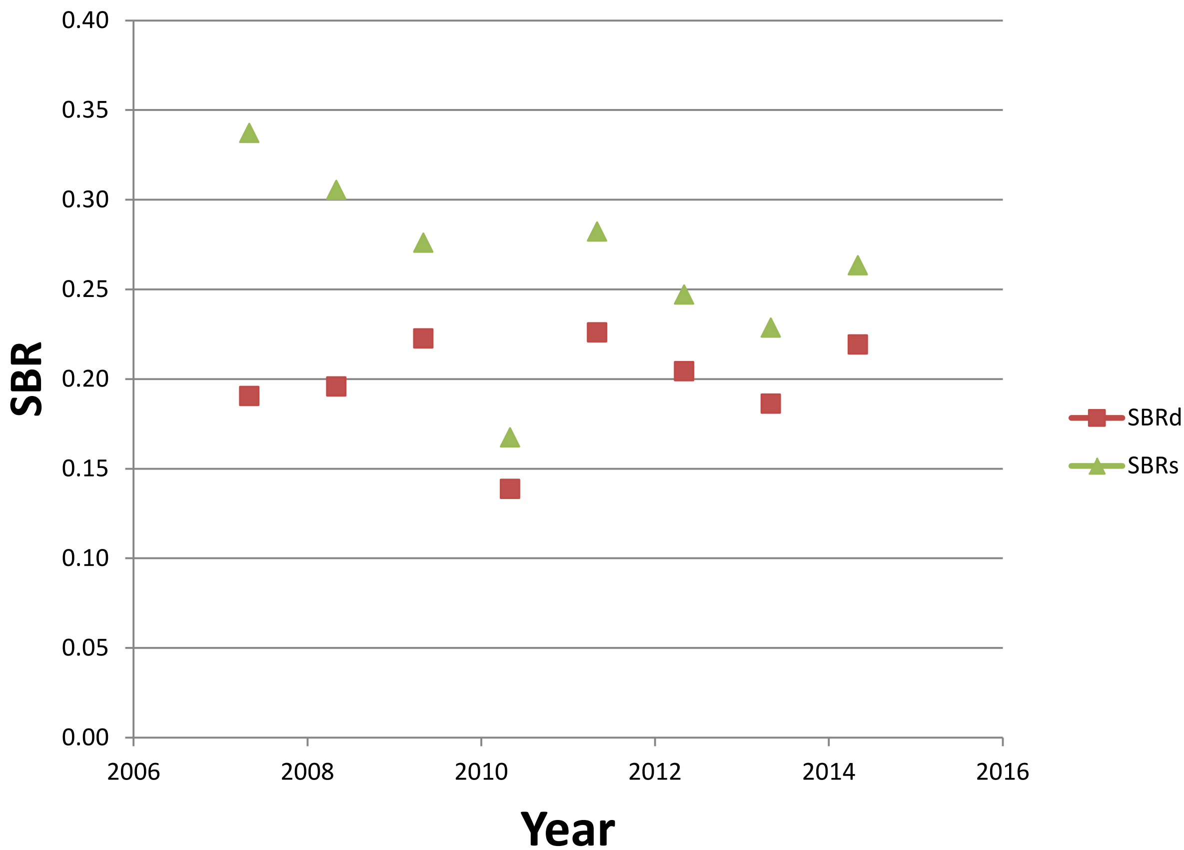


FIGURE 21 Estimates from the base case for the Spawning biomass ratio (SBR) obtained by two methods: static (SBRs) and dynamic (SBRd).

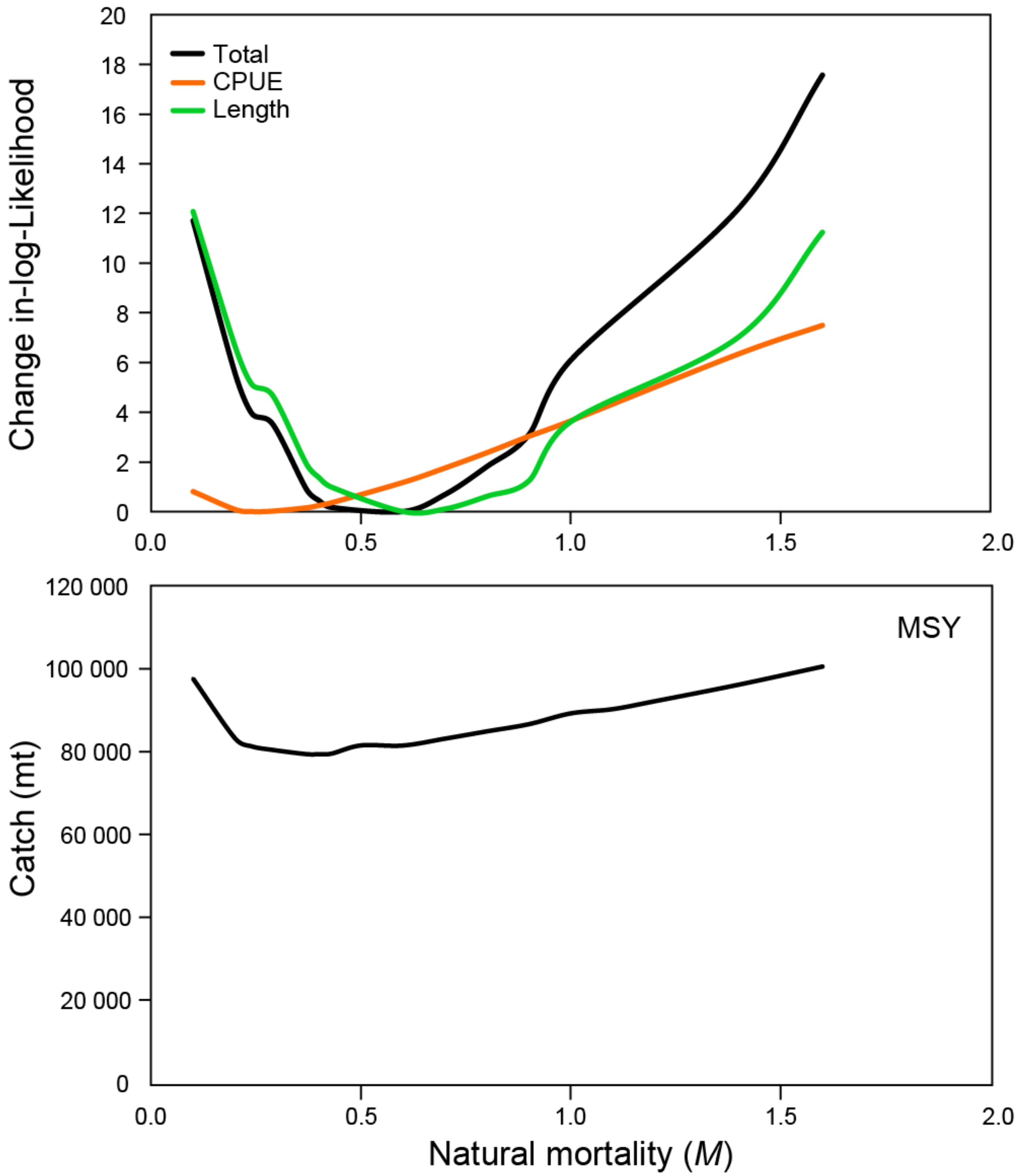


FIGURE 22. Top panel: Likelihood profile on natural mortality (*M*) for the total likelihood (Total), Ecuadorean CPUE (CPUE) and length composition data (Length). Bottom panel: maximum sustainable yield (MSY) in metric tons.

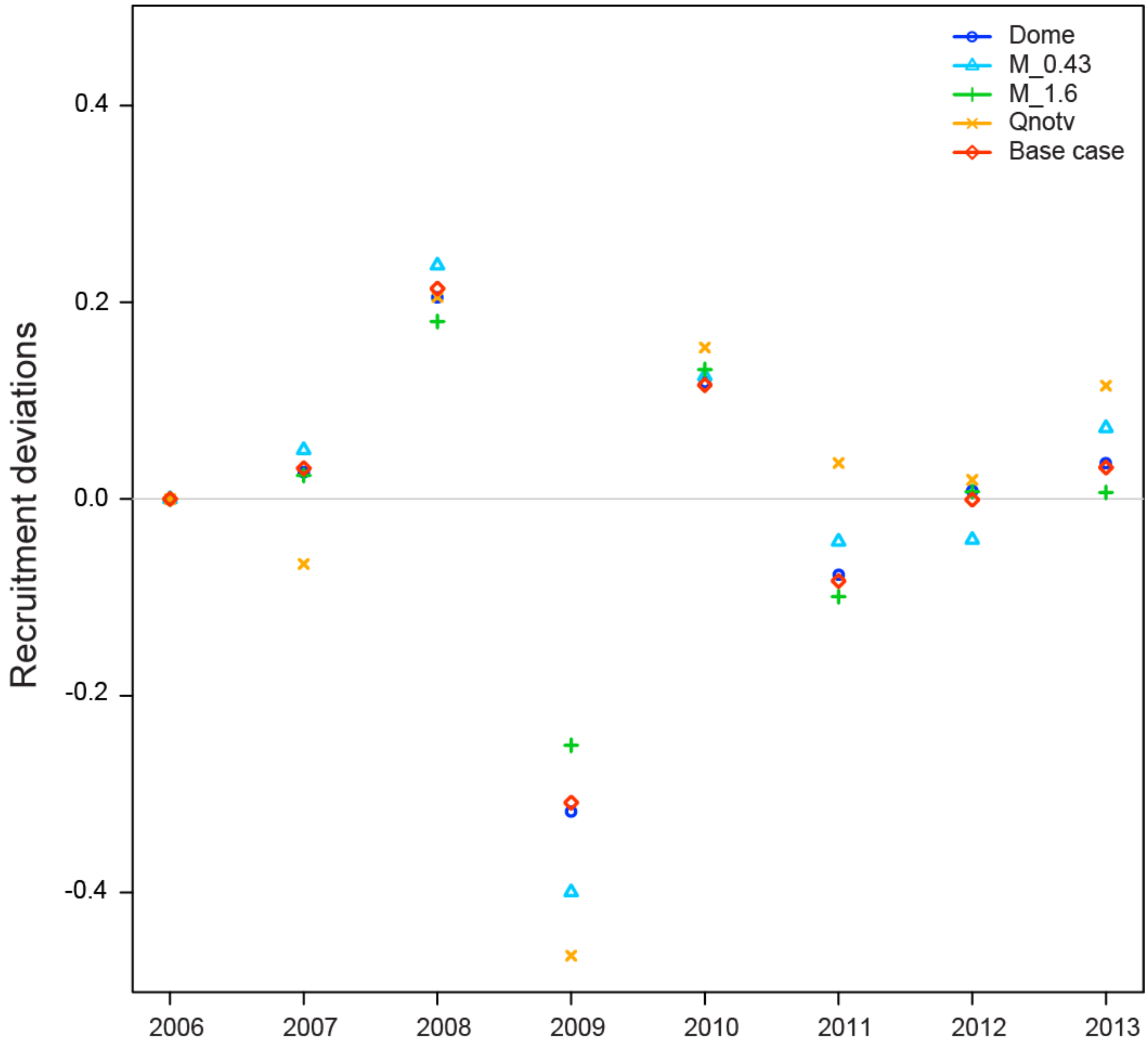


FIGURE 23. Recruitment deviations between 2006 and 2013 as estimated in the Base case (Base) compared to sensitivities to dome selectivity (Dome), natural mortalities of either *M*: 0.43 or *M*: 1.6 (M_0.43 and M_1.6, respectively), and no time-varying selectivity (Qnotv).

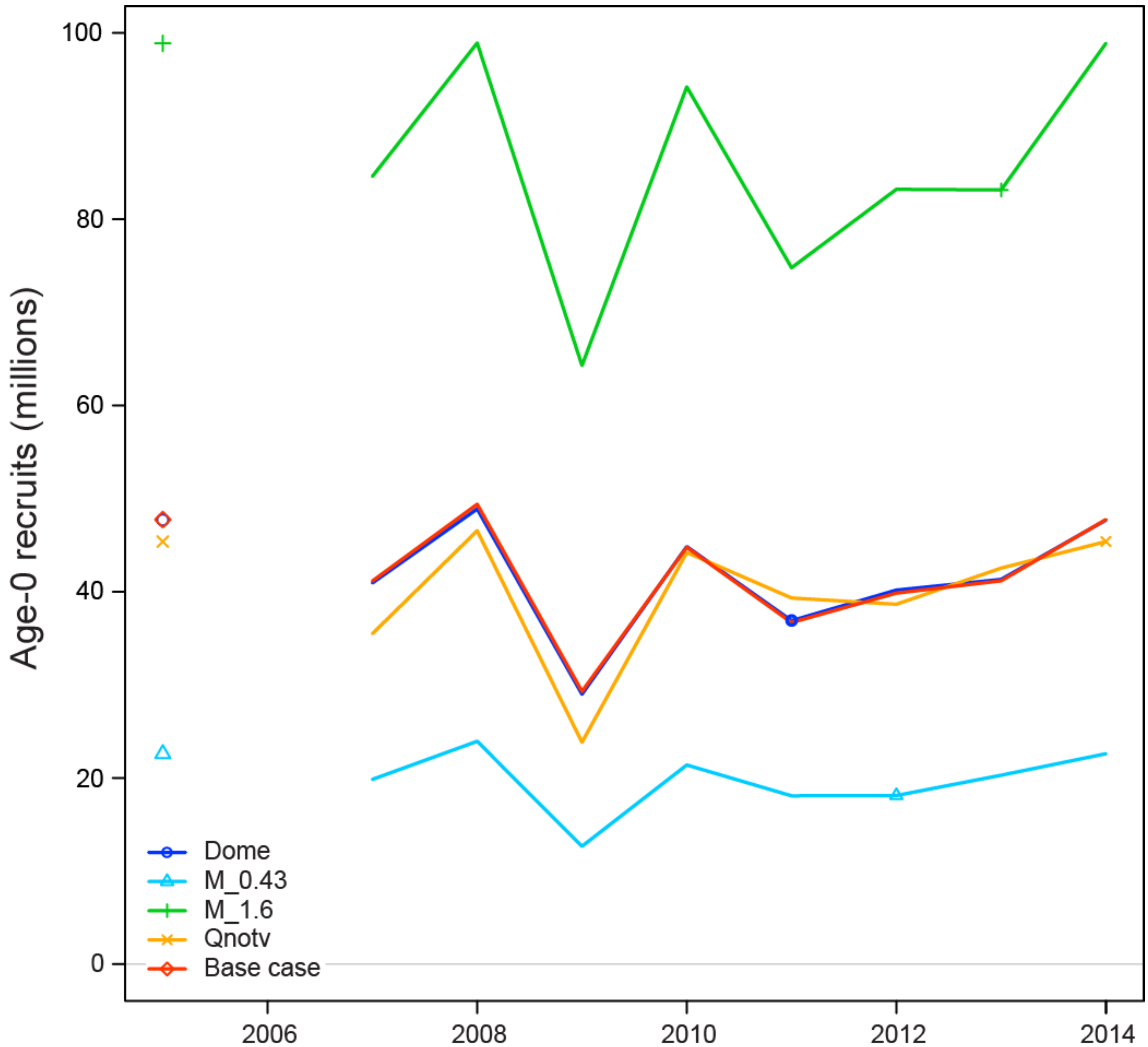


FIGURE 24. Recruitment estimates of age 0 dorado between 2006 and 2013 from the Base case (Base) compared to sensitivities to dome selectivity (Dome), natural mortalities of either *M*: 0.43 or *M*: 1.6 (M_0.43 and M_1.6, respectively), and no time-varying selectivity (Qnotv).

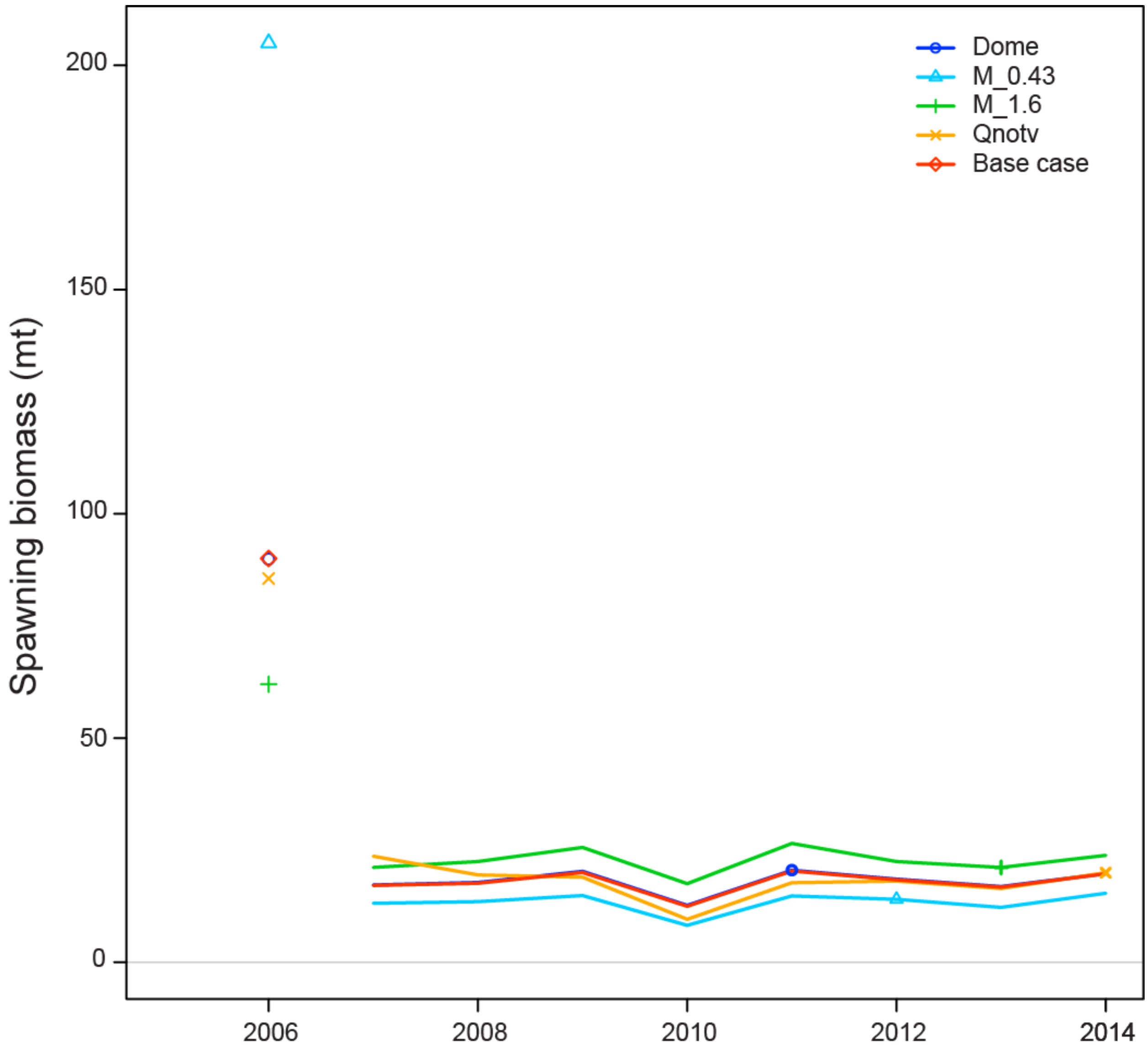


FIGURE 25. Spawning biomass (mt) estimates between 2006 and 2013 from the Base case (Base) compared to sensitivities to dome selectivity (Dome), natural mortalities of either *M*: 0.43 or *M*: 1.6 (M_0.43 and M_1.6, respectively), and no time-varying selectivity (Qnotv).

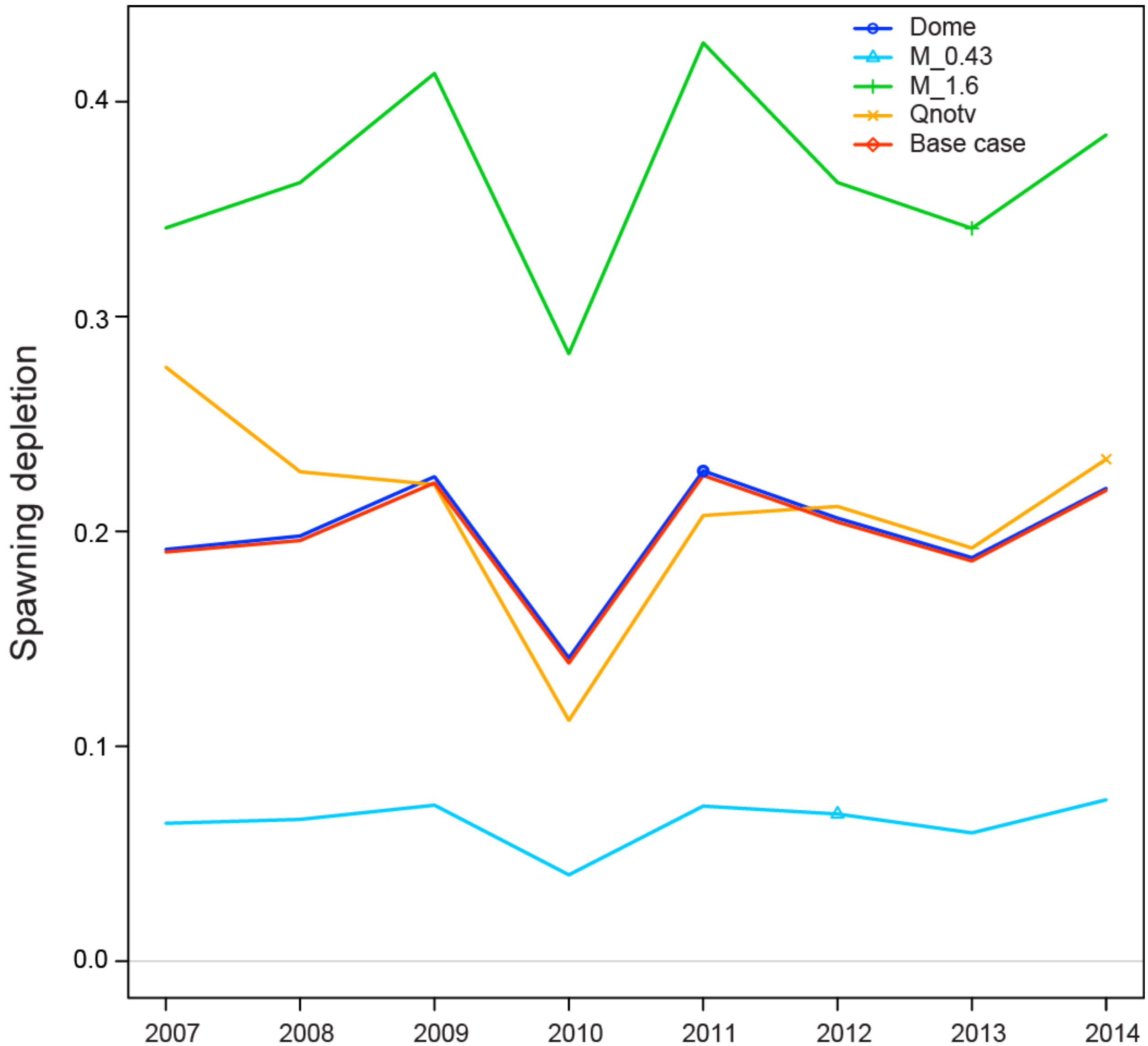


FIGURE 26. Spawning depletion estimates between 2006 and 2013 from the Base case (Base) compared to sensitivities to dome selectivity (Dome), natural mortalities of either *M*: 0.43 or *M*: 1.6 (M_0.43 and M_1.6, respectively), and no time-varying selectivity (Qnotv).

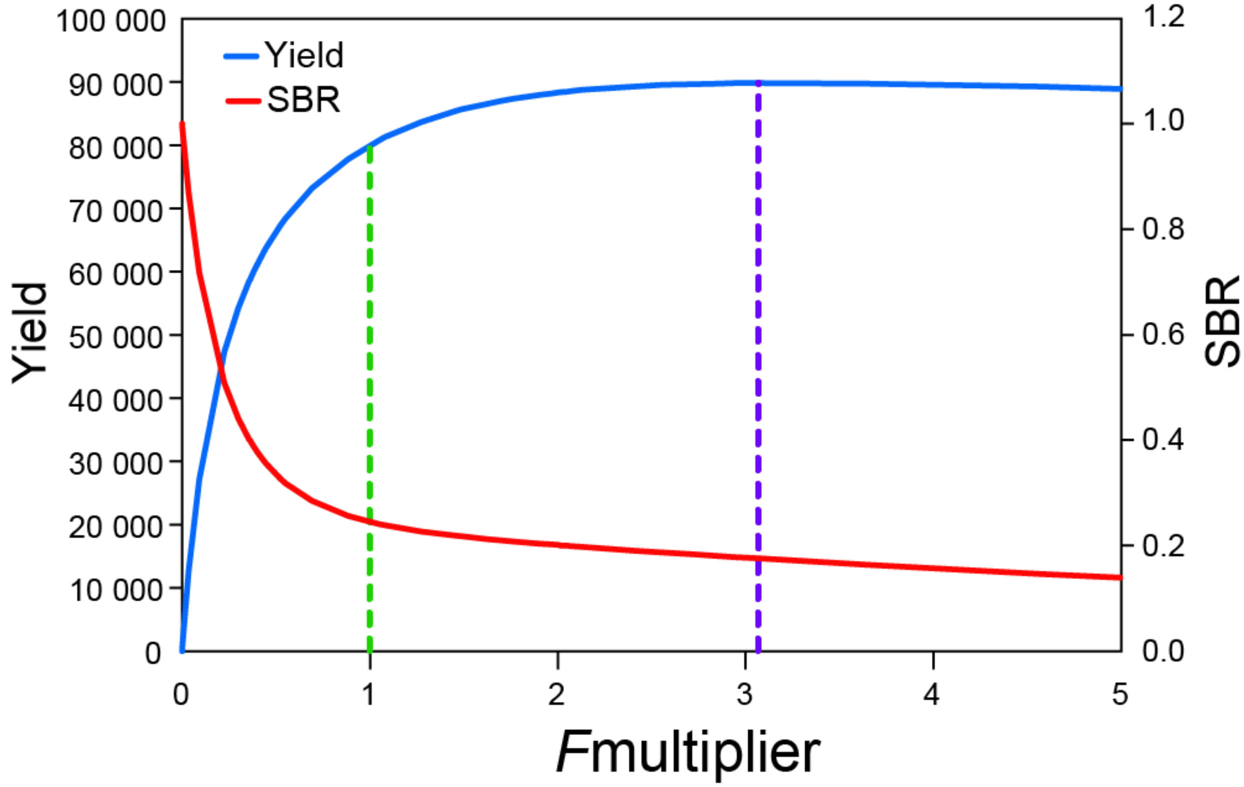


FIGURE 27. Equilibrium yield and spawning biomass ratio (SBR) versus the Stock Synthesis scaling factor on current fishing mortality (so current apical fishing mortalities from all fisheries sum to one)

Appendix A.

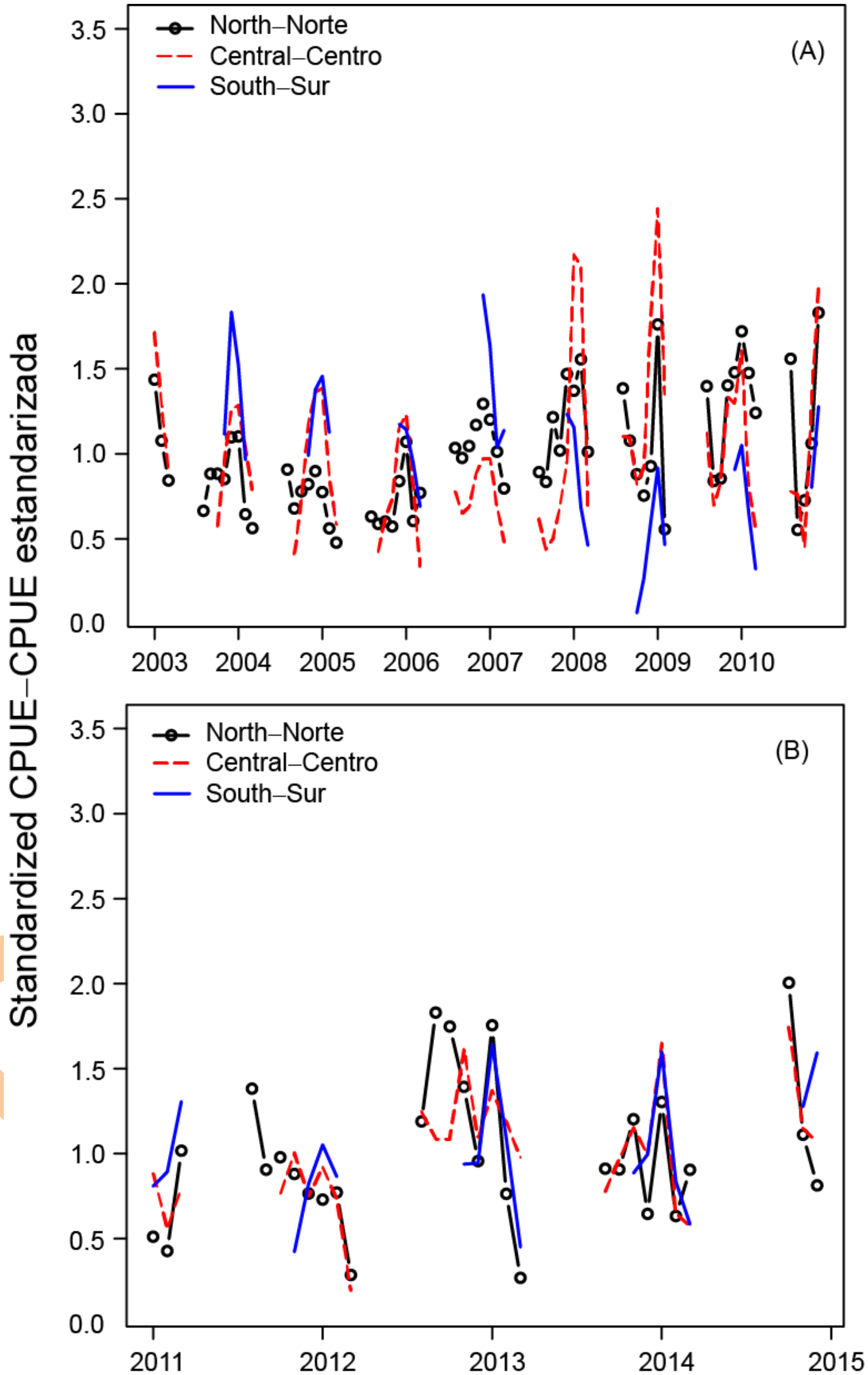


FIGURE A.1. Standardized CPUE from the Gamma GAMs for CPUE in weight of dorado caught by Peruvian artisanal fisheries. The standardized CPUE were computed for three regions: Northern (Paita), Central (Chimbote-Pucusana) and Southern (Ilo). Two historic periods were separate in the analysis: 2003-2010 and 2011-2014.

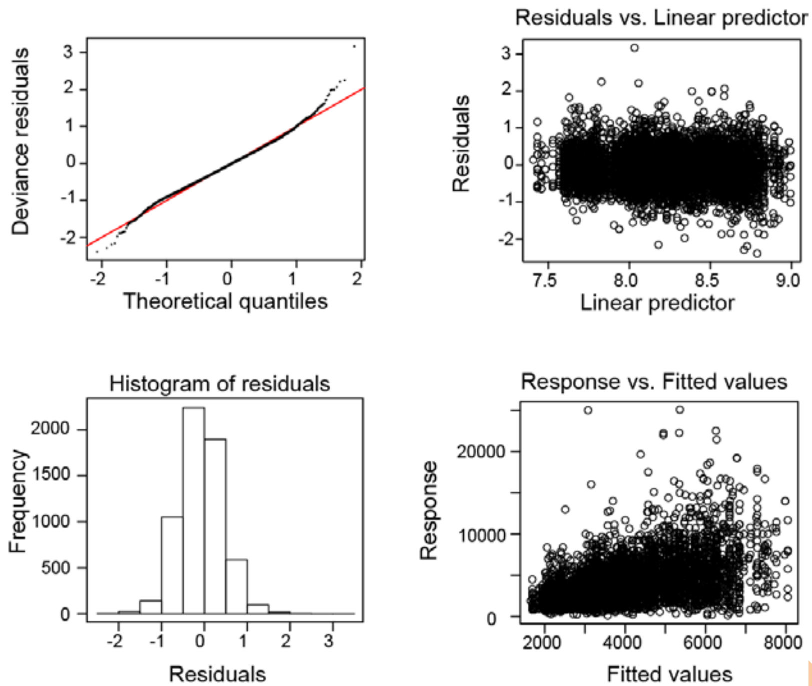


FIGURE A.2. Diagnostic plots for the GAM using CPUE in weight for the Peruvian artisanal fisheries operating in the Northern area (Paita) during the early period (2003-2010). GAM assumed Gamma distribution with log link.

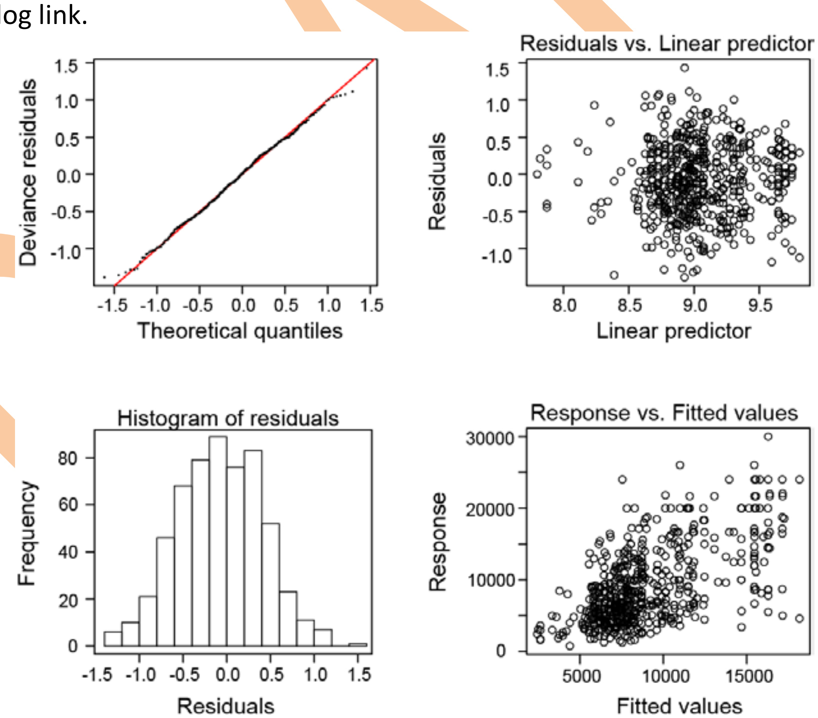


FIGURE A.3. Diagnostic plots for the GAM using CPUE in weight for the Peruvian artisanal fisheries operating in the Northern area (Paita) during the later period (2011-2014). GAM assumed Gamma distribution with log link.

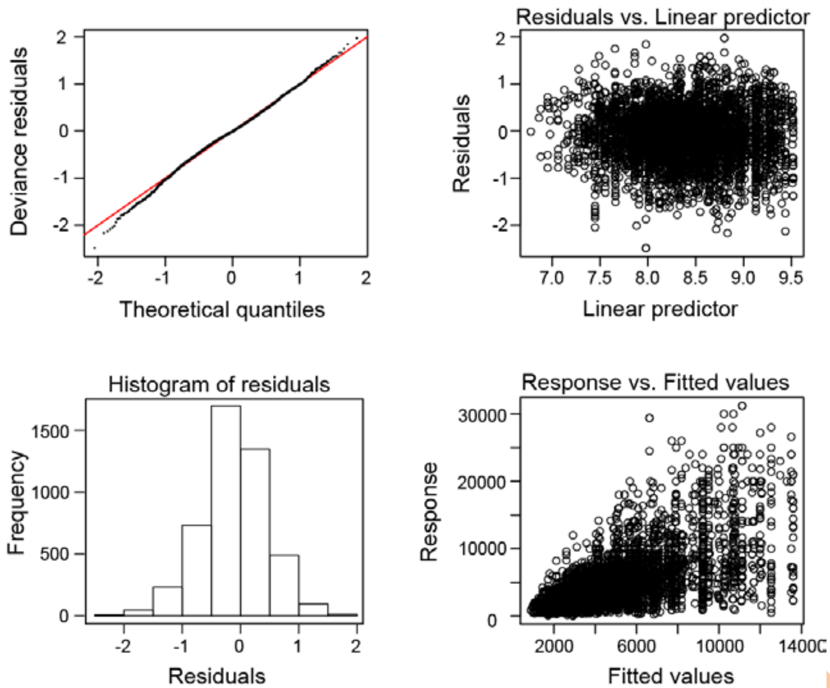


FIGURE A.4. Diagnostic plots for the GAM using CPUE in weight for the Peruvian artisanal fisheries operating in the Central area (Chimbote-Pucusana) during the early period (2003-2010). GAM assumed Gamma distribution with log link.

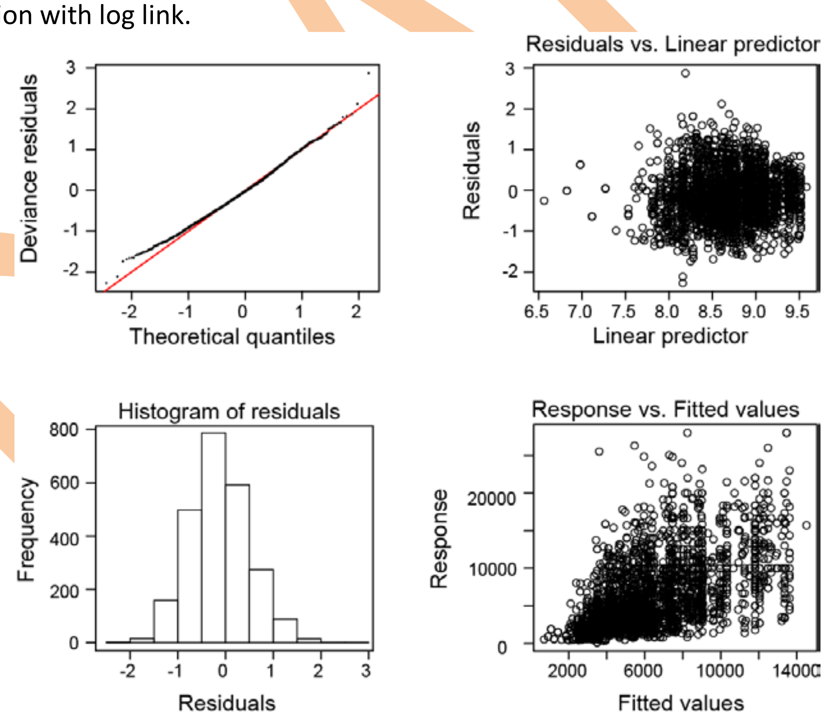


FIGURE A.5. Diagnostic plots for the GAM using CPUE in weight for the Peruvian artisanal fisheries operating in the Central area (Chimbote-Pucusana) during the later period (2011-2014). GAM assumed Gamma distribution with log link.

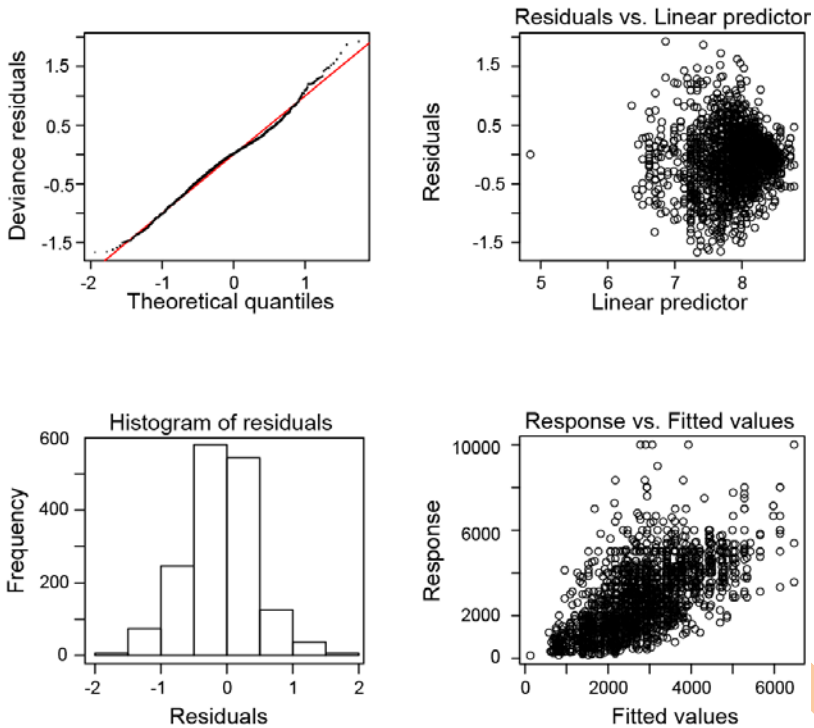


FIGURE A.6. Diagnostic plots for the GAM using CPUE in weight for the Peruvian artisanal fisheries operating in the Southern area (Chimbote-Ilo) during the early period (2003-2010). GAM assumed Gamma distribution with log link.

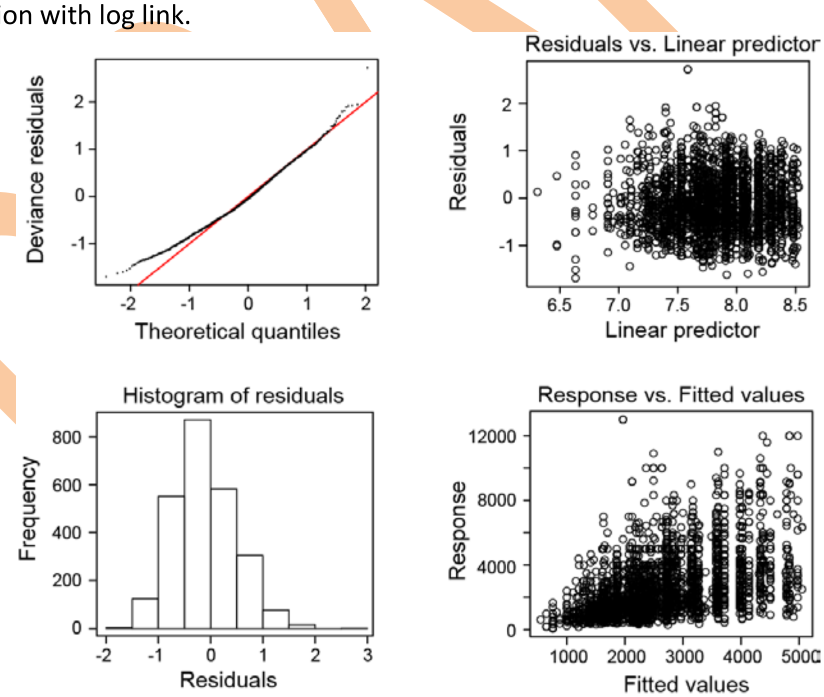


FIGURE A.7. Diagnostic plots for the GAM using CPUE in weight for the Peruvian artisanal fisheries operating in the Southern area (Ilo) during the later period (2011-2014). GAM assumed Gamma distribution with log link.

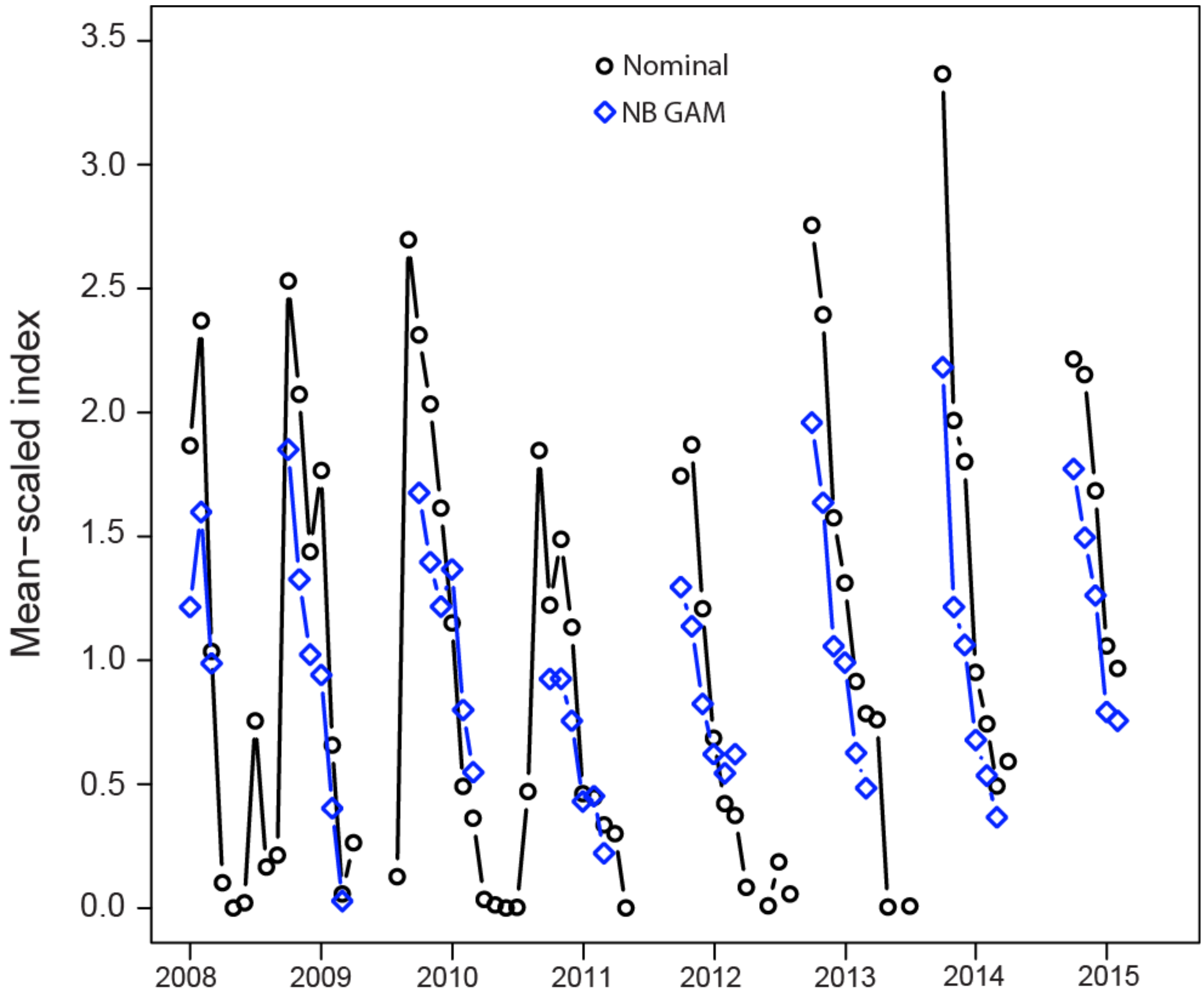


FIGURE A.8. Standardized CPUE from the Negative binomial (NB) GAM for counts of fish caught by Ecuadorian artisanal fisheries (taking into consideration fishing effort). The nominal CPUE are also shown.

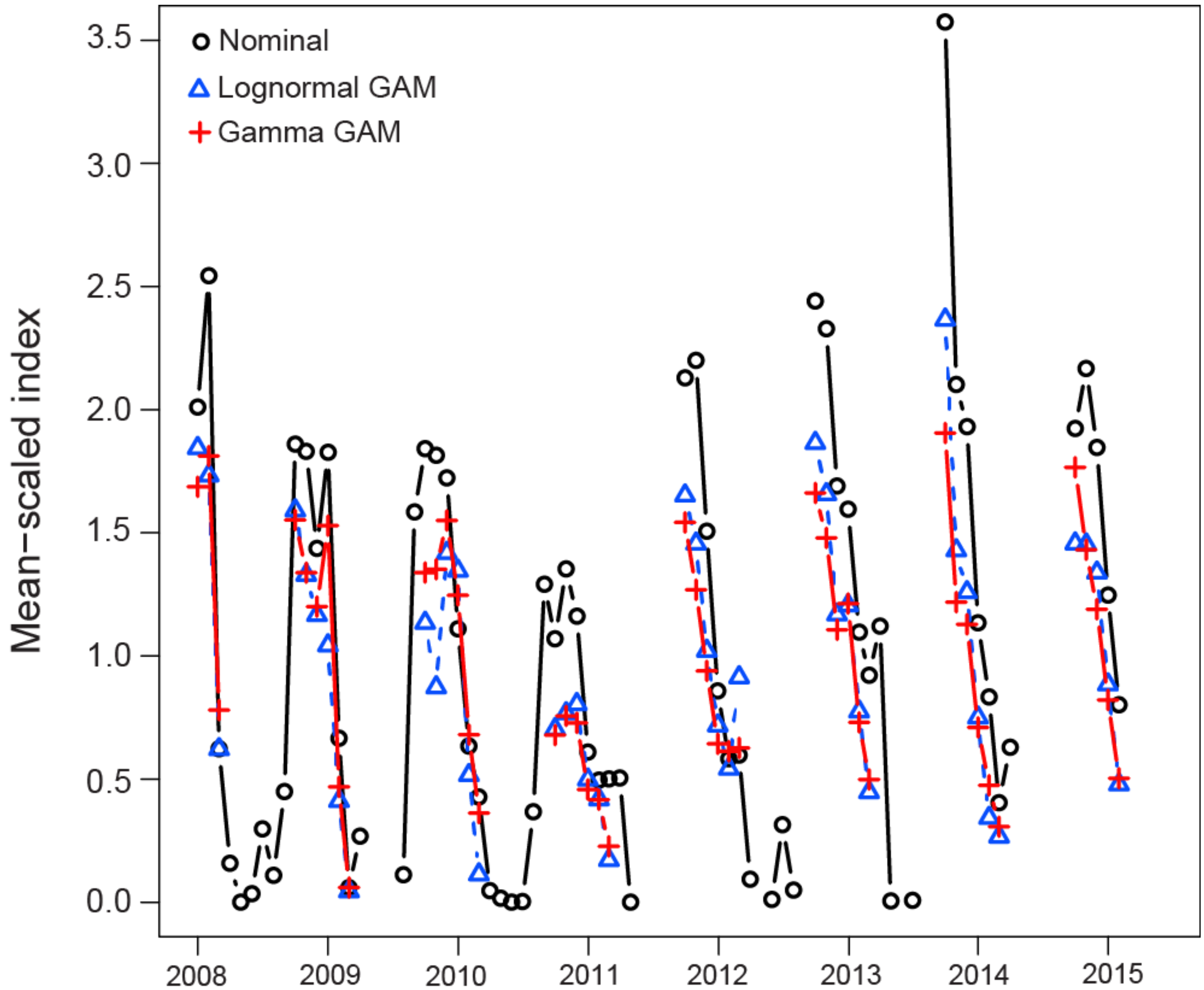


FIGURE A.9. Standardized CPUE from the Lognormal and Gamma GAMs for CPUE in weight of dorado caught by Ecuadorian artisanal fisheries. The nominal CPUE are also shown.

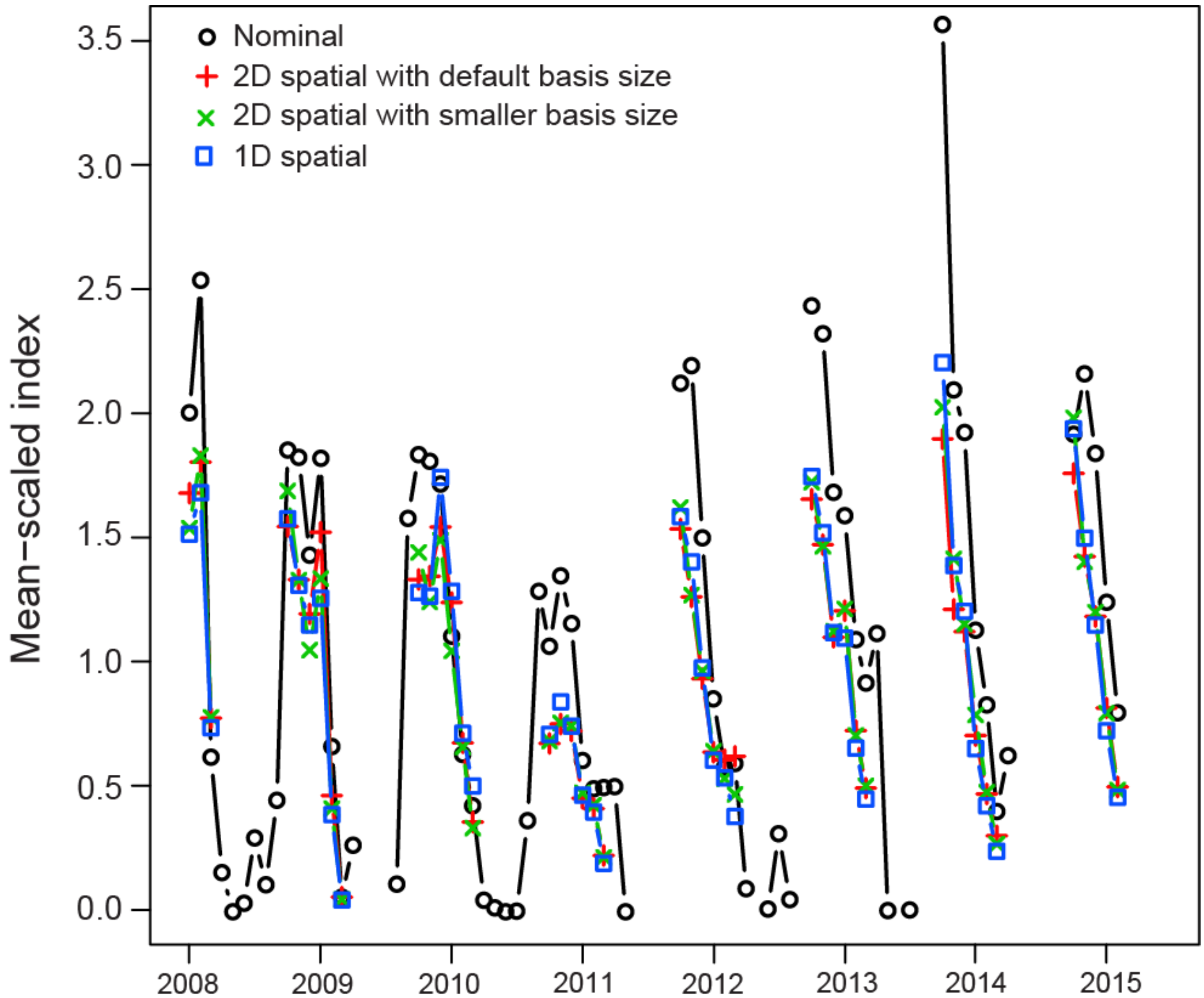


FIGURE A.10. Standardized CPUE from the Gamma GAMs for CPUE in weight of dorado caught by Ecuadorian artisanal fisheries. GAM models with different set up odf spatial terms were used. The nominal CPUE are also shown.

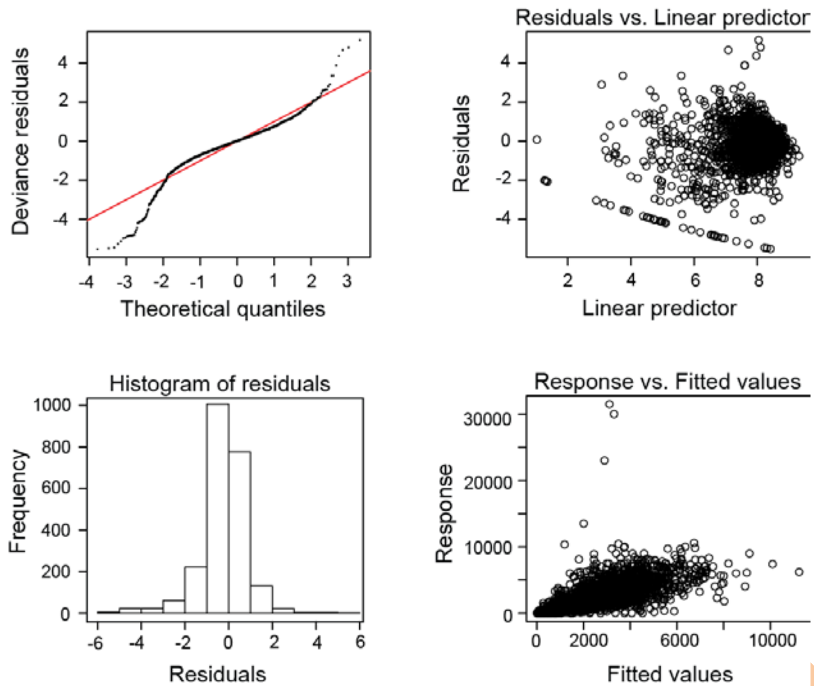


FIGURE A.11. Diagnostic plots for the Negative Binomial GAM for counts of fish caught by Ecuadorian artisanal fisheries (taking into consideration fishing effort).

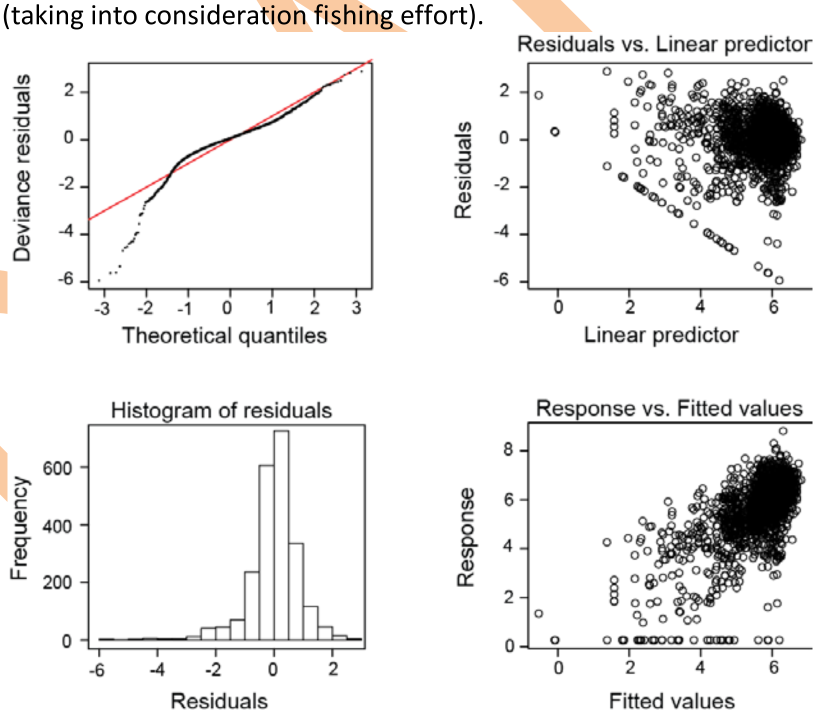


FIGURE A.12. Diagnostic plots for the Lognormal GAM for CPUE in weight of dorado caught by Ecuadorian artisanal fisheries.

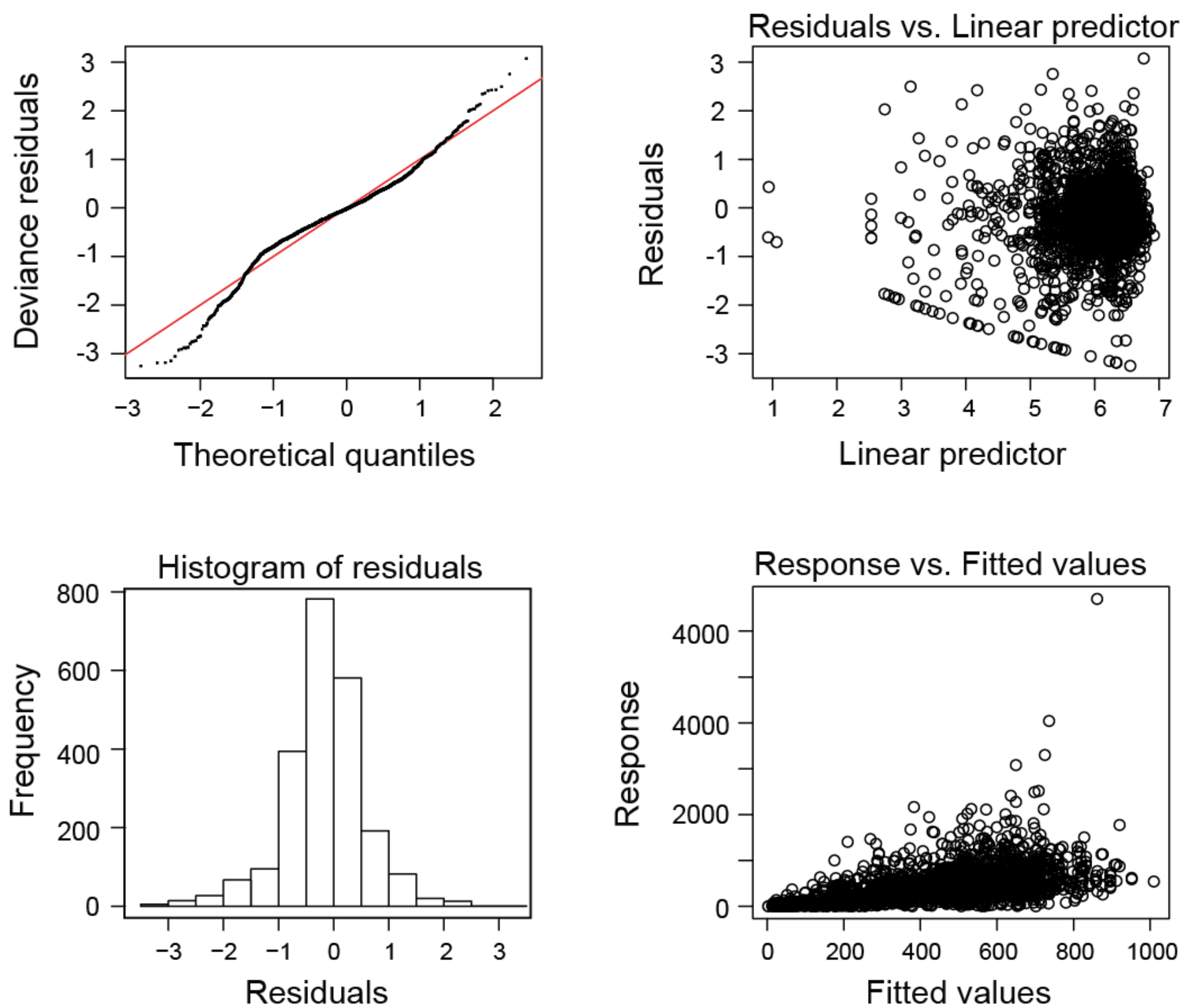


FIGURE A.13. Diagnostic plots for the Gamma GAM for CPUE in weight of dorado caught by Ecuadorian artisanal fisheries.

Appendix B

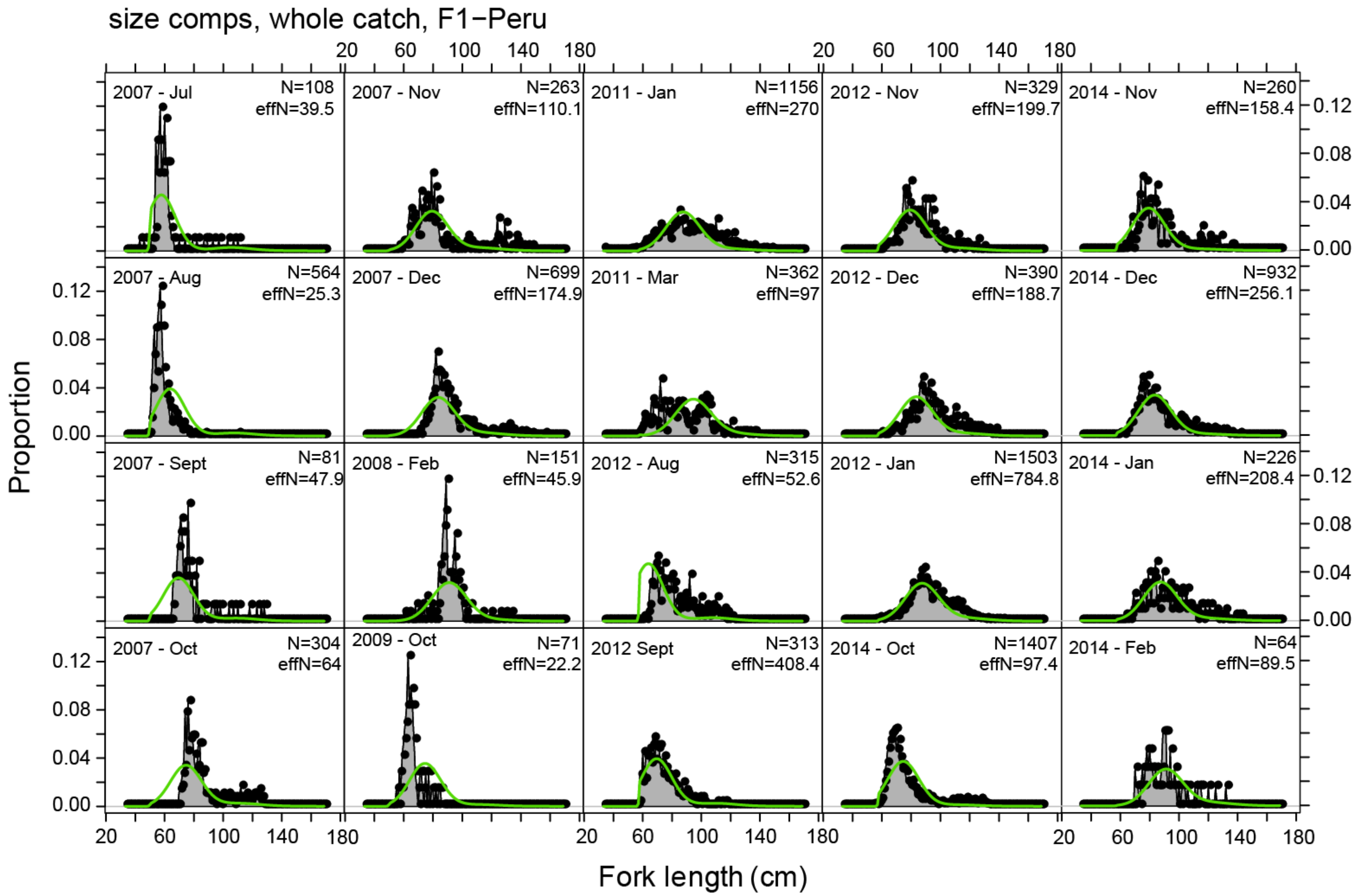


FIGURE B.1. Observed (black dots and grey areas) and predicted (green lines) length compositions of Peruvian artisanal fishery (F1)

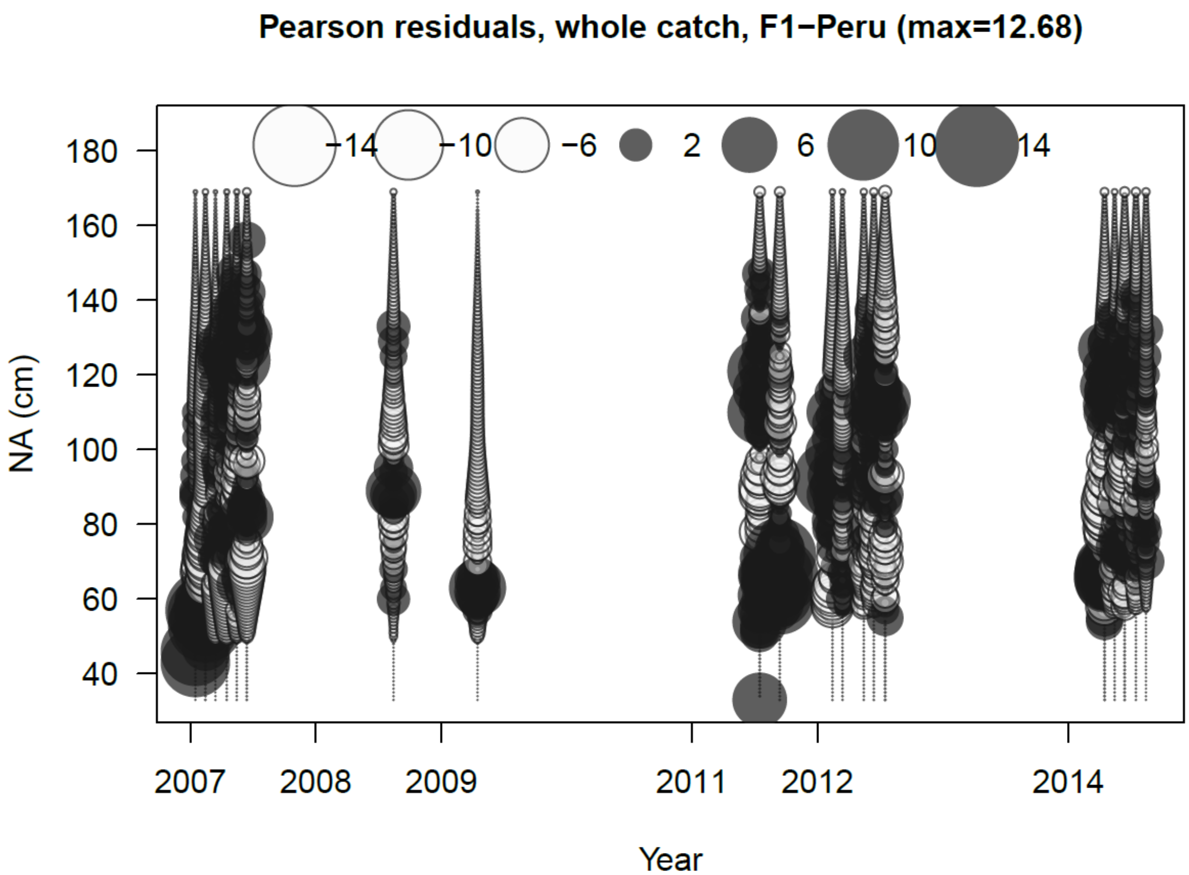


FIGURE B.2. Residuals to the length composition fir to Peruvian artisanal fishery (F1)

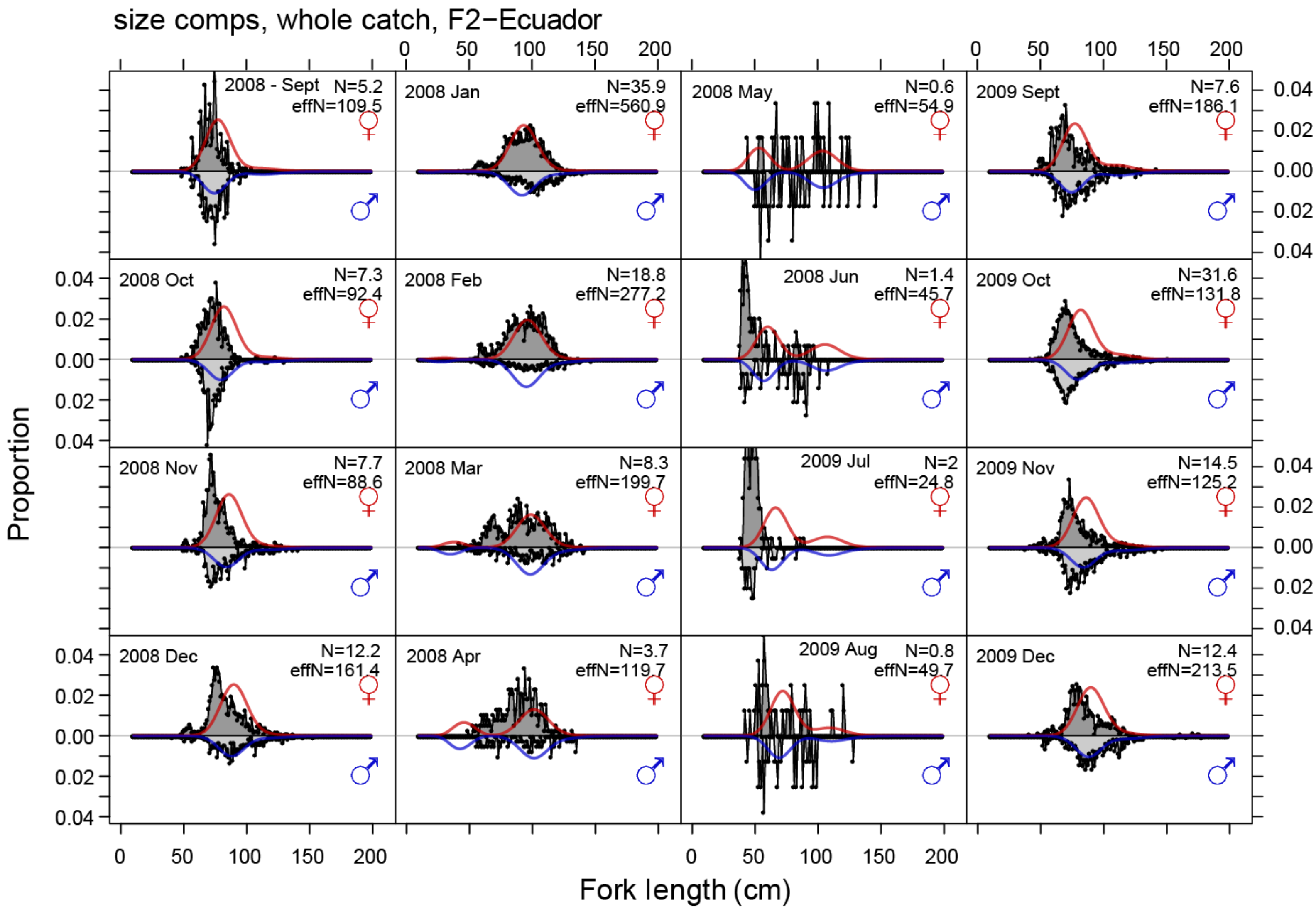


FIGURE B.3. Fit to length composition data by month in the fishery in Ecuador by sex (fit to males in blue lines and below the horizontal line, females in red lines above the horizontal line)

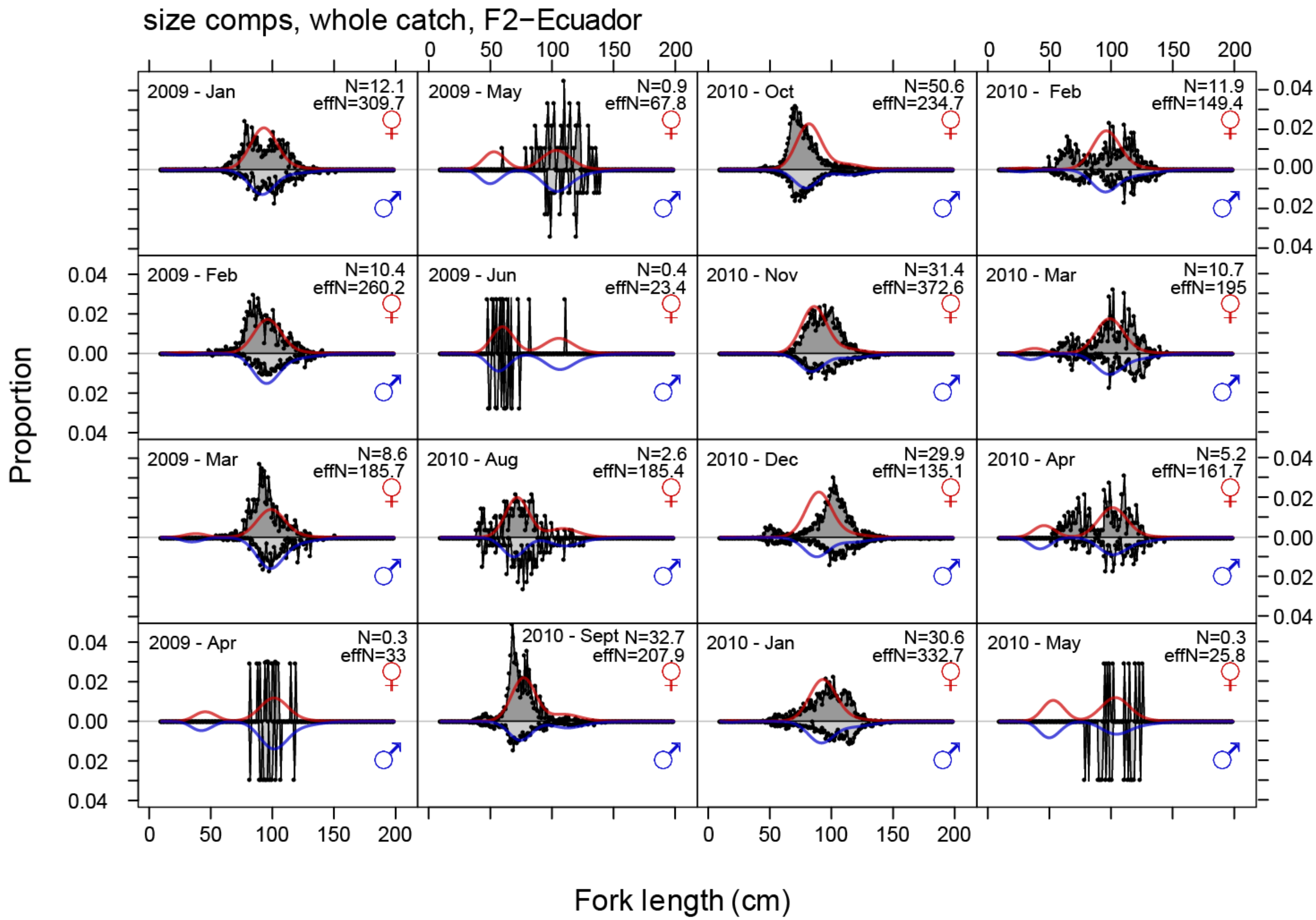


FIGURE B.3 (continued). Fit to length composition data by month in the fishery in Ecuador by sex (fit to males in blue lines and below the horizontal line, females in red lines above the horizontal line)

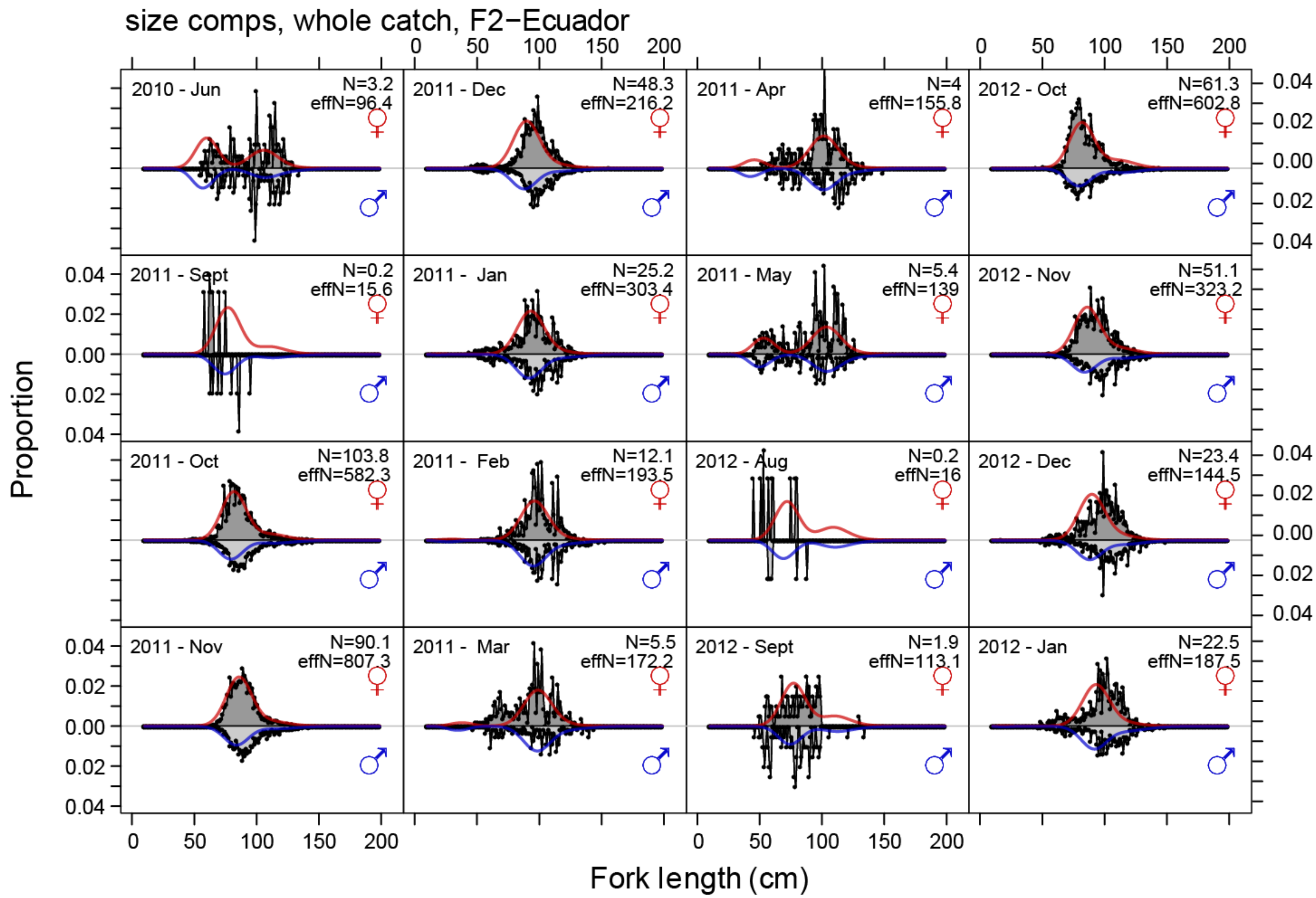


FIGURE B.3 (continued). Fit to length composition data by month in the fishery in Ecuador by sex (fit to males in blue lines and below the horizontal line, females in red lines above the horizontal line)

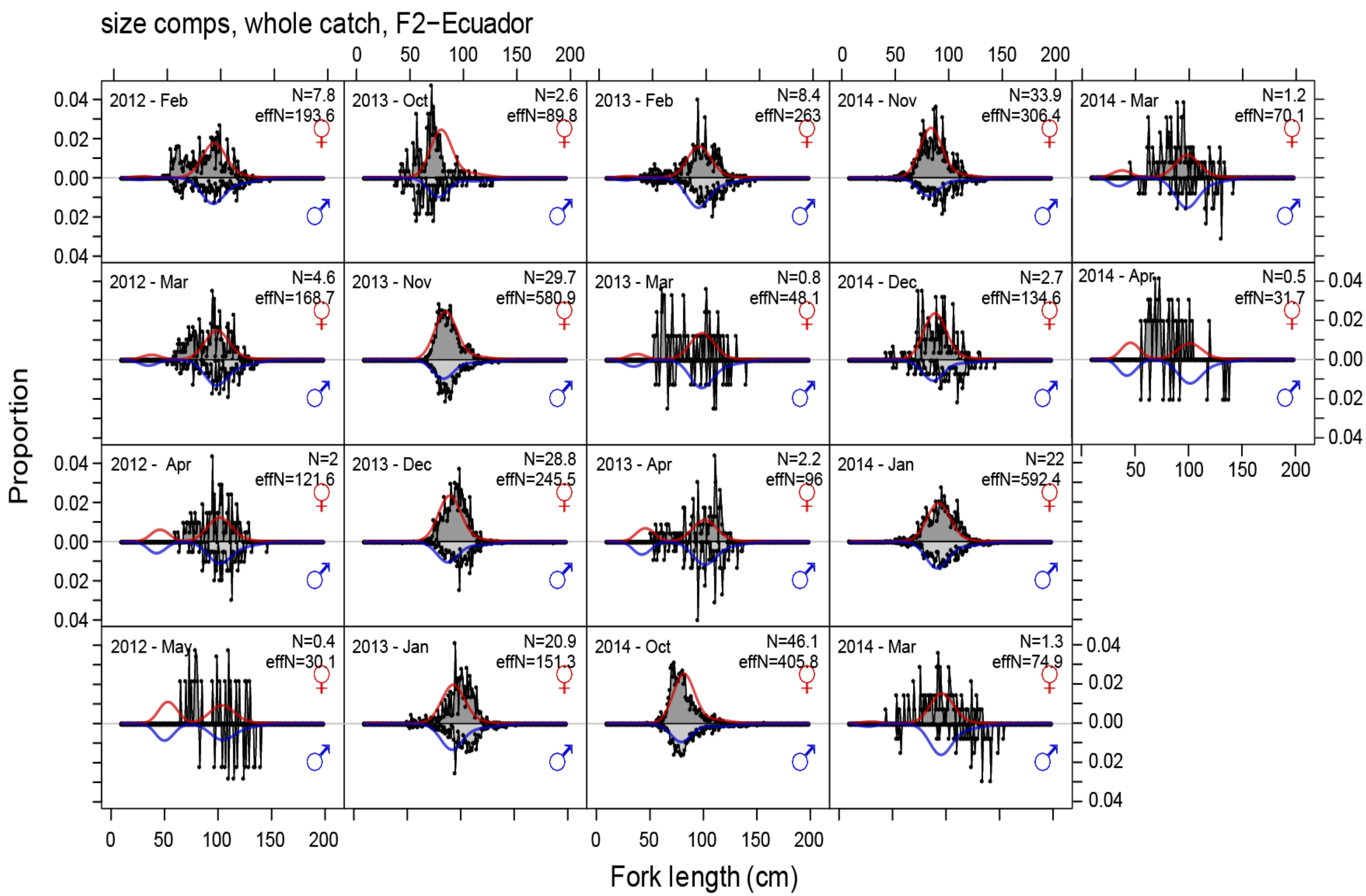


FIGURE B.3 (continued). Fit to length composition data by month in the fishery in Ecuador by sex (fit to males in blue lines and below the horizontal line, females in red lines above the horizontal line)

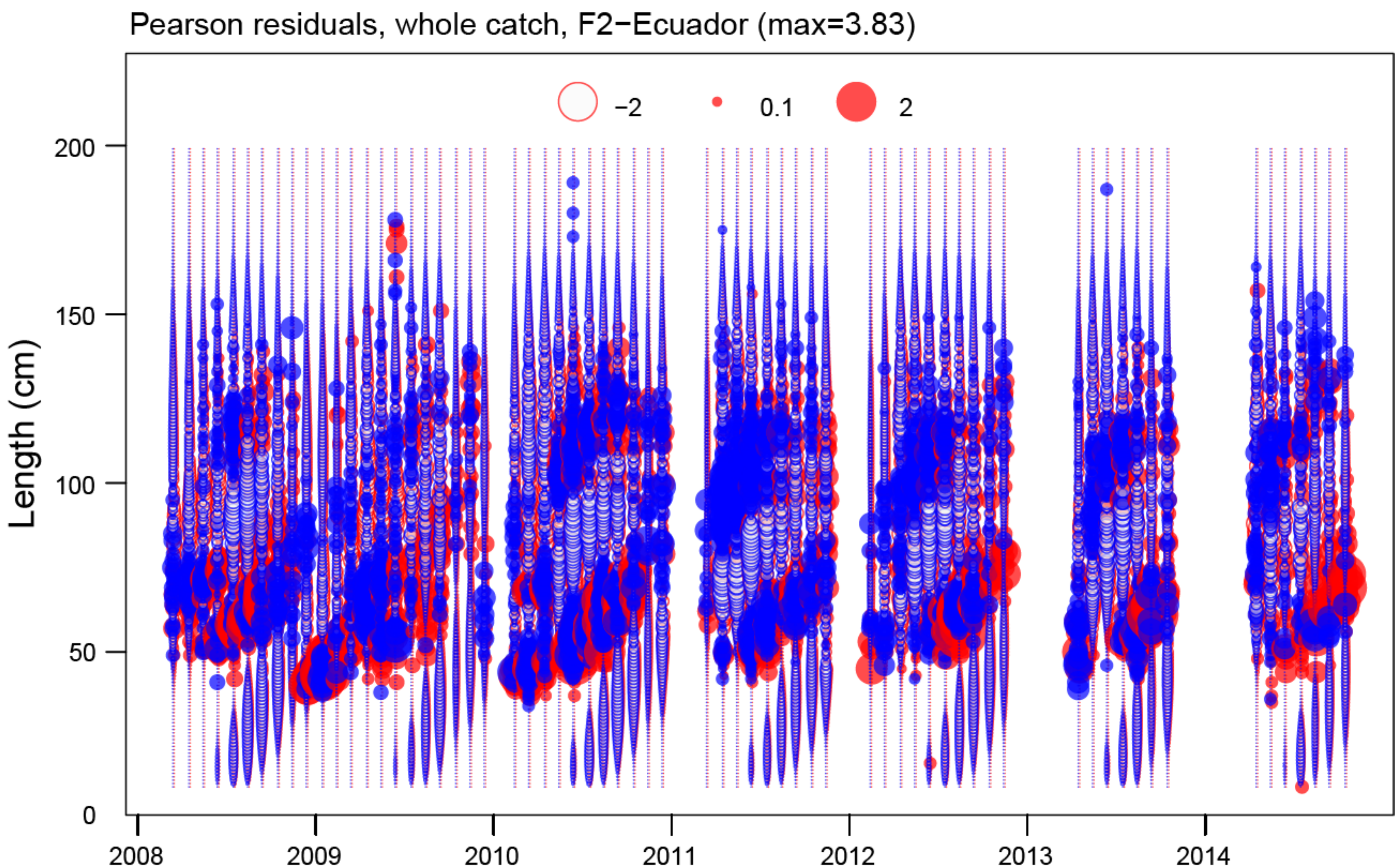


FIGURE B.4. Residuals to the length composition fit to Ecuadorean artisanal fishery (F2) by sex (females in red, males in blue) and month.