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POTENTIAL REFERENCE POINTS AND HARVEST CONTROL RULES FOR DORADO (*Coryphaena hippurus*) IN THE EASTERN PACIFIC OCEAN

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SUMMARY

Dorado is one of the most important species caught in the artisanal and recreational fisheries of the coastal nations of the eastern Pacific Ocean (EPO), representing between 47% and 70% of the total world catches of this species. The IATTC staff, at the request of coastal State Members, facilitated collaborative regional research that resulted in three technical meetings between 2014 and 2016. An exploratory stock assessment for the "core" of the dorado stock (Aires-da-Silva *et al*., 2016) and an exploratory management strategy evaluation (MSE) for the South EPO (Valero *et al*., 2016) were conducted. Available data for dorado in the North EPO are more limited, handicapping the use of conventional stock assessments. The IATTC staff has developed a monthly depletion estimator approach that could be used as a basis for management advice in such data-limited situations if CPUE data are available. In this report we summarize potential reference points and harvest control rules that could be considered for dorado in the EPO.

1. INTRODUCTION

Dorado (*Coryphaena hippurus*) is widely distributed throughout the tropical and subtropical waters of the world's oceans. It is one of the most important species caught in the artisanal and recreational fisheries of the coastal nations of the eastern Pacific Ocean (EPO), from Chile in the south to Mexico in the north. Recent annual catches of dorado in the EPO are around 71 thousand metric tons (t), representing between 47% and 70% of the total world catches of this species. 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[1]. The IATTC staff, at the request of coastal State Members, facilitated collaborative regional research that resulted in three technical meetings in 2014 (IATTC, 2015), 2015 (IATTC, 2016), and 2016. The available data for the South EPO were considered sufficient to conduct an exploratory stock assessment for the "core" of the dorado stock (Aires-da-Silva *et al*., 2016), as well as an exploratory management strategy evaluation (MSE) for the South EPO (Valero *et al*., 2016). The available data for the North EPO are more limited, handicapping the use of conventional stock assessments. The staff also developed a monthly depletion estimator approach (Maunder *et al*., 2016) that could be used as a basis for management advice in such data-limited situations, if CPUE data are available. Although the focus of this report is on potential reference points and harvest control rules for dorado, they cannot be considered by themselves without understanding other elements of management system, such as population assessments and harvest strategy that are either in place or alternatives that can be considered. A brief summary of the exploratory stock assessment, exploratory MSE and monthly depletion work is provided in the following sections as context for the discussion of potential reference points and harvest control rules for dorado in the EPO.

1.1. Exploratory stock assessment of dorado in the South EPO

An exploratory stock assessment (Aires-da-Silva *et al*., 2016) was conducted for dorado in the South EPO, considered to be 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 was implemented in Stock Synthesis (SS) with a monthly time step for the years 2007 to 2014, fitted to sex-combined length-composition data from Peru and purse-seine bycatch and sex-specific length-composition data and CPUE from Ecuador. The monthly time step allowed depletion caused by catches (from Peru and Ecuador, and the purse-seine bycatch) and measured by the CPUE to inform the estimates of absolute abundance. This work synthesized the knowledge about the population dynamics of dorado and its history of exploitation in the South EPO, without drawing conclusions about stock status, because no reference points, target or limit, have been defined for dorado in the EPO. Nonetheless, some management quantities were presented and discussed for consideration. Results showed that recent catches were near the estimates of maximum sustainable yield (MSY[2]) from the stock assessment, and that the yield per recruit (YPR) curve was very flat, with the fishing mortality required to achieve MSY poorly defined.

1.2. Exploratory MSE of dorado in the South EPO

A simplified version of the SS model used for the exploratory assessment (Aires-da-Silva *et al*. 2016) was used as the operating model for the MSE (Valero *et al*. 2016). The exploratory work focused on testing the current management strategy, which is based on seasonal closures, and alternatives including different monthly fishery closures and openings, size limits for the fish in the catch, and discard mortality rates. Population and fisheries dynamics were projected for 2015-2019 under the alternative harvest strategies and discard mortality rates. The alternative harvest strategies were also evaluated retrospectively for 2007-2014. YPR analyses were conducted to describe expected YPR and spawning biomass ratio (SBR[3]) as a function of age of entry to the fishery and annual fishing mortality (F). There were tradeoffs between

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[1] Note: the ongoing Marine Stewardship Council certification assessment process for the longline fishery for dorado in Ecuador announced in February 2019 that, since there are no reference points available to assess the target stock status, the assessment will follow a risk-based framework (MSC, 2019).

[2] 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 recruitment maintained at average levels

[3] The ratio of the current spawning biomass to that of the unfished stock (S_{current}/S_0)

SBR and yield for strategies based on alternative season openings, closures, and minimum size limits with different assumptions regarding discard mortality rates of undersized fish. Alternative season closures and openings have similar general effects on SBR and total yield; later season openings, however, increase SBR without marked reductions in expected yield, while earlier closures increase SBR but at the expense of reduced catch. YPR analyses showed that the age of entry that will produce the maximum YPR is around 10 months, based on the annual *F* estimated by the assessment. That would mean that a fishery opening around October-November would be consistent with YPR considerations. The age of entry consistent with maximum YPR would be higher at *F* higher than those estimated by the exploratory assessment. SBR is expected to increase with minimum size limits, while yield is expected to increase with no or moderate discard mortality and to decrease with greater discard mortality. Under assumed moderate discard mortalities, increasing minimum size limits is expected to result in increased SBR, but at the expense of reduced yield.

1.3. Monthly depletion estimator

The data available for the North EPO are more limited, hampering the use of conventional stock assessments. Maunder *et al*. (2016) developed a depletion estimator that uses monthly catch and CPUE to estimate absolute abundance and depletion. This approach consists of simple models of advancing complexity, from a simple log-linear regression of within-year monthly CPUE, similar to a catch-curve analysis, to a monthly depletion estimator that has several modifications similar to those used in the full integrated SS model.

2. REFERENCE POINTS: METRICS AND DERIVATION

There is a large variety of reference points, which can be divided into several categories depending on their metric (*e.g.* biomass, fishing mortality, empirical), derivation (*e.g.* estimated by models, proxies) and other factors. Valero *et al*. (2017) reviewed reference points and harvest control rules for marine resources and their applicability to tunas and billfishes; here we summarize those we consider relevant for dorado in the EPO.

2.1. Biomass reference points

Biomass reference points can be used as a benchmark to evaluate whether a stock is overfished. Although different biomass quantities can be estimated for a stock (*e.g.* total, mature, vulnerable, spawning including both sexes, female spawning biomass), typically female or total spawning biomass is the metric that is used for reference points. The justification is that spawning biomass is more directly related to recruitment, and limit reference points are often defined in terms of reduced recruitment. Since management actions do not directly control biomass, stock biomass relative to biomass reference points is typically used to trigger management actions that affect catch limits, fishing effort or *F* (Sainsbury, 2008). There are several alternative biomass reference points (Table 1), and their use has varied around the world. For two tropical tuna stocks (bigeye and yellowfin), the IATTC staff evaluates stock status on the basis of calculations based on spawning biomass and MSY estimated by annual integrated stock assessment models (benchmark assessments approximately every three years, update assessments in the intervening years). The exploratory stock assessment of dorado (Aires-da-Silva *et al*., 2016) estimated biomass and MSY-related quantities. SBR can be considered as a *static* quantity (*s*SBR), since it is related to the unfished equilibrium status of a stock, or as *dynamic* quantity (*d*SBR), computed as the ratio of the spawning biomass at the start of the spawning season with fishing to that without fishing (Wang *et al*. 2009).

In the base-case exploratory stock assessment model for dorado (Aires-da-Silva *et al*., 2016), *s*SBR was computed as the ratio of the spawning biomass in a given year to that of the unfished stock, both measured at the start of the spawning season (November). The *s*SBR estimates were quite stable over the assessment period, averaging about 0.20 (Figure 1), which coincides with the base-case estimate of the sSBR corresponding to the MSY (*s*SBR_{MSY}; Table 3). Using the dynamic method (*d*SBR) produced higher estimates than the *s*SBR (Figure 2). The 2016 exploratory model base-case estimate of the MSY of dorado in the South EPO was 89,211 tonnes (t), which is above the maximum recorded total annual catch of about 76,000 t (Aires-da-Silva *et al*., 2016). However, because the yield curve is flat, the *F* needed to achieve MSY was estimated as three times the current *F* (see next section). Estimates of MSY and SBR are sensitive to model assumptions about natural mortality (*M*), catchability and selectivity (Table 3).

2.2. *F*-based reference points

Although the biological processes relevant to stock productivity and sustainability are more related to stock biomass (and its relationship to abundance and density), *F* (and its relationship with catch or fishing effort limits) is more directly under management control than biomass. Biomass may also fluctuate in part due to factors beyond management control, such as environmental influences on processes such as recruitment, natural mortality, and growth. There is a variety of alternative *F* reference points (Table 2) and their use has varied around the world. For example, the US National Standards requires that *F* for each fish stock must not exceed F_{MSY}, which is a limit reference point, in contrast F_{MSY} is the target reference point established by the IATTC for tropical tunas.

The yield curve resulting from the YPR analysis for dorado (Aires-da-Silva *et al*. 2016) is very flat-topped, and the *F* that maximizes the YPR (F_{MAX}) is three times higher than the current *F* (*F* multiplier ≈ 3) (*Figure 4*). A fishing strategy aimed at maximizing YPR is not recommended, since increasing *F* by a factor of three would result in small gains in yield. A range of proxies and alternatives can be used if F_{MAX}, F_{MSY} or MSY cannot be reliably estimated. For example, ICES sets limit reference points for *F* by selecting a precautionary limit reference point (F_{pa}) that is expected to result in a very low probability of exceeding the intended *F* limit (F_{lim}) when taking into account estimation uncertainty (ICES, 2003). There are other possibilities, such as $F_{0.1}$ (the *F* corresponding to 1/10th the slope of the YPR curve at the origin) and *F* = x%*M* (*F* set at x% of *M*), depending on the data and analyses available (Table 2). The exploratory dorado assessment (Aires-da-Silva *et al*. 2016) estimated an annual *F* of between 0.53 and 0.85 during 2007-2014, while *M* was assumed to be 1. Alternative levels of *F* would affect the timing and length of the fishing season (Figure 5), a component of current dorado fisheries management in the EPO.

2.3. Empirical reference points

Although biomass- and *F*-based reference points can be related to population and fishery processes by formal rationales, they are not measured directly, but are estimated using models. Stock assessment models can be mis-specified and/or biased (Maunder and Piner, 2015), with potential impacts on the reliability of estimated reference points (Hilborn 2002). Empirical reference points focus on quantities that can be more or less directly measured, such as catch, fishing effort, catch rates, fishing season length, size of the fish in the catch (*e.g.* average fish length or a percentile value), spatial range of the stock or habitat use (*e.g.* spawning locations), and sex ratio (Sainsbury 2008, Clarke and Hoyle 2014). The appeal of empirical reference points is not only that they are derived from more direct observations/estimation than those based on *F* or biomass, but also in that they are easily understood and communicated, and are, in theory at least, logistically simpler to implement. However, one difficulty with using empirical reference points is the rationale for their construction. Intuitively, limit reference points based on historical quantiles (for example, the lowest CPUE, or the 5% percentile of CPUE levels) might be reasonable if the stock recovered from those levels. However, the lowest historical CPUE or highest *F* may have occurred in only a few years, or in particular environmental conditions that allowed recovery, and may be inappropriate in other years. Targets could be based on the estimated CPUE of the fishery when it was healthy, or on social, economic or other factors: for example, a limit reference point could be based on CPUEs that are unprofitable, or a target reference point on CPUEs that maximize profits.

The only extant stock assessment of dorado in the EPO is the exploratory study by Aires-da-Silva *et al*. (2016), and that is for the South EPO only; therefore, empirical reference points are of interest. The next two sections focus on two possibilities based on data available for most dorado fisheries: longline CPUE and fish size.

2.3.1. CPUE

Catch rate is a basic indicator in fishery management, used typically as an index of stock abundance within a stock assessment model. However, it has been used as the basis for empirical reference points: reference points have been based on commercial catch rates for New Zealand rock lobster (Starr *et al*., 1997) and Australian toothfish (Tuck *et al*. 2001), while survey catch rates at fixed locations during a historical period considered sustainable have been the basis for abalone reference points (Worthington *et al*. 2002). Punt *et al*. (2001) evaluated alternative empirical reference points, including catch rates, for Australian swordfish, and found that they do not perform well, by being either too sensitive or not sensitive enough to changes in stock levels. An alternative decision rule for the same swordfish stock (Davies *et al*. 2007) was shown to be robust to incorporating a hierarchical decision approach to identify management actions given processes behind the change in the empirical indicators (*i.e.* growth, recruitment or fisheries dynamics). Also in Australia, catch rate thresholds were used to trigger management actions for low-value or data-poor stocks (Dowling *et al*. 2008). The IATTC staff proposed using standardized catch rates for purse-seine sets on floating object to assess and manage silky sharks (Aires-da-Silva *et al*. 2014), and other indicators of stock status for skipjack (Maunder, 2017), bigeye (Maunder *et al*. 2018) and yellowfin (Minte-Vera *et al*. 2019) tunas, some of which might inform the development of alternative empirical reference points.

Monthly CPUE data from longline fisheries for dorado throughout the EPO are either available, or could be relatively easily collected, for use as the basis for reference points. The longline artisanal fishery in Ecuador mainly exploits a single cohort of between about 10 and 16 months of age from October to April (Aires-da-Silva *et al*. 2016); therefore, the monthly longline CPUE represents the relative abundance, in numbers, of the cohort in that month. This is similar to catch-curve analysis, but uses CPUE rather than proportion-at-age in the catch to measure the relative abundance of a cohort as it ages during the year. Maunder *et al*. (2016) used monthly longline CPUE data from Ecuador to illustrate the use of a monthly depletion estimator. During fishing years (July to June) 2009-2013, monthly CPUE decreased from maximum values in October to minimum values in April[4] (Figure 6), when they were on average 0.126 of their October value (Table 4), ranging from 0.048 in 2009 to 0.267 in 2011 (Table 4). However, CPUE would be expected to decrease substantially even without fishing, given the high M of dorado: for example, CPUE in April would be 0.6 of its value in October if M = 1 year^{-1} (the M assumed in the base case 2015 dorado assessment, Aires-da-Silva *et al*., 2016) and no fishing (Figure 6). Recalculating the reduction as a ratio to the expected reduction in the absence of fishing during 2009-2013 resulted in a reduction to 0.208 with M = 1 year^{-1}, 0.343 with M = 2 year^{-1}, and 0.162 with M = 0.5 year^{-1} (Figure 7; Table 5).

2.3.2. Fish size

Punt *et al*. (2001) evaluated alternative empirical reference points for Australian swordfish, including catch rates, percentiles of the distribution of fish length in the catch, and percentiles of the distribution of fish weights in the catch. Critical weight[5] has been used by the staff in its Stock Assessment Reports; it is compared to the average weight in the total catch and the average weight in each fishery, as predicted

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[4] Other months, when the fishery is not fully targeting dorado, were not included in this analysis

[5] The weight corresponding to the critical age (the age at which the gains from growth balance the losses from natural mortality, and the yield from the fishery is thus maximal)

by the stock assessment model (Maunder, 2003). Stock indicators based on the size of the fish in the catch relative to size at maturity, optimum size for maximizing yield, and conservation of large individuals (Cope and Punt, 2009), have been used for Atlantic skipjack tuna (ICCAT, 2014).

The Ecuadorian length-composition data show the clear dominance and progression of a single cohort of dorado over the months of each fishing year (Aires-da-Silva *et al*., 2016). The smallest sizes of dorado (40-60 cm FL) are recruited to the fishery as early as June-July, and this new cohort is then targeted by the fishery until the end of the fishing season around March-April. The mean length of the fish in the catches gradually increases as the fishing season progresses and the fishery targets a single cohort growing in size (Aires-da-Silva *et al*., 2016). The mean size of the fish in the catches drops sharply at the end of the fishing season, as the recruits of the following cohort enter the fishery. Since 2011 in Ecuador and 2014 in Peru, the fishery has been closed from May through October. The short lifespan of dorado, and the annual nature of its population dynamics, complicate the use of mean size of the fish in the catch as a potential reference point.

3. REFERENCE POINTS: BENCHMARKS FOR MANAGEMENT

Reference points, regardless of their type and method of calculation, are benchmarks used to determine the status of fish stocks relative to desirable and undesirable states, defined by target and limit reference points, respectively. Various other reference points, such as threshold/trigger points (intermediate states that may require additional management action) and rebuilding targets (for depleted stocks), are available to management (for example, Valero *et al*., 2017), but these are not currently relevant to dorado.

3.1. Target reference points

Target reference points (TRPs) reflect the explicit or implicit economic, social or political objectives of the fishery; therefore, managers and stakeholders typically have a role in identifying candidate TRPs related to management objectives. Generally, the management objectives of the regional fisheries management organizations for tunas (t-RFMOs) are based on "optimal utilization" or "long-term conservation and sustainable use" (Anonymous, 2015), so TRPs are usually around levels of F that achieve high yields or high catch rates, while avoiding limit reference points (LRPs). At a workshop sponsored by the International Seafood Sustainability Foundation (ISSF) in 2013, there was considerable discussion on whether F_{MSY} should be considered a target or a limit reference point (Anonymous, 2013). The consensus was that, if there is little or no quantitative analysis of uncertainty, F_{MSY} should be used as an LRP, although both it and B_{MSY}[6] are used as a TRP or an LRP in some cases (*e.g.* tropical tunas at IATTC, IOTC). If uncertainty is well quantified, the use of F_{MSY} as a TRP has potential, with appropriate considerations of risk; however, if there is little or no quantitative analysis of uncertainty on their incorporation in HCRs, or where F_{MSY} is determined assuming perfect knowledge, F_{MSY} has been recommended for use as an LRP (Anonymous, 2015). Following this rationale, a precautionary buffer should be considered between F_{MSY} and target F. On the other hand, in most situations, using F_{MSY} as an LRP is expected to be very cautious, because F_{MSY} is not usually associated with being beyond biologically safe limits. Given recruitment variability and steepness assumptions, a potentially large range of biomass levels could be expected at F_{MSY}, so whether F_{MSY} should be considered an LRP or a TRP should probably be decided individually for each case (Anonymous, 2015).

At present, no target reference points have been established for dorado in the EPO. The level of specificity in management objectives for dorado fisheries varies greatly across the region. Ecuador (SRP-MAGAP, 2013) and Peru (PRODUCE, 2016) have management plans in place, with the general objective of "*ensuring the conservation and sustainable use*" of dorado in their jurisdictional waters. Although there is no explicit

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[6] The stock biomass (B) capable of supporting the maximum sustainable yield (MSY)

mention of MSY in either plan, and although management so far has been based on actions at the national level, management of other species in the EPO, such as tropical tunas, has used TRPs based on B_{MSY} and F_{MSY} (IATTC, 2016b). The 2015 exploratory assessment (Aires-da-Silva *et al*., 2016) estimated that annual catches of dorado in the South EPO, with a recorded maximum of about 76,000 t, had been below the estimated MSY of 89,211 t, while the SBRs (both static and dynamic) were quite stable over the assessment period, averaging between 0.20 and 0.25 (Figure 1 and Figure 2) which is near the base case model estimates of SBR_{MSY} (Table 3). If TRPs based on MSY were considered for dorado in the EPO, there is the issue of how to determine both the TRPs and the corresponding estimates (either *F* or biomass) to be compared to the TRP to determine status. Unlike the tropical tunas, with their benchmark assessments about every three years (for bigeye and yellowfin; skipjack is dependent on bigeye) and update assessments in between, there has been only one initial exploratory assessment for dorado, and only for the South EPO (Aires-da-Silva *et al*., 2016), and it has not been repeated nor updated since then. Each year the dorado fisheries focus on mainly one cohort that passes through the population and fisheries, leaving almost nothing of that cohort for the following year. Aires-da-Silva *et al*. (2016) used data up to the end of 2014, which means that by the time the study was presented at SAC-07 in May 2016, very few, if any, of the fish from the 2014 cohort were still alive. In view of the fast dynamics and variability of the dorado stock (almost an annual species), its fisheries (fisheries from adjacent countries may have diametrically opposed landings in the same year) and its ecological environment (CPUE influenced by oceanographic conditions (Martínez-Ortiz, 2015; Torrejón-Magallanes, 2018), additional and updated analyses are essential.

If TRPs were to be based on YPR considerations, it would be more appropriate to use $F_{0.1}$ (the fishing mortality corresponding to 1/10th the slope of the YPR curve at the origin) than $F_{MSY,}$ given the flatness of the production curve (Figure 4). Other alternatives, such as $F = x\%M$ (*F* set at x% of *M*), are possible, as are others based on data and analyses available in different countries or regions (Table 2).

TRPs could also be based on empirical considerations, such as a level of CPUE reduction relative to CPUE at a fixed date at the beginning of the season, either total reduction (Figure 6, Table 4) or reduction relative to that expected with no fishing (Figure 7, Table 5).

3.2. Limit reference points (LRPs)

Limit reference points are intended to reflect the biological limits to sustainable exploitation. Therefore, it is a role of scientists to identify, and provide objective advice on, candidate LRPs, taking into account undesirable processes such as impaired recruitment and depensation (disproportionally large negative impacts on stocks at low abundance). However, in some cases the LRP could also be set based on socio-economic factors such as catch rates that are unprofitable. Ideally, stocks should be managed so that there is a very low (but not zero) probability that the LRP will be reached (Clarke and Hoyle, 2014); however, the probability should not be too low, because estimates of probabilities at the tail of the distribution are notoriously uncertain. Risks and management actions associated with approaching or reaching an LRP should be recognized, discussed and agreed, even if an LRP has not been reached.

Myers *et al*. (1994) evaluated alternative spawning biomass LRPs for 71 stocks, and defined recruitment overfishing as seriously reduced recruitment. While warning that no method performed well in all circumstances, so generalization was difficult, they recommended a biomass LRP of $50\%R_{max}$ (biomass associated to 50% of the maximum predicted average recruitment). This often corresponds to very low limit spawning biomass levels, from 10% to less than $5\%B_0$, for a broad range of life histories (Myers *et al*. 1994); for bigeye and yellowfin in the EPO it corresponds to $7.7\%B_0$ (assuming a stock-recruitment steepness (*h*) of 0.75; Maunder and Deriso, 2014). Sainsbury (2008) argued that, although the spawning biomass corresponding to $50\%R_{max}$ is understandably a limit to be avoided (*e.g.* FAO definition of a recruitment overfished stock showing a significantly reduced average recruitment), it would set the LRP at a level where the stock impact has already occurred. Other management bodies (*e.g.* ICES 2003) have taken a more conservative approach, defining a spawning biomass LRP such that average recruitment is not reduced, instead of 50% reduced as in 50%R_{max} (Sainsbury, 2008). The origin of 20%B_0 as a commonly used LRP to define overfished stocks can be traced to the 1980s (Beddington and Cooke, 1983). The rationale behind it was to avoid driving stocks to levels low enough to cause severe, perhaps irreversible, damage to biological processes that would jeopardize the long-term sustainability of the stock. Myers *et al*. (1994) analyzed 20%B_0 as an LRP and found it a reasonable limit for recruitment overfishing under the definitions used by ICES (2000) and Cooke (1984), given that it corresponds to a small reduction in recruitment. Myers *et al*. (1994) mostly used productive stocks for their work; later work (Mace *et al*., 2002) found that a more appropriate limit for less productive stocks is 30%B_0. The study by Preece *et al*. (2011) was the basis for the WCPFC implementation of LRPs of 20%B_0 limit, which refers to both Beddington and Cooke (1993) and Myers *et al*. (1994). In New Zealand, the use of 20%B_0 as an LRP affects the definition of B_{MSY}, requiring that stocks not fall below 20%B_0 more than 10% of the time under an MSY harvest strategy (Sullivan *et al*., 2005). This results in a biomass TRP higher than that calculated from yield curves alone.

The primary concern about a stock being below 20%B_0 is reduced recruitment. Except for stocks with the lowest steepness values, significant loss of yield is not expected at that level; in fact, the yield at 20%B_0 is very close to the MSY for most fish stocks. For example, Thorson *et al*. (2012) found that B_{MSY} ranged from 26–46%B_0 for a range of 147 stocks, with SB_{MSY}/SB_0 values lower for Clupeiformes and Perciformes and higher for Gadiformes and Scorpaeniformes. For tuna stocks assessed by the IATTC staff, SB_{MSY}/SB_0 is about 0.21 for bigeye and 0.27 for yellowfin (Valero *et al*., 2017); for dorado, the 2015 assessment (Aires-da-Silva *et al*. 2016) estimated SB_{MSY}/SB_0 = 0.20 (Table 3).

Other possible concerns about lower stock sizes are depensation, recruitment declines, distributional changes or ecological shifts. Some of the more serious potential effects can be depensatory if stocks are reduced to abundances low enough that survival and/or recruitment are affected in a manner that is not proportional to the reduction in abundance or density, for example by interfering with the chances of finding mates (Allee effect; see Liermann and Hilborn, 2001), increased predation on offspring at the same level of predation pressure (Liermann and Hilborn, 2001), or niche invasion by other species (Utne-Palm *et al.*, 2010). Several studies have explored the evidence for depensatory mechanisms in recruitment across a wide range of stocks (see review by Valero *et al*., 2017). In summary, stocks that have been driven to low abundance almost always recovered when fishing pressure is reduced, as predicted by non-depensatory models. There is also evidence that stock productivity is commonly impacted by changes in environmental regimes (Vertpre *et al*. 2013). Although there is evidence that some stocks, such as Pacific bluefin tuna (ISC, 2016), can rebuild from very low abundances (less than 1%B_0), there are very few populations with data suitable for depensation studies, so depensation at such low stock sizes cannot be ruled out (Hilborn *et al.*, 2014).

In summary, there is no conclusive evidence supporting any particular level of spawning biomass reduction as an appropriate LRP, for dorado or any other species, so any LRP is at least partially arbitrary. If LRPs for dorado, and the population estimates and status determinations from those LRPs, were based on stock assessments, considerations similar to those mentioned for TRPs apply (lack of updated assessments or plans for conducting them regularly). LRPs could be based empirically, on the lowest historical within-year CPUE reduction, for example. A percentile such as the lowest 5% could also be considered, except that, at present, monthly CPUE data are available for only a few years (2008-2013).

4. HARVEST CONTROL RULES

Harvest control rules (HCRs) specify a pre-agreed course of management action as a function of identified stock status and other economic, societal or environmental conditions, relative to agreed reference points

(Berger *et al*., 2012). HCRs may have associated reference points (for example, specifying different levels of fishing mortality for different states of the stock relative to reference points (*e.g.* Restrepo and Powers, 1998)), or not (for example, specifying different levels of *F* depending on trends of stock indicators (*e.g.* southern bluefin tuna; Hillary *et al*., 2015). Formal implementation of HCRs by tuna RFMOs has been limited: they include the empirical HCR of the CCSBT Management Procedure for (Hillary *et al*., 2015) and the HCR for tropical tunas (yellowfin, bigeye and skipjack) adopted by the IATTC in 2016. A recent review of global tuna stocks relative to Marine Stewardship Council criteria (Powers and Medley, 2016) found that well-defined HCRs have been implemented for only three (IATTC yellowfin, bigeye, and skipjack) of the 19 stocks of tropical and temperate tunas, although HCRs are at different stages of development and adoption for individual fisheries across the other RFMOs (Anonymous, 2015; Powers and Medley, 2016). However, there are no explicit statements on how to implement TRPs and LRPs, although this is implicit in some simple HCRs, such as reducing F to F_{MSY} if it exceeds that value in the IATTC management system (Maunder and Deriso, 2013). A preliminary evaluation by Maunder *et al*. (2015) of the IATTC interim reference points under a proposed HCR found that the chance of falling below the LRP over a 9-year management period was less than 10%, although mis-specifying *h* and *M* increase the risk.

It has been argued that wide stakeholder involvement during the development, evaluation and implementation of HCRs is crucial for their success (Clarke and Hoyle, 2014; Hilborn *et al*., 2014), with examples of such involvement from CCSBT (Hillary *et al*., 2015) and outside tuna RFMOs. A well-managed fish stock or fishery with an appropriate HCR should operate near or around a TRP, and have a very low probability (*e.g.* less than 10%) of exceeding an LRP (Sainsbury, 2008). The decision about which reference points are appropriate should be made in the context of the management action to be applied if the reference points are exceeded. For example, LRPs can be treated as “soft” or “hard” in relation to the management action associated with a stock falling, or being at risk of falling, below an LRP (Anonymous, 2008). Punt and Smith (2001) outline the appropriate use of LRPs in managing fish stocks. Reaching or falling below an LRP should not mean that the species has a high risk of biological extinction: reducing *F* would be a more appropriate response than closing the whole fishery. If an LRP is appropriately set, the probability of exceeding it should be low, but not zero.

To date there has been no concerted stakeholder involvement in the development of HCRs for dorado in the EPO, although the three regional workshops on dorado during 2014-2016 (IATTC, 2015, 2016) provided an informal forum for the exchange of ideas among fishers, NGOs, scientists and other stakeholders. There have been four binational meetings on dorado between Ecuador and Peru during 2014-2018, with more planned in the future, but it is unclear whether any discussion on HCRs is planned.

5. DISCUSSION

Given the worldwide lack of reference points and HCRs for dorado, we focused on recent reviews of approaches and rationales in developing reference points and HCRs across tuna RFMOs (Nakatsuka *et al*. 2017; Valero *et al*. 2017), which found a wide diversity of approaches and degrees of implementation across species and RFMOs. We also point out opportunities and issues to take into account when considering alternative reference points and HCRs for dorado in the EPO.

One important consideration in the selection of reference points and HCRs is how TRPs relate to LRPs and the actions taken when the limit is exceeded. If drastic action is taken when an LRP is exceeded (*e.g.* the fishery is closed or severely restricted) then the TRP needs to be set at a level that will ensure a low probability of exceeding the LRP, to avoid potential social and/or economic problems. However, the probability should not be too low, because estimated probabilities at the tail of a distribution are notoriously uncertain. The TRP should be set in the context of the LRP, the action taken when the LRP is exceeded, the overall HCR, and the uncertainty in the method (*e.g.* the stock assessment) used to determine whether a limit has been exceeded.

There are a number of unresolved issues that should be taken into account when considering alternative reference points and HCRs for dorado, some of which are summarized below.

5.1. Dorado stock structure in the EPO

The stock structure of dorado in the EPO is still unclear. Aires-da-Silva *et al*. (2016) reviewed available information on potential stock structure and found no clear evidence that there is more than one population of dorado in the EPO. However, a conceptual model developed during the 2nd dorado workshop (IATTC 2016) postulated two sub-stocks (Figure 8), a resident coastal sub-stock and an oceanic sub-stock that migrates seasonally towards the coast. The degree of connectivity between dorado from the dorado stocks in the South and North EPO is also poorly known (Aires-da-Silva *et al*., 2016).

5.2. Reference points and HCRs vs. current and alternative management strategies

Current management measures for dorado vary greatly across the EPO, from none in some Central American countries to a ban on commercial retention in Mexico. Both Ecuador and Peru have management measures in place that include minimum size limits and seasonal closures, which have been shown to be consistent with YPR and performed well against simulated alternative size limits and seasonal closures (Valero *et al*., 2016) while maintaining the stock slightly above levels estimated to produce MSY (Aires-da-Silva *et al*. 2016). In the context of Ecuador and Peru, the advantages, disadvantages and feasibility of moving to management strategies reliant on reference points and HCRs, in terms of both the increasing need for analyses (stock assessments or empirical indicators) and of implementing management changes, are still not clear.

5.3. Geographic scope and frequency of assessments

There are no stock assessments available for dorado in the North EPO. For the South EPO there has been only the initial exploratory assessment for dorado, using data through 2014, by Aires-da-Silva *et al*. (2016), and it has not been repeated nor updated since then. Each year the dorado fisheries focus on mainly one cohort that passes through the population and fisheries, leaving almost nothing of that cohort for the following year, so the available stock assessment was in any case outdated by the time it was published. In view of the fast dynamics and variability of the dorado stock (almost an annual species), its fisheries (fisheries from adjacent countries may have diametrically opposed landings in the same year) and its ecological environment (CPUE influenced by oceanographic conditions (Martínez-Ortiz, 2015; Torrejón-Magallanes, 2018), additional and updated analyses would benefit the estimation of alternative TRPs based on stock assessments. If stock assessments cannot be completed in a timely way because of the fast dynamics of the stock, logistic considerations, or lack of data, it may be more feasible to implement alternative strategies that include empirical reference points and HCRs, or that are based on size limits and seasonal closures.

5.4. Geographic scope of management

Unlike other fisheries in the EPO, such as those for tropical tunas, which are managed regionally with reference points and HCRs (IATTC 2016b), dorado fisheries are managed nationally (IATTC 2015). Although Ecuador and Peru, the main EPO dorado-fishing countries by landing amounts, have held four bilateral meetings on dorado during 2014-2018, with more planned in the future, it is unclear whether the discussions will include potential reference points and HCRs.

5.5. Data availability across time and space

Availability of data for dorado varies greatly across the EPO (IATTC 2015, 2016). For Ecuador and Peru, there are enough data to conduct integrated stock assessments (Aires-da-Silva *et al*. 2016), but in other cases, especially in the North EPO, data are more limited, thus precluding integrated stock assessments, although in some cases approaches based on monthly CPUE (Maunder *et al*. 2016), for example, may be feasible. In either case, given the fast population and fisheries dynamics of dorado, it is important to streamline the availability of data in a timely way, either for considerations of either intra-annual or interannual management.

5.6. Development and implementation of reference points, HCRs and alternatives

The development, evaluation and implementation of reference points do no happen in a vacuum, but as part of a management strategy in a management system. Three phases have been described (Davies and Basson, 2009; Clarke and Hoyle, 2014) in the development of reference points: 1) selecting appropriate types of reference points, 2) defining specific values for the selected reference points, and 3) operationalizing the selected reference points within the management system. In order for each element of the process and associated tradeoffs to be understood and accepted, all stakeholders are expected to be involved in each phase of the process (Clarke and Hoyle, 2014). Hilborn (2002) highlighted some potential issues in management systems based on reference points, including (1) uncertainties in the estimates of current and virgin stock biomass used in developing reference points, (2) whether reference points should be used for stocks for which they were not derived, (3) the tendency to focus too much on reference-points and to produce an environment in which stock-assessment scientists rarely evaluate alternative management policies, and (4) overemphasis on reference points, to the detriment of more pressing issues in fisheries management. It has been argued that at least some of these issues could be mitigated by relying on more data-based approaches, and there are examples from several life history and management systems, for instance the New Zealand rock-lobster fishery (Starr *et al*., 1997) and southern bluefin tuna (Hillary *et al*., 2015). There has been an increased interest in the application of reference points worldwide, driven in part by Marine Stewardship Council (MSC) certification criteria (see, for example, Powers and Medley, 2016). However, in the specific case of dorado, the certification by MSC of the Ecuadorian longline fishery will follow a risk-based framework (MSC, 2019), since there are no reference points available to assessing the status of the target stock.

6. CONCLUSION

A variety of reference points and HCRs have been proposed in the literature and applied to stocks worldwide. The main differences among them are whether MSY reference points are treated as limits or targets and the level of implementation of HCRs. The selection of reference points, particularly limit reference points, should take into consideration the action implemented when the reference point is exceeded. Reference points and HCRs cannot be properly evaluated outside a fishery management strategy and management system, or without including uncertainty, risk, robustness and tradeoffs between all the elements of each fishery. Ideally, a range of different HCRs, and the associated data inputs and assessment methods to be used in the implementation, should be tested using MSE, and the combination that best meets the objectives for the fishery should then be selected (Anonymous, 2018). In the context of Ecuador and Peru, the advantages, disadvantages and feasibility of moving to management strategies reliant on reference points and HCRs, in terms of both the increasing need for analyses (stock assessments or empirical indicators) and of implementing management changes, are still not clear. The increased interest in the development and implementation of reference points worldwide has been driven in part by Marine Stewardship Council (MSC) certification criteria. In the specific case of dorado, the certification by MSC of the Ecuadorian longline fishery will follow a risk-based framework, which does not rely on the adoption of reference points to assess the status of dorado stocks.

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TABLE 1. Common biomass reference points.
TABLA 1. Puntos de referencia comunes basados en biomasa.

Reference Point	Description	Pros	Cons	Target / limit

XB_{MSY}, $XSSB_{MSY}$	Ratio of biomass, or spawning stock biomass (SSB), needed to produce MSY	Considers recruitment and growth overfishing	Difficult to estimate, sensitive to recruitment and selectivity	Either
XB_0 or $XSB_{current, F=0}$	Ratio of biomass stock relative to unfished, or spawning biomass expected in the absence of fishing.	Can be used for data poor stocks; measures relative abundance in cases where absolute abundance is difficult to estimate.	Unfished biomass estimates depend on assumptions, may be unreliable.	Either
B_{XR0} or B_{XRMAX}	Biomass expected to produce X fraction of virgin/maximum recruitment.	Considers recruitment overfishing	Depends on current and historical recruitment estimates	Limit
B_{MAX}	Biomass or spawning biomass produced when $F = F_{MAX}$ in equilibrium	Considers growth overfishing	Difficult to estimate when the yield curve is flat topped, sensitive to assumptions when curve is flat topped, Not consider recruitment overfishing;	Either
$B_{0.1}$	Biomass or spawning biomass produced when $F = F_{0.1}$	Considers growth overfishing, adjusts for flat topped YPR curve, adjusts somewhat for the stock-recruitment relationship	Difficult to estimate when the yield curve is flat topped Does not explicitly consider recruitment overfishing.	Either
B_{loss}	Minimum biomass (or SSB)	Considers recruitment overfishing	Does not consider growth overfishing.	Limit

TABLE 2. Common fishing mortality reference points.
TABLA 2. Puntos de referencia comunes basados en mortalidad por pesca.

Reference Point	Description	Pros	Cons	Target / limit
F_{MSY}	Fishing mortality rate that results in MSY on average	Considers recruitment and growth overfishing	Difficult to estimate when the yield curve is flat-topped. Sensitive to assessment assumptions	Either
F_{MAX}	Fishing mortality rate producing the maximum yield per recruit.	Considers growth overfishing; easy to calculate.	Does not consider recruitment overfishing; Difficult to estimate/ sensitive to assumptions if yield curve is flat topped	Limit
$F_{0.1}$	*F* at which slope of Y/R is 10% of value at origin	Consider growth overfishing; more conservative than F_{MAX}; estimable even if yield curve is flat topped	Does not explicitly consider recruitment overfishing.	Either
$F_{X\%}$, $F_{X\%SPR}$	*F* that reduces SSB/R to a certain % of unfished	Considers recruitment overfishing.	Does not consider growth overfishing	Either
F_{MED}	*F* that can be supported by estimated survival rates from spawning to recruitment in 50% of years.	For recruitment overfishing; based on the historical time series of recruitment.	Does not consider growth overfishing; appropriateness dependent on the stock-recruitment relationship	Either
$F_{SSB\text{-}Min}$	*F* that prevents SSB from falling below the minimum observed SSB	Reference point for recruitment overfishing.	Risk-prone; sensitive to period for calculations No consideration of growth overfishing	Limit
F_{loss}	*F* expected to keep biomass at B_{loss}	Reference point for recruitment overfishing; relatively easy to calculate.	Risk-prone; no consideration of growth overfishing; assumes good understanding of the stock-recruitment	Limit
F_{crash}	Lowest *F* that would eventually drive the stock to extinction	Based on the stock-recruit relationship but easier to calculate	Risk-prone, allows the stock to be on path to extinction	Limit
***F* = X%M**	*F* is set at a % of natural mortality	Can be used in data-poor situations	Uncertainty in estimation of M, possibly too high for longer-lived species.	Limit

TABLE 3. Sensitivities to different configurations of the base case model for the exploratory assessment for dorado (Aires-da-Silva *et al.*, 2016). *M*: natural mortality; *Q*: catchability; Dome: dome-shaped selectivities.

TABLA 3. Sensibilidad a distintas configuraciones del caso base de la evaluacion exploratoria de dorado (Aires-da-Silva *et al.*, 2016). *M*: mortalidad natural; *Q*: capturabilidad; Dome: curva de selectividad con forma de domo.

	Base case Caso base	Sensitivity analyses - Análisis de sensibilidad			
		1		2	3
		*M*_0.43	*M*_1.6	*Q*_notv	Dome
S_0 (t)	90,045	205,001	62,015	85,577	89,952
B_0 (t)	254,687	545,880	192,791	242,067	254,429
S_{MSY}-S_{RMS} (t)	17,987	15,336	22,351	17,196	17,893
MSY-RMS (t)	89,211	79,502	100,530	84,490	89,010
S_{2014}/S_0	0.22	0.08	0.38	0.23	0.22
S_{MSY}/S_0-S_{RMS}/S_0	0.20	0.07	0.36	0.20	0.20
S_{2014}/S_{MSY}-S_{2014}/S_{RMS}	1.10	1.00	1.07	1.16	1.11

TABLE 4. Monthly ratio of average Ecuadorian longline CPUE to average CPUE in October during 2009-2013. Avg.: Monthly average ratio for 2009-2013.

TABLA 4. Promedio mensual de la razón de CPUE de palangre de Ecuador relativo al valor CPUE en octubre durante 2009-2013. Prom.: Promedio para el periodo 2009-2013.

	2009	2010	2011	2012	2013	Avg. – Prom.
Oct	1.000	1.000	1.000	1.000	1.000	1.000
Nov	0.671	0.737	0.802	0.603	0.757	0.654
Dec	0.450	0.543	0.644	0.364	0.573	0.450
Jan - Ene	0.302	0.400	0.517	0.220	0.434	0.320
Feb	0.203	0.295	0.414	0.133	0.328	0.232
Mar	0.136	0.217	0.333	0.080	0.249	0.170
Apr - Abr	0.091	0.160	0.267	0.048	0.188	0.126

TABLE 5. Monthly average ratio of mean Ecuadorian longline CPUE to average CPUE in October during 2009-2013, relative to that expected in the absence of fishing under annual natural mortalities (*M*) of 0.5, 1 and 2 year^{-1}. *M* = 1 year^{-1} is the value used in the 2015 dorado exploratory stock assessment (Aires-da-Silva *et al*. 2016) and management strategy evaluation (Valero *et al*. 2016).
TABLA 5. Promedio mensual de la razón de CPUE de palangre de Ecuador relativa al CPUE promedio en octubre para el periodo 2009-2013, relativo al esperado en ausencia de pesca y mortalidad natural (*M*) de 0.5, 1 y 2 año^{-1}. *M* = 1 año^{-1} es el valor utilizado en la evaluación exploratoria de dorado (Aires-da-Silva *et al*. 2016) y la evaluación exploratoria de estrategia de explotación (Valero *et al*. 2016).

	Average – Promedio		
	***M* = 0.5**	***M* = 1**	***M* = 2**
Oct	1.000	1.000	1.000
Nov	0.682	0.711	0.773
Dec	0.489	0.532	0.628
Jan - Ene	0.362	0.410	0.527
Feb	0.274	0.323	0.451
Mar	0.209	0.258	0.391
Apr - Abr	0.162	0.208	0.343

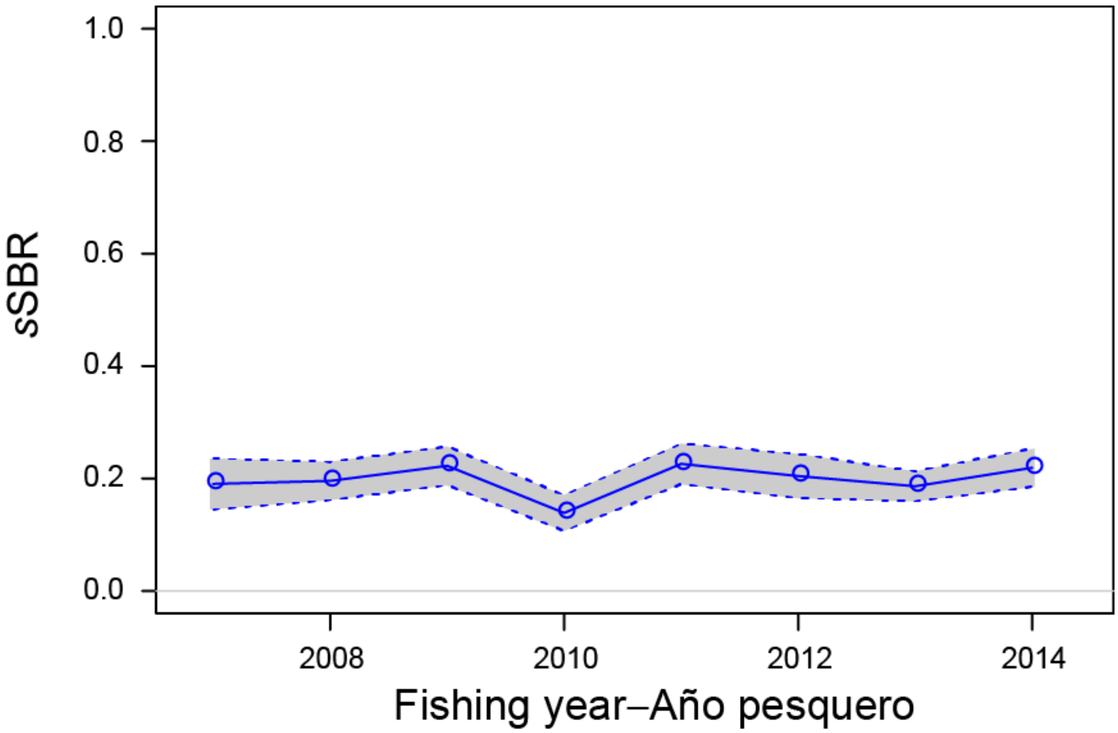

FIGURE 1. Estimated static spawning biomass ratios (sSBR) of dorado recruited to the fisheries of the South EPO (Aires-da-Silva *et al*. 2016). The solid blue line connects the maximum likelihood estimates (open circles). The shaded area indicates the approximate 95-percent confidence intervals around these estimates.

FIGURA 1. Cocientes de biomasa reproductora estáticos (*s*SBR) estimados de dorado reclutado a las pesquerías del OPO sur (Aires-da-Silva *et al*. 2016). La línea azul conecta las estimaciones de verosimilitud máxima (círculos abiertos). El área sombreada indica los intervalos de confianza de 95% alrededor de estas estimaciones.

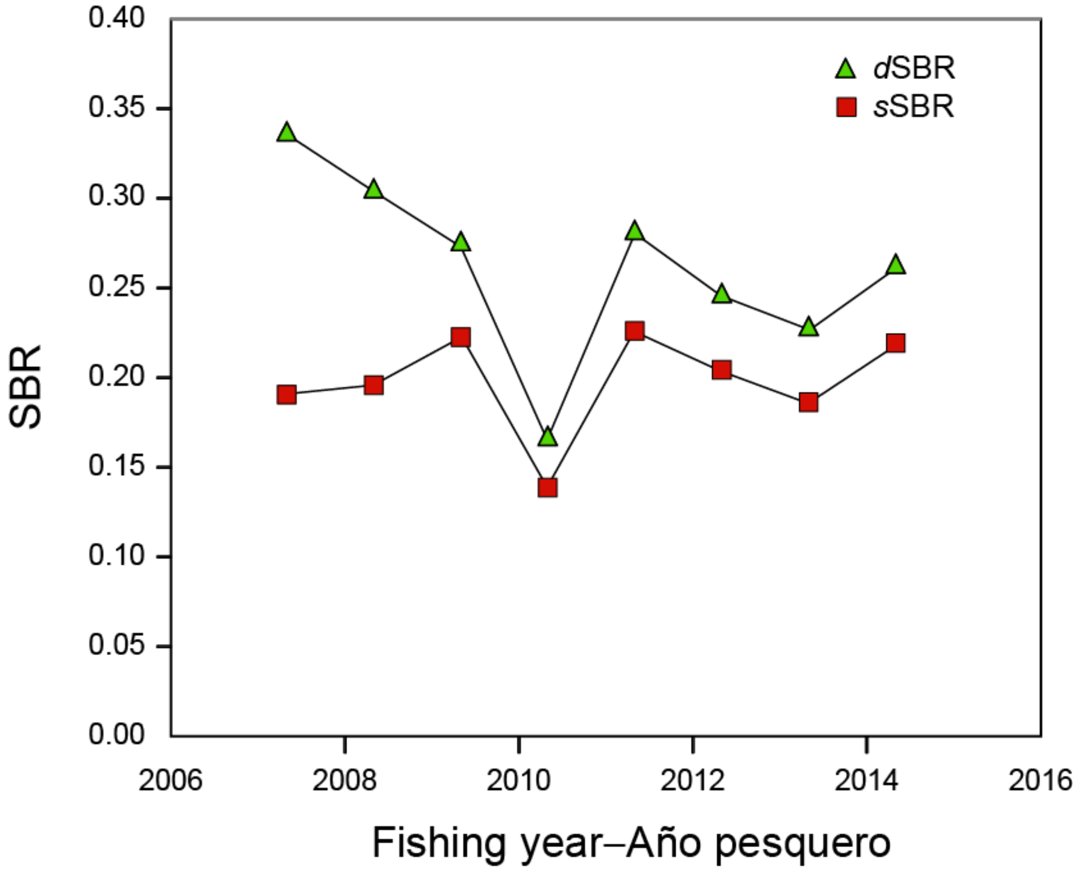

FIGURE 2. Estimates from the base case (Aires-da-Silva *et al*. 2016) for the Spawning biomass ratio (SBR) obtained by two methods: static (*s*SBR) and dynamic (*d*SBR).

FIGURA 2. Estimaciones del cociente de biomasa reproductora (SBR) del caso base (Aires-da-Silva *et al*. 2016) obtenidas con el método estático (*s*SBR) y dinámico (*d*SBR).

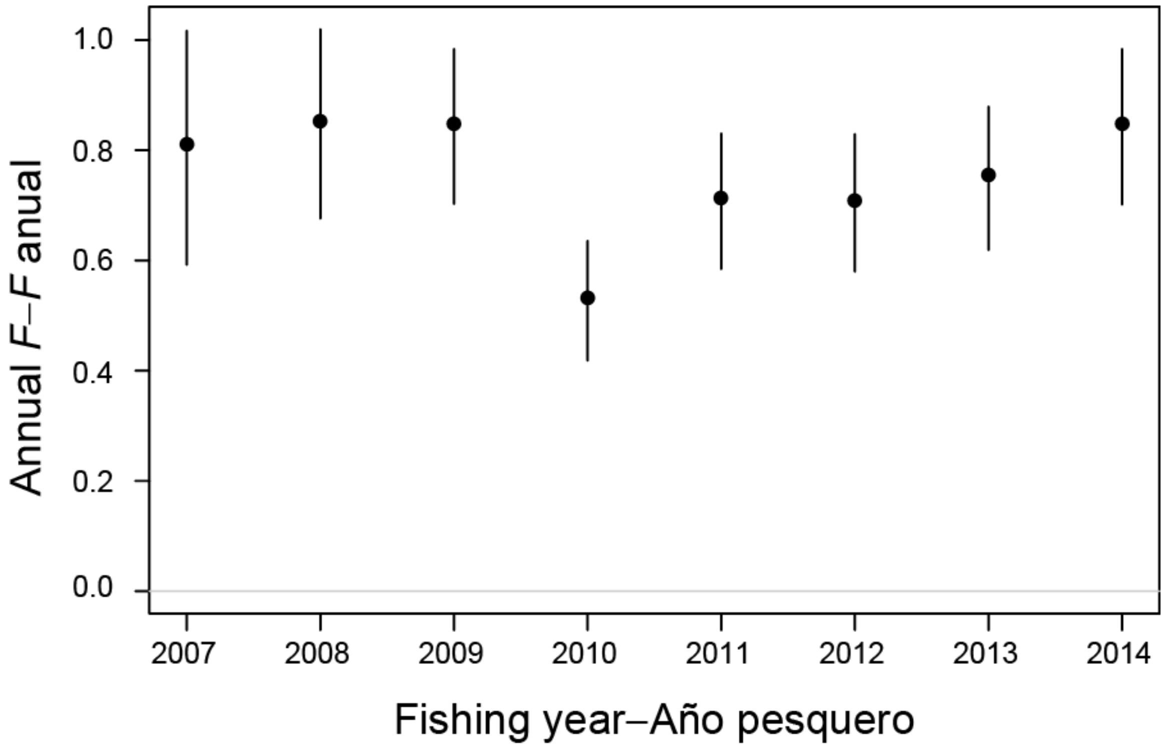

FIGURE 3. Annual fishing mortality (*F*), for all dorado fisheries of the South EPO, estimated by the 2016 exploratory stock assessment (Aires-da-Silva *et al*. 2016).
FIGURA 3. Mortalidad por pesca (*F*) anual, de todas las pesquerías, de dorado reclutado a las pesquerías del OPO sur (Aires-da-Silva *et al*. 2016).

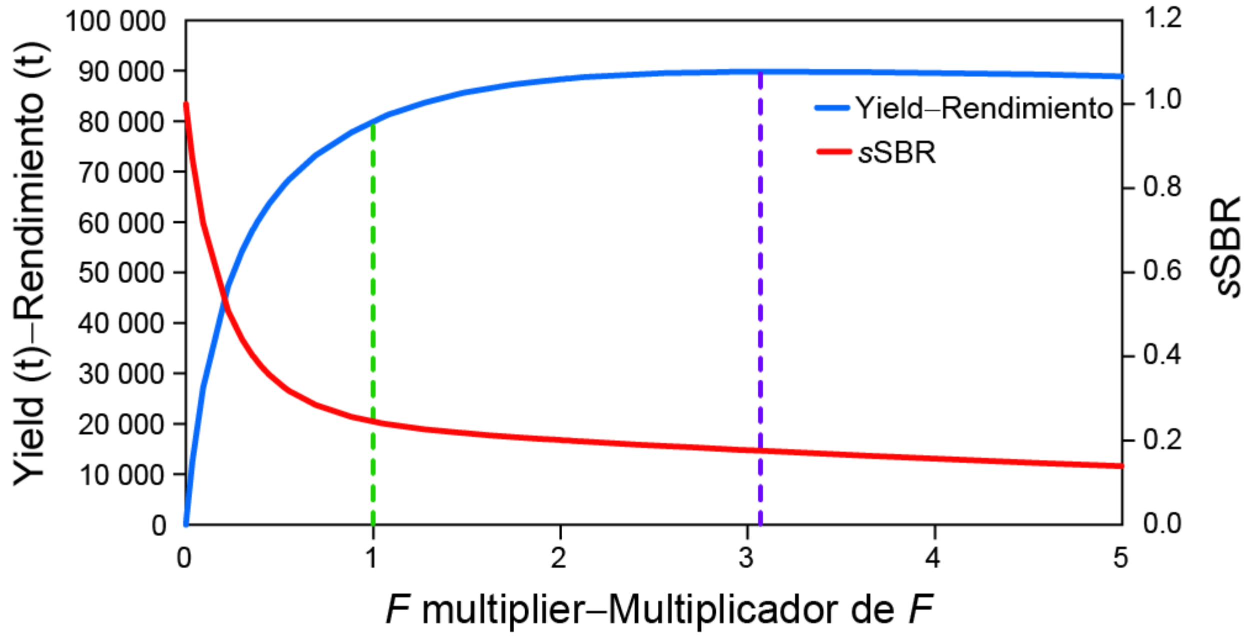

FIGURE 4. Equilibrium yield, in tons, and static spawning biomass ratio (*s*SBR) versus the *F* multiplier (vertical blue dashed line), which indicates how many times effort would have to be effectively increased from the current level (vertical green dashed line) to achieve MSY (so current apical fishing mortalities from all fisheries sum to one).

FIGURA 4. Rendimiento de equilibrio, en toneladas, y cociente de biomasa reproductora estático (*s*SBR) como funciones del multiplicador de *F* (línea de trazos vertical azul), que indica cuántas veces se ha de incrementar el esfuerzo del nivel actual (línea de trazos vertical verde) para lograr el RMS (para que las mortalidades por pesca apicales actuales de todas las pesquerías sumen uno).

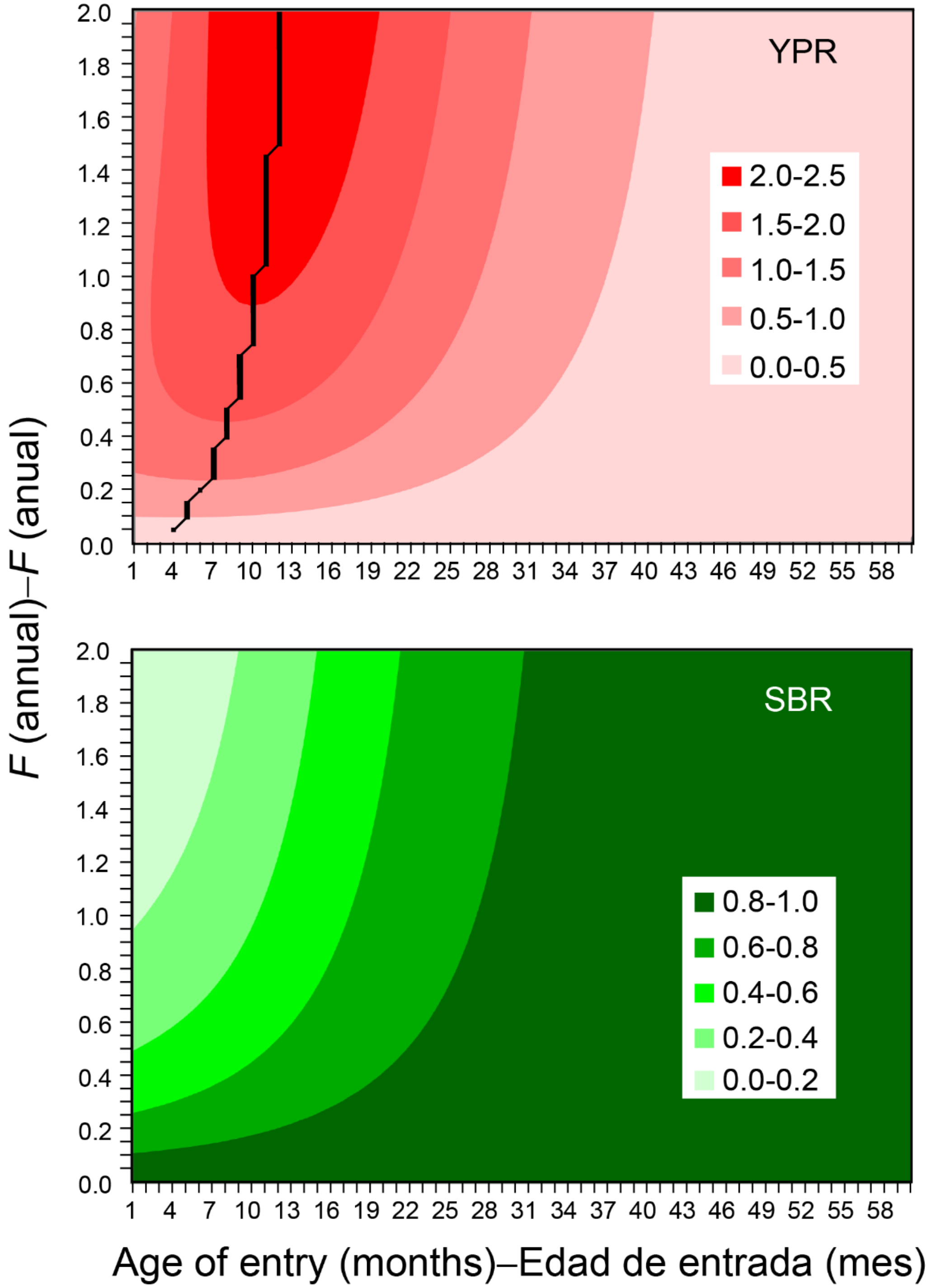

FIGURE 5. Yield per recruit (YPR, top panel) and spawning biomass ratio (SBR, bottom panel) as a function of age of entry to the fishery, in months, and annual fishing mortality (*F*). The black line in the YPR plot is the age corresponding to the maximum YPR at each level of fishing mortality.

FIGURA 5. Rendimiento por recluta (YPR, panel superior) y razón de biomasa reproductora (SBR, panel inferior) como función de la edad de entrada en la pesquería, en meses, y la mortalidad anual por pesca (*F*). La línea negra en la figura de YPR es la edad correspondiente al YPR máximo a cada nivel mortalidad por pesca.

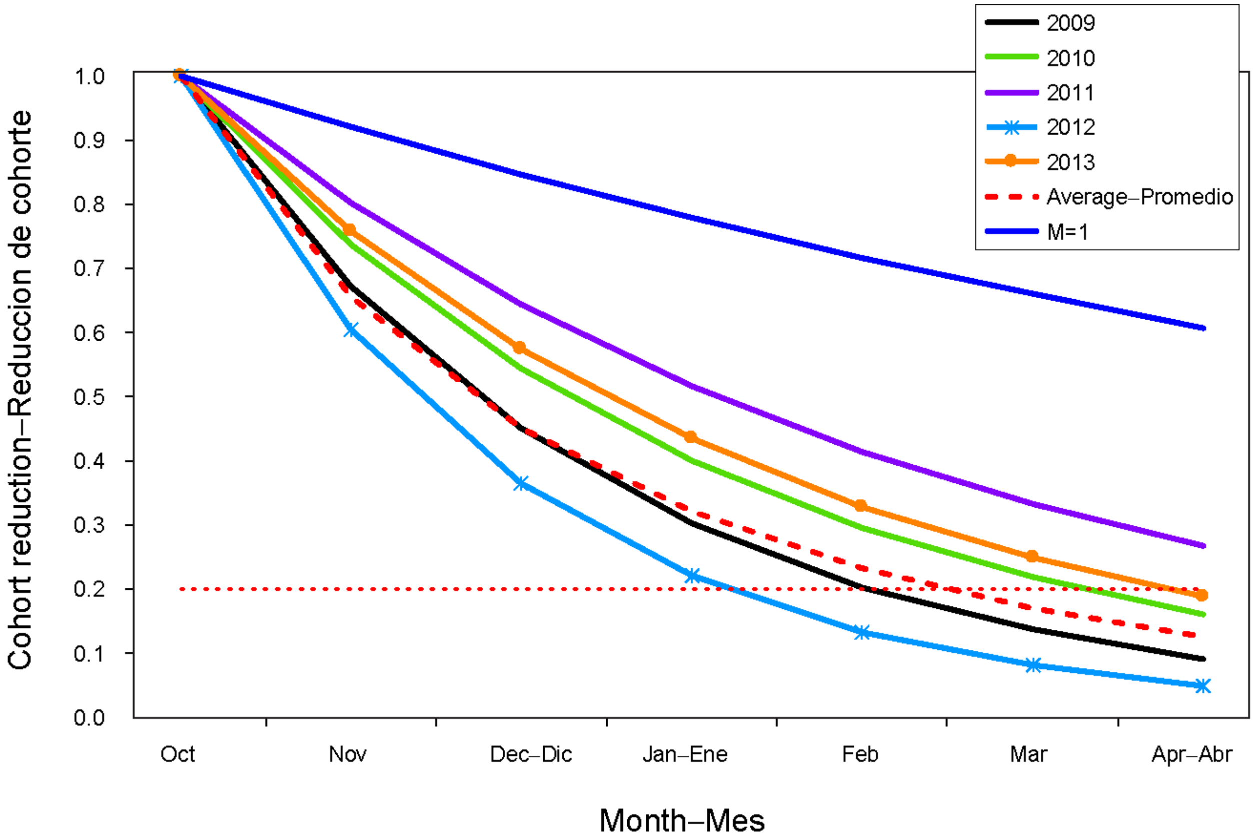

FIGURE 6. Cohort reduction based on dorado Ecuadorian longline monthly CPUE relative to CPUE values in the month of October for fishing years (July to June) 2009 to 2013. Avg: Average cohort reduction for years 2009 to 2013; M = 1: Expected cohort reduction in the absence of fishing corresponding to a value of natural mortality *M* = 1 year^{-1}. The red dashed line corresponds to a cohort reduction of 0.2.

FIGURA 6. Reducción de cohorte basada en CPUE mensual de dorado en palangre de Ecuador relativa a valores de CPUE en el mes de Octubre para los años pesqueros (Julio a Junio) 2009 to 2013. Prom: Promedio de reducción de cohorte para los años 2009 a 2013; M = 1: Reducción de cohorte esperada sin pesca correspondiente a un valor de mortalidad natural *M* = 1 anio^{-1}. La línea de guiones roja corresponde a una reducción de cohorte de 0.2.

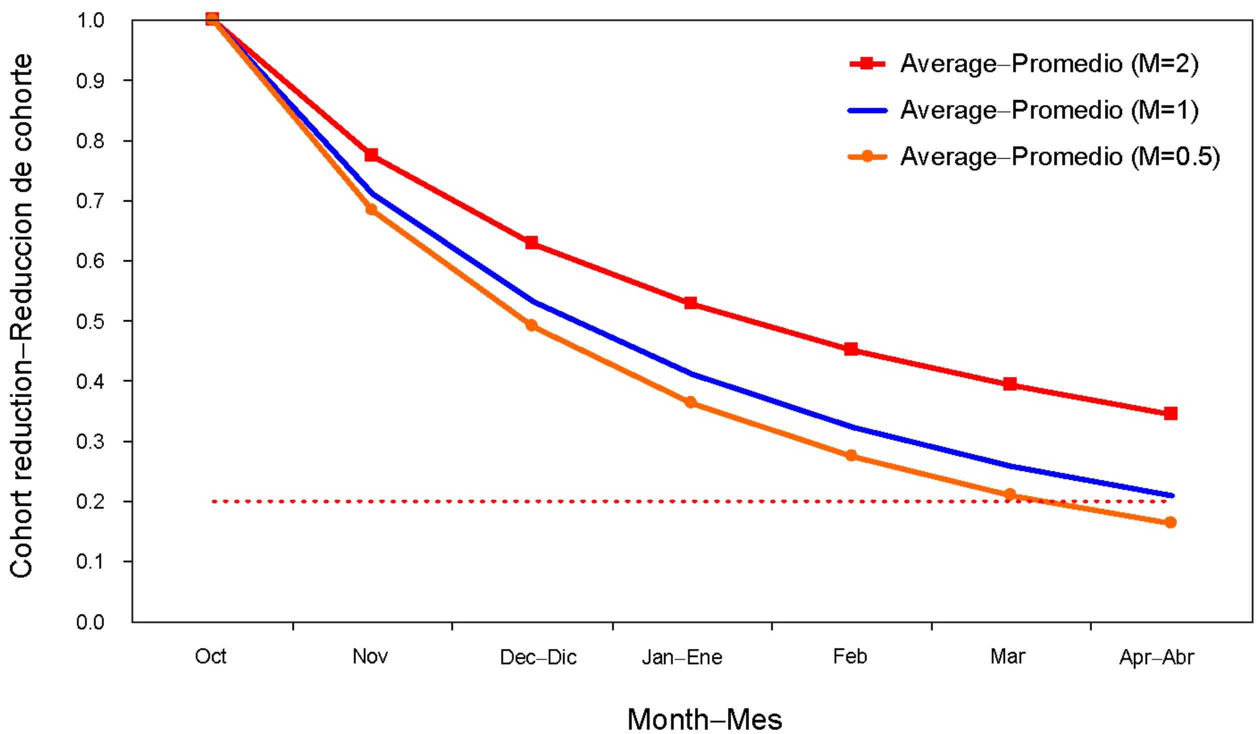

FIGURE 7. Average cohort reduction based on dorado Ecuadorian longline monthly CPUE relative to CPUE values in the month of October for fishing years (July to June) 2009 to 2013. Values are the ratio of the observed cohort reductions to those expected under no fishing and natural mortality values of 2, 1 or 0.5 year^{-1}. The red dotted line corresponds to a cohort reduction of 0.2.

FIGURA 7. Promedio de reducción de cohorte basada en CPUE mensual de dorado en palangre de Ecuador relativa a valores de CPUE en el mes de Octubre para los años pesqueros (Julio a Junio) 2009 to 2013. Valores son la razón de la reducción de cohorte observada relativa a la esperada sin pesca y mortalidad natural de 2, 1 or 0.5 year^{-1}. La línea de guiones roja corresponde a una reducción de cohorte de 0.2.

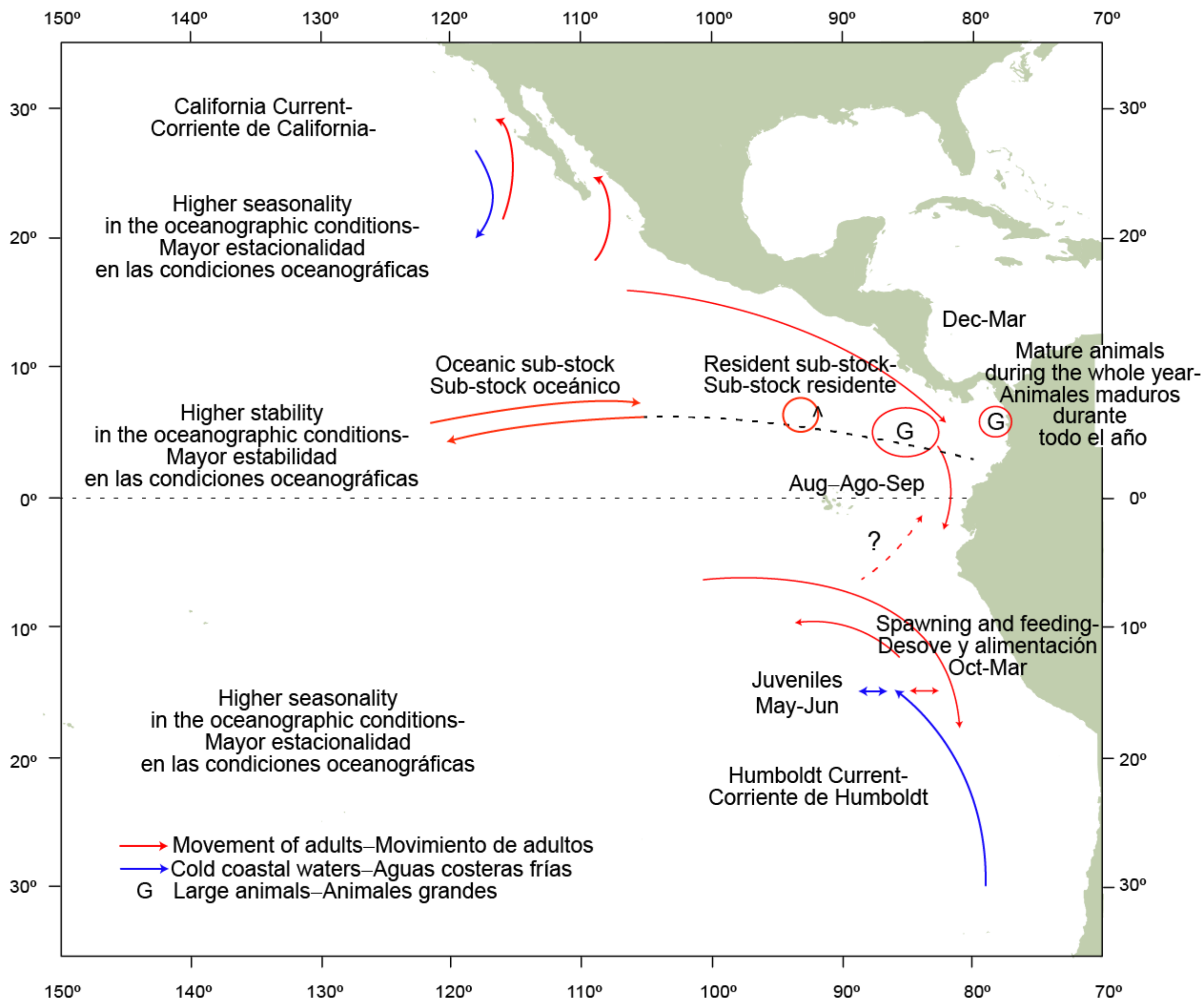

FIGURE 8. Conceptual model of the movements and spatial distribution of dorado (from Aires-da-Silva *et al*. 2016).

FIGURA 8. Modelo conceptual de los desplazamientos y la distribución espacial del dorado (de Aires-da-Silva *et al*. 2016).