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Contribution to the Themed Section: '*International Billfish Conference*'

Original Article

Factors related to the decline and rebuilding of billfish stocks in the Atlantic and Indian oceans

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The article examines factors related to the decline and rebuilding of billfish stocks in the Atlantic and Indian oceans. Longline effort has declined over the last 10–15 years in both oceans. This decline in fishing pressure has led to the recovery of some stocks, but some species that are caught incidentally in industrial longline fisheries remain overexploited. Using a simple moving average technique on fishing mortality trajectories, we estimated a threshold effort size of 240 million hooks for the Atlantic Ocean and 364 million hooks for the Indian Ocean where stocks start experiencing overfishing. In addition, we highlight differences in the economic characteristics of the major fleets catching billfish in the two oceans and discuss how this may be associated with differences in management, enforcement, and stock rebuilding.

Keywords: billfish, effort, global, governance, optimal fishing, sustainable.

Introduction

The general term "billfish" includes many species from the families Istiophoridae (marlin, sailfish, and spearfish) and Xiphidae (swordfish). Although most billfish are taken as incidental catch in industrial fisheries, some species that have a coastal shelf distribution, such as sailfish, are targeted by artisanal fisheries off the coasts of Africa and Asia (IOTC, 2016a). In addition, there are some directed sport and recreational fisheries in the Atlantic and Indian oceans. Fishing characteristics of longline fleets are similar in both oceans; however, the Indian Ocean has a larger artisanal component that targets sailfish (*Istiophorus platypterus*) and, to a lesser extent, black marlin (*Istiompax indica*) (IOTC, 2016b).

Global analyses on the status of billfish have shown that most of these stocks are experiencing high fishing mortality, and some of them are highly depleted (Restrepo *et al.*, 2003; Collette *et al.*, 2011). The decline is more pronounced for some marlins and sailfish than for swordfish (*Xiphias gladius*) (Pons *et al.*, 2017). In the Atlantic and Indian oceans, these stocks have been either overfished or have been experiencing overfishing for the last two decades. In this article, the term "overfished" refers to stocks with biomass (B) below the biomass that produces the maximum sustainable yield (B_{MSY}), and the term "overfishing" refers to stocks showing fishing mortality rates (F) greater than the fishing mortality that produces the maximum sustainable yield (F_{MSY}). B/B_{MSY} and F/F_{MSY} are the reference points commonly used by tuna regional fisheries management organizations (tRFMOs) to define stock status. The stocks of billfish and other highly migratory species are regionally assessed and managed by these tRFMOs, including the International Commission for the Conservation of Atlantic Tunas (ICCAT), Indian Ocean Tuna Commission (IOTC), Inter-American Tropical Tuna Commission (IATTC), Western and Central Pacific Fisheries Commission (WCPFC), and Commission for the Conservation of Southern Bluefin Tuna (CCSBT).

Globally, tRFMOs have different exploitation and management histories, and some of these management actions have had a strong impact on the status of tuna and billfish stocks in their respective jurisdictions (Parma *et al*., 2006; Pons *et al*., 2017). All tRFMOs have implemented some form of input (or effort) controls (primarily for purse-seine fisheries), but only some of them have implemented output (or quota) controls [e.g. CCSBT, IOTC, and ICCAT historically, and recently IOTC, WCPFC, and IATTC for yellowfin (*Thunnus albacares*), Pacific bluefin (*Thunnus orientalis*), and bigeye (*Thunnus obesus*), respectively]. Although there has been considerable discussion about the elements required for successful fisheries management (Beddington *et al*., 2007; Hilborn, 2007), the effectiveness of management measures for tunas and billfishes have only recently been analysed on a global scale (Pons *et al*., 2017). These authors demonstrated the major factors affecting the status and recovery of tuna and billfish stocks on a broad scale across the Pacific, Atlantic, and Indian oceans. The study indicated that stocks are more likely to be depleted if they have high commercial value, are long-lived species, have a low prefishing biomass, and have been subject to intense fishing pressure for a long period of time (particularly for tunas). In addition, the implementation of total allowable catches (TACs) has had a positive influence on rebuilding overfished tuna and billfish stocks, particularly in the case of Atlantic swordfish and Atlantic bluefin tuna (*T. thynnus*). Although catch controls are probably the most reliable means of regulating fishing mortality (typically in conjunction with other measures), they are certainly not the only way (Beddington *et al*., 2007; Hilborn, 2007). Well-regulated and enforced input controls can also be an effective method of management. These are often more feasible and practical to implement in a wider range of circumstances than output controls and have been implemented successfully in areas such as the United States, Australia, Canada, and parts of northern Europe (Hilborn, 2007).

This study analyses finer-resolution data to evaluate the potential role other factors might play in influencing billfish stock status and management in the Atlantic and Indian oceans to assess how the effects, and resulting dynamics, might be used to achieve healthy population levels across the two oceans. Factors such as fisheries characteristics (artisanal or industrial) and the economic status of the major countries catching billfish have not been considered in previous studies for the Istiophoridae family. This was achieved through exploring (i) the variation in longline effort over time (the gear responsible for the majority of billfish catch) and potential estimated threshold limits for overall longline effort for the two oceans, and (ii) potential factors affecting the status of billfish in each ocean (including economic status and fleet characteristics of the major fleets catching billfish). Differences in governance and management between the two oceans and the implications for the resulting stock status are discussed.

Methods

Effort data

Fleet dynamics for the longline sector are the only component for which effort has been measured consistently for the last 60 years. Although set-level operational data were not available for this analysis, an overall measure of effort (number of longline hooks in the water) is publically available for both oceans. Total reported effort data in $5^\circ \times 5^\circ$ in space and over time between the 1950s and 2015 were extracted from www.iccat.int and www.iotc.org for ICCAT and IOTC, respectively. The reported overall catch estimates by each ocean or tRFMO are comparable, as are the methods to estimate overall effort (ICCAT, 2016; IOTC, 2016a). The baseline hypothesis for this article is that fleet dynamics of the longline sector are broadly indicative of the changes (increase) in effort of other sectors as well as illustrated by the catch trajectories in both oceans (Polachek, 2006).

Spatial patterns in the movement of the various longline fleets in the Atlantic and Indian oceans were assessed through developing global maps of effort plotted at a spatial scale of $5^\circ \times 5^\circ$ grids by decade. In addition, effort trajectories by the different fleets operating in both oceans were compared in an exploratory manner temporally and spatially.

Time-series analysis (moving average trends) were developed for each ocean using overall effort as a variable that may be controlled by management and evaluated by year against F/F_{MSY} and B/B_{MSY} reference points estimates from the assessments conducted by ICCAT and IOTC. Both commissions have explicit objectives to maximize the sustainable yield from the fisheries. This has implicitly meant that management ensures that fishing mortality is maintained at F_{MSY} to ensure that stock biomass remains at a size that optimizes the long-term yield (MSY, the point at which this occurs is B_{MSY}). Both tRFMOs have agreed to manage stocks to these target reference points; hence, the analyses presented here are correspondingly based on these target reference points.

Threshold effort levels that meet these targets were estimated by species and ocean based on criteria where F is greater than F_{MSY} for 3 consecutive years. Sustained overfishing for more than 3 years can cause stocks to fall below B_{MSY} targets unless productivity dramatically increases (Magnuson-Stevens Act in the United States has similar provisions for B_{MSY} targets to do an overfishing fishing management plan, if stocks are below B_{MSY} targets, and fishing is above F_{MSY} targets for 3 years in a row).

Effort in the third year when F remained above F_{MSY} was selected as the threshold effort level for the species. These thresholds were then averaged across species by ocean to derive an indicative effort level that would maintain at least 50% of the billfish stocks at healthy levels in each ocean. This method assumes that longline effort can be used as an indicator for changes in effort of other gear types. To test this assumption, a simple correlational analysis was used to explore the correlation between effort and total F, as obtained from the stock assessments undertaken by the respective tRFMOs, using a 3-year time-lag, as indicated by biomass trajectories.

Note that both B/B_{MSY} and F/F_{MSY}, while being computed by different assessment techniques (stock reduction methods, surplus production models, or integrated assessments) by different tRFMOs (ICCAT, 2016; IOTC, 2016a), are still dimensionless properties and are good indicators of stock status (Preece *et al*., 2011) and comparable across oceans and species.

Catch and gross domestic product data

Aggregated catch data across all billfishes were compiled by countries that account for 75% of the catch using ICCAT (2016) and IOTC (2016a) databases from 1950 to 2014. In addition, gross domestic product (GDP) data from these countries were collected from www.statisticstimes.com/economy/countries-by-projected-gdp.php and ranked in relation to their overall global rank of GDP. We only considered the GDP of the countries which account for ≥75% of the catch.

Relationship between stock status and GDP

We computed the number of years it took for F/F_{MSY}, once exceeding 1, to fall below 1 to measure the time taken for stock recovery (i.e. end overfishing). This method does not take into account B/B_{MSY} as once $F/F_{MSY} < 1$, it is only a matter of time before $B/B_{MSY} > 1$, if it was below 1. Nevertheless, in some cases for IOTC, although $F/F_{MSY} > 1$, $B/B_{MSY} > 1$, indicating that though overfishing may have been/still be occurring the stock is not yet overfished. Recovery time (i.e. number of years it took to end overfishing or the time taken for $F/F_{MSY} > 1$ to decrease until the point that $F/F_{MSY} < 1$ and $B/B_{MSY} > 1$) was explored in relation to GDP rank. The implicit hypothesis here is that the tRFMO made up of countries with the lowest GDP rank, which indicates a stronger economy, would be better situated to control and govern catches and enable quicker rebuilding of populations (Melnychuk *et al.*, 2012, 2017; Pons *et al.*, in review) implying a shorter recovery time as expressed by the number of years that $F/F_{MSY} > 1$.

Results

Effort analysis

Spatial patterns in effort exerted by the different longline fleets across both oceans are presented in Figures 1 (Indian Ocean) and 2 (Atlantic Ocean). Although billfish are not generally considered as target species of the longline fleets, but rather as incidental catches, information available from the industrial longline fleets is considered more complete than for other fleets, particularly regarding historical data. To test whether longline effort is a good indicator of effort changes by other gear types, a simple correlational analysis was used to explore (next section) the correlation between effort and F (as obtained from the assessments), and with a time-lag (3 years) as indicated by biomass trajectories.

Indian Ocean effort summary

In the early period (1970s), longline effort in the Indian Ocean was dominated by Japan (Figure 1). However, through the 1980s and 1990s, effort by Taiwanese vessels increased, and in the most recent years, most of the effort has been exerted by the Taiwanese fleets. The Korean fleet also operated in the Indian Ocean in the early decades, but effort was low and now almost negligible.

The spatial patterns by fleet varied drastically (this is even more apparent when examined on an annual basis, not shown here). Although the Japanese fleet operated predominantly in the southern hemisphere waters of South Africa and Australia (primarily because of bluefin tuna targeting; Polacheck, 2012), both Taiwanese and Korean fleets dominated effort in the Arabian Sea, around the Arabian Gulf, and also around Somalia and the horn of Africa (this last area showed large declines due to Somali piracy after 2005; Kaplan *et al.*, 2014). In recent years, the Taiwanese fleet also operated in the eastern Indian Ocean around Thailand and Indonesia, near the Andaman Islands in the Bay of Bengal (Figure 1).

Atlantic Ocean effort summary

As in the Indian Ocean, effort by the Korean fleet has dramatically declined in recent years in the Atlantic (Figure 2). The majority of longline fishing effort is undertaken by Taiwanese and Japanese fleets. Although the Taiwanese fleet operates mostly in the South Atlantic off the coasts of South Africa and South America, the Japanese fleet has an Atlantic-wide distribution, although it has gradually reduced its effort off the coast of Guinea in recent years.

Effort trends across oceans

Effort trends appear to have reached a peak in both oceans between 1999 and 2001 (Figure 3a), with a declining trend since 2006 in the Indian Ocean and since 2008 in the Atlantic Ocean. Across all longline fleets operating in both oceans, effort has remained between 185 and 445 million hooks in the Indian Ocean and between 290 and 395 million hooks in the Atlantic Ocean between 2000 and 2014 (Figure 3b).

Effort and stock trajectories

Figures 4 and 5 indicate the effort trajectory over time with respect to two quantities of interest or reference points: B/B_{MSY} and F/F_{MSY} for the Indian and Atlantic oceans, respectively. If B/B_{MSY} is >1, then the stock is considered healthy or underexploited (lower right or upper right quadrants in Figures 6 and 7). In contrast, if the fishing mortality is >1 with respect to the optimal F, this implies that the stock is experiencing overfishing (upper right or upper left quadrant in Figures 6 and 7). When the stock is both experiencing overfishing and below optimal biomass, then the stock is considered overexploited (upper left quadrant).

Simple correlational analysis (Table 1) indicates that billfish fishing mortality in the Atlantic is directly related to longline effort. Correlations > 0.7 with respect to fishing mortality levels indicate that they are positively correlated with effort, and these are both inversely related to stock status health (Table 1). For the Atlantic, effort was significantly and positively related to F ($\rho > 0.7$) for the majority of species [other than blue (*Makaira nigricans*) and white marlin (*Kajikia albidus*)]. The relationship between stock status (with a 3-year time-lag) and effort showed a significant negative correlation in the Atlantic ($\rho < -0.7$) across all stocks.

Conversely, in the Indian Ocean (Table 2) effort for only two stocks, swordfish and striped marlin (*Kajikia audax*), were positively correlated with respect to F. However, biomass (with a 3-year lag effect) was negatively correlated with effort for all stocks in the Indian Ocean. As sailfish and black marlin (and to some extent blue marlin) have a coastal shelf distribution and are affected more by artisanal gears than pelagic longline gear, there is no significant relationship between longline effort and total F in the Indian Ocean for these two species. However, increases in effort of the longline fisheries are associated with a corresponding decline in biomass for all billfish stocks in the Indian Ocean, suggesting that effort in these fisheries may be a good indicator of the trend in effort of some of the coastal artisanal fisheries targeting marlins in the Indian Ocean.

Although other stocks are not highly correlated ($\rho < 0.7$), a regression run on all stocks (not shown here) with either F (with no time-lag) or B (with a 3-year lag) as the dependent variable and effort as the independent variable shows a positive relationship between effort and fishing mortality, and a negative relationship between effort and biomass. Finally, correlations across stocks in both oceans indicate that common exploitation patterns are probably affecting fishing mortality and stock biomass levels in both oceans in similar manners.

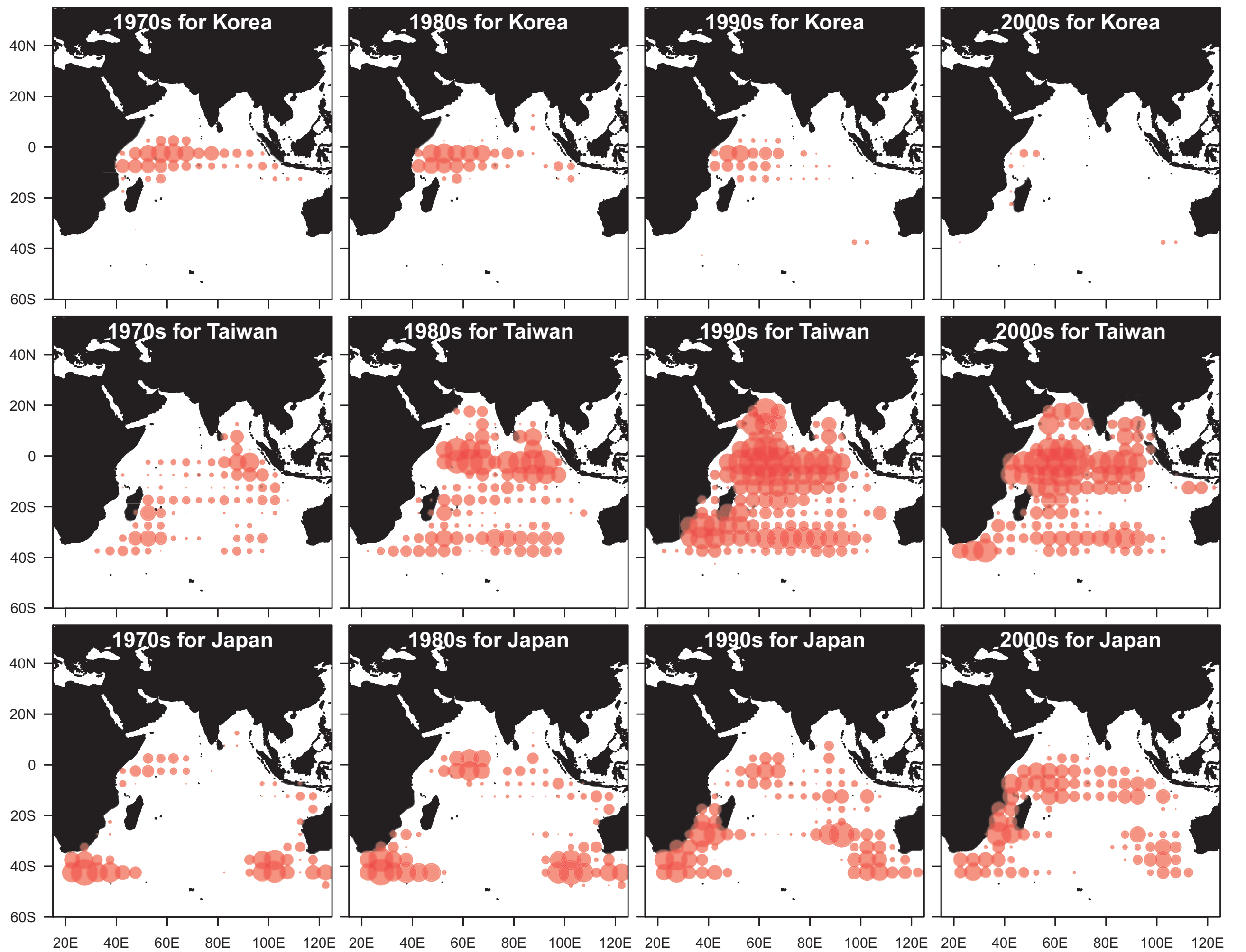

Figure 1. Korean, Taiwanese, and Japanese longline effort in the Indian Ocean by decade from the 1970s to the 2000s (log-scaled by 1.5 million hooks).

Both the Atlantic and the Indian oceans have stocks that experienced particularly high fishing pressure for the period 1992–2008 (Figure 3). As a result, most stocks were experiencing overfishing (Figure 4) and are essentially overfished at the present time or are at the margin of being overfished in the Indian Ocean (with the exception of swordfish) (Figure 6). A similar feature is observed in the Atlantic, with a different story regarding swordfish, where we see evidence of rebuilding in recent years (Figures 5 and 7).

Estimating threshold effort size

Threshold effort levels across stocks were calculated for each stock by monitoring the estimated F trajectories over time. When F exceeded F_{MSY} (a target reference point used by both tRFMO commissions) for 3 consecutive years, effort in the third year was selected as the threshold effort value for the species (Table 3). It appears that this threshold was exceeded in the Atlantic Ocean as early as 1964 for white marlin (74 million hooks), and longline effort has remained above this level ever since. However, for the majority of other species, overfishing began in the late1980s or early 1990s. Estimated thresholds ranged from 175 million hooks for sailfish to 395 million hooks for swordfish in the Atlantic. An overall equally weighted average threshold effort for the Atlantic is 240 million hooks.

Results from the Indian Ocean indicate a later history of over-exploitation (2000s for swordfish and blue marlin and 2013 for sailfish). Striped marlin (which was targeted and also caught incidentally off the coast of Australia in the Southeast Indian Ocean in the 1970s and 1980s) is an exception, reaching the threshold in the 1980s. Equally weighting exceeded effort thresholds across species for the Indian Ocean indicate a threshold effort of 364 million hooks.

Catch analysis: who takes the bulk of the billfish catch?

Overall trends in billfish catches by species are shown for the two oceans in Figure 8 and Table 3. Catches in the Atlantic peaked in 1987 and have since been declining, possibly due to catch constraints implemented across fisheries (Restrepo *et al.*, 2003). In contrast, billfish catches in the Indian Ocean have dramatically increased over the same time-period and are still increasing (Figure 8). The majority of the catch in the Atlantic Ocean (>75%) comes from developed countries (i.e. European Union

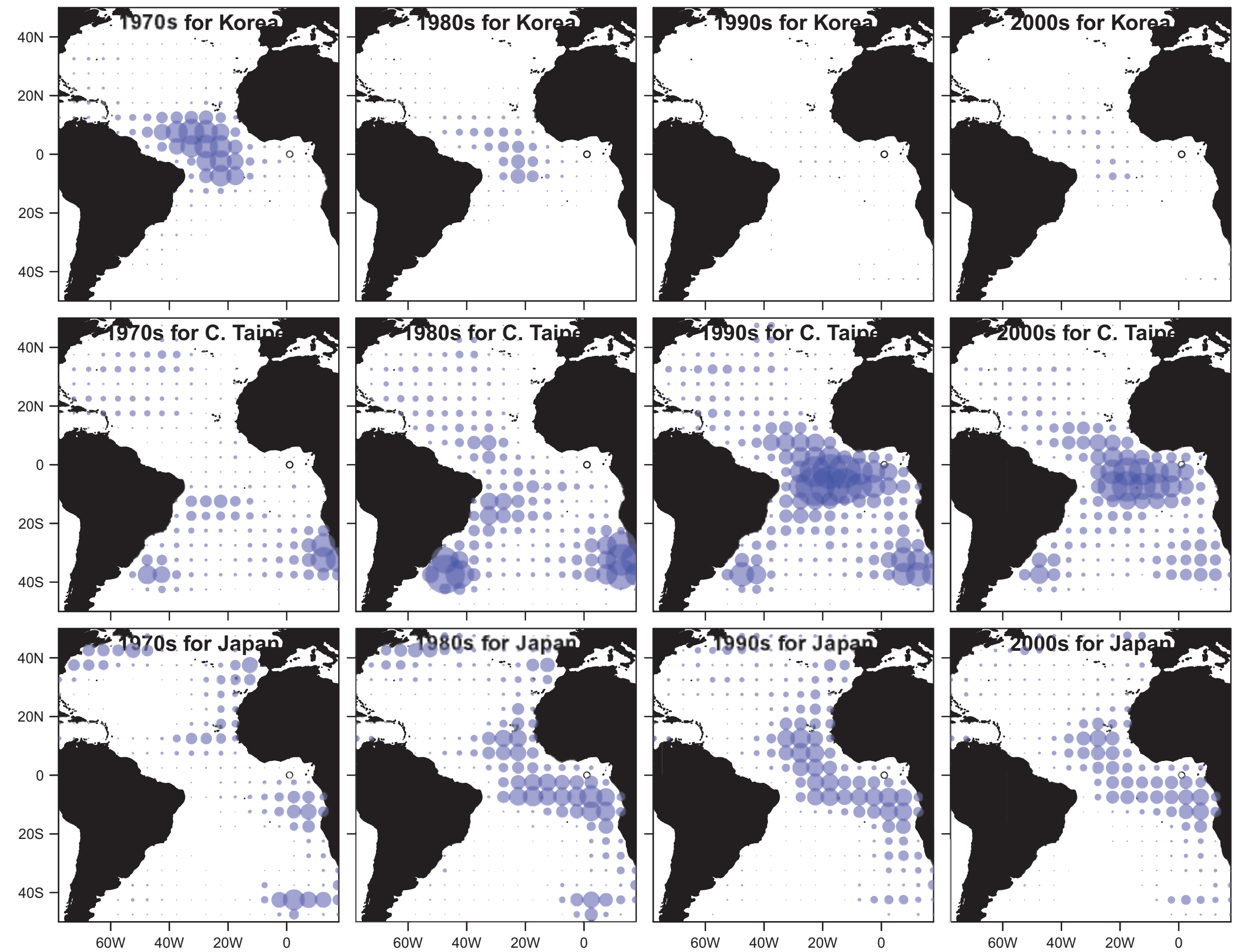

Figure 2. Korean, Taiwanese, and Japanese longline effort in the Atlantic Ocean by decade from the 1970s to the 2000s (log-scaled by 5 million hooks).

and United States), whereas in the Indian Ocean, catch arises primarily from developing nations, i.e. Indonesia, Iran, and Sri Lanka (Figure 8).

Relationship between stock status and GDP

Figure 9 displays the overall composite GDP rank of the main countries reporting billfish catches (those contributing up to 75% of the total catch), the number of years that the stocks were experiencing overfishing, and the expected recovery time based on available data for each tRFMO. In the case of IOTC, no stock has been overfished (other than striped marlin), so recovery time is defined as the number of years overfishing ($F > F_{MSY}$), even though the stock is not overfished ($B > B_{MSY}$). Northern and southern swordfish stocks in the Atlantic Ocean are considered to have been rebuilt (i.e. B is currently above B_{MSY}). White marlin is also not currently experiencing overfishing (i.e. F is below F_{MSY}), but it remains overfished (i.e. B is below $B_{MSY,}$ Figure 7). The mean GDP was higher (implying a lower rank, indicating higher development) for the countries reporting billfish catches in ICCAT than in IOTC. Moreover, the mean calculated number of years of overfishing was higher in ICCAT than in IOTC, and the average time of recovery was higher in the Atlantic than in the Indian Ocean (Figure 9, Table 3).

Discussion

It is clear from the results that the current level of effort across both oceans is too high to sustain nontarget species like marlin and sailfish, with many stocks showing signs of overfishing or being overfished based on the most recent assessments produced by the respective tRFMOs. Effort levels have actually been fairly similar for the Indian and Atlantic oceans, but the Indian Ocean has a higher estimated threshold level, which has taken longer to reach, and many of the stocks are only now experiencing overfishing.

Effort has steadily increased over time in both oceans, but has declined since the early 2000s. This is linked to the ability of the fleets to improve their catch and search patterns due to learned experience fishing different areas of the Atlantic and Indian oceans (Clarke, 1990; Allen *et al.*, 2010). Longline fishing effort is distributed widely across the tropical and temperate areas in both oceans, based on the targeting strategies for tuna species in these areas (Allen *et al.*, 2010). The overlapping distribution of these species with nontarget species such as billfish (and sharks) means

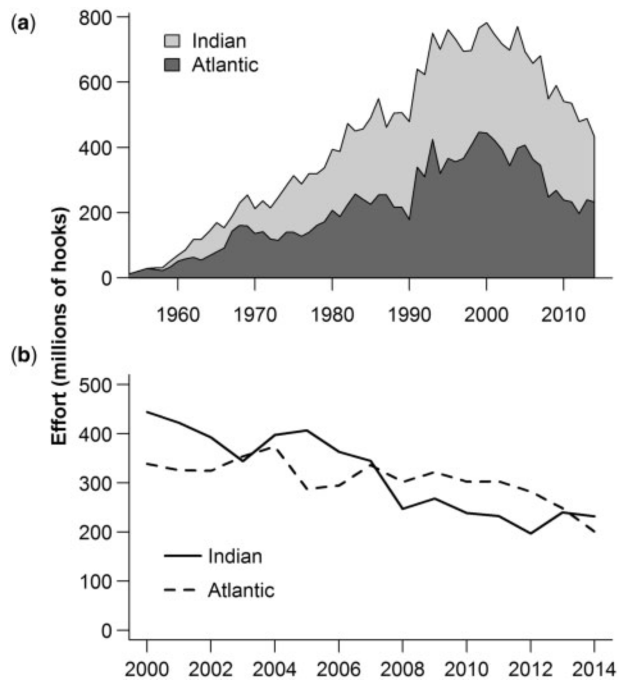

Figure 3. Overall longline effort in the Atlantic and Indian Oceans over the entire series (a) and in recent years (b).

that the resulting effort on these stocks can also be high. Nevertheless, effort trajectories across both oceans have been largely declining in recent years (Figure 3). If billfish were the main species targeted, such a decline would indicate that both oceans are at full capacity and that biomass trajectories show declining trends in both oceans with respect to effort (Figures 4 and 5). When this happens, i.e. overcapitalization of effort (Allen *et al.*, 2010), fleet efficiency would be less than optimal and a consequential natural reduction in effort should occur based on maximum economic yield concepts (Clarke, 1990). However, since billfish are not the targeted species, the observed effort declines have largely not occurred as catch of other high-value species (bluefin, bigeye, and yellowfin tunas), which may be more abundant and profitable, and as the main target species of these longline fisheries dominate the economics of the fishery.

Despite having a smaller total area and lower productivity than the Atlantic (Tomczak and Godfrey, 2003), it appears that the Indian Ocean supports a higher threshold effort level, which, in turn, implies higher productivity of istiophorid billfishes in this ocean basin. Although the Atlantic has a higher total productivity, much of this occurs in temperate regions where istiophorid billfishes are less prevalent. However, despite these differences, almost all stocks in the Indian Ocean are currently on the verge of being overfished. Swordfish is the exception, although some model scenarios suggest that overfishing of swordfish could also be occurring in the Indian Ocean (Sharma and Herrera, 2014).

Atlantic swordfish (north and south) and western Atlantic sailfish (2016 assessment, ICCAT, 2016) remain the three billfish stocks which have rebuilt from overfished conditions. In the case of Atlantic swordfish, a combination of strict, country-specific catch limits coupled with productive biology and favourable recruitment (Neilson *et al.*, 2013; Pons *et al.*, 2017) allowed the stock to recover. For western sailfish, it is mandatory to release the species in most of the western Atlantic longline fisheries. In addition, the species is primarily found in coastal regions where longline effort is lower (Horodysky *et al.*, 2016). In the Indian Ocean, a similar reversal of declining abundance occurred through a reduction in fishing pressure due to external forcing events, i.e. piracy (Kaplan *et al.*, 2014). The decline in effort in the Indian Ocean can largely be attributed to the threats to boats from pirates operating around the horn of Africa (primarily Somalia). However, with the reduced threat of piracy in recent years, effort appears to be increasing again (Figure 3). In the Atlantic and Indian oceans, declining catches and higher fuel prices could be attributed to the larger basin-wide effort declines as fishery profitability is affected by these factors (Clarke, 1990).

In both oceans, swordfish stocks exhibit different behaviour from other billfishes and are either recovered (ICCAT) or not close to overfished or undergoing overfishing (IOTC). This is potentially due to the biology of swordfish, making the species among the fastest growing of all billfish species (Neilson *et al.*, 2013) and their broader distribution in pelagic waters. Large female swordfish make extensive foraging migrations to northern (and presumably southern) temperate waters (Neilson *et al.*, 2014) that are subjected to less longline effort (Figures 1 and 2), making them less vulnerable to the fisheries targeting tunas. In addition, fisheries have shifted to targeting tropical tunas (primarily bigeye) as the most profitable species which has likely reduced targeted longline effort on swordfish; hence, effective effort has likely declined faster than total effort. Last, swordfish, whether targeted or not, are generally landed, making output controls (quotas) far easier to monitor and far more effective than for other billfish, which often are not retained. In contrast, the other billfishes are either prohibited from being retained by some fleets or are not always retained. Also, given the epipelagic nature of both istiophorids and the target tunas compared with the more mesopelagic nature of swordfish (Brill and Lutcavage, 2001; Braun *et al.*, 2015), it is harder to avoid istiophorid billfishes when targeting tunas. Hence, output controls, when istiophorid billfishes remain as incidental catches of the tuna-targeted fisheries, will have limited effectiveness without other conservation measures in place (Horodysky *et al.*, 2016).

Our main hypothesis was that reversing overfishing of billfish stocks (i.e. reducing fishing mortality to optimal fishing mortality rates) would be quicker in the Atlantic where governance capacity is greater than in the Indian Ocean. However, Figure 9 indicates the opposite, whereby the average time taken to reverse the trend in overfishing (Figure 9c) was greater in the Atlantic than in the Indian Ocean. This is largely because stocks in the Atlantic Ocean have experienced overfishing for a longer period of time and reversing this process through catch limits, effort restrictions, and other measures is taking more time (Figure 9b). Moreover, much (>60%) of the reversal in overfishing in the Indian Ocean is attributable to the piracy-related (>60%) declines in effort after 2006 (Figure 3), with a consequential reduction in catches off the coast of East Africa (Somalia, Kenya, and Mozambique). As piracy-related activities have declined in recent years, effort has begun to rise, increasing the potential for overfishing to reoccur given the notable absence of binding, country-specific catch controls which have been effective in the Atlantic (Neilson *et al.*, 2013; Hilborn and Ovando, 2014; Pons *et al.*, 2017). Clearly, overfishing can be controlled and rectified rather quickly through internal (catch restrictions) or external (piracy) factors, but the

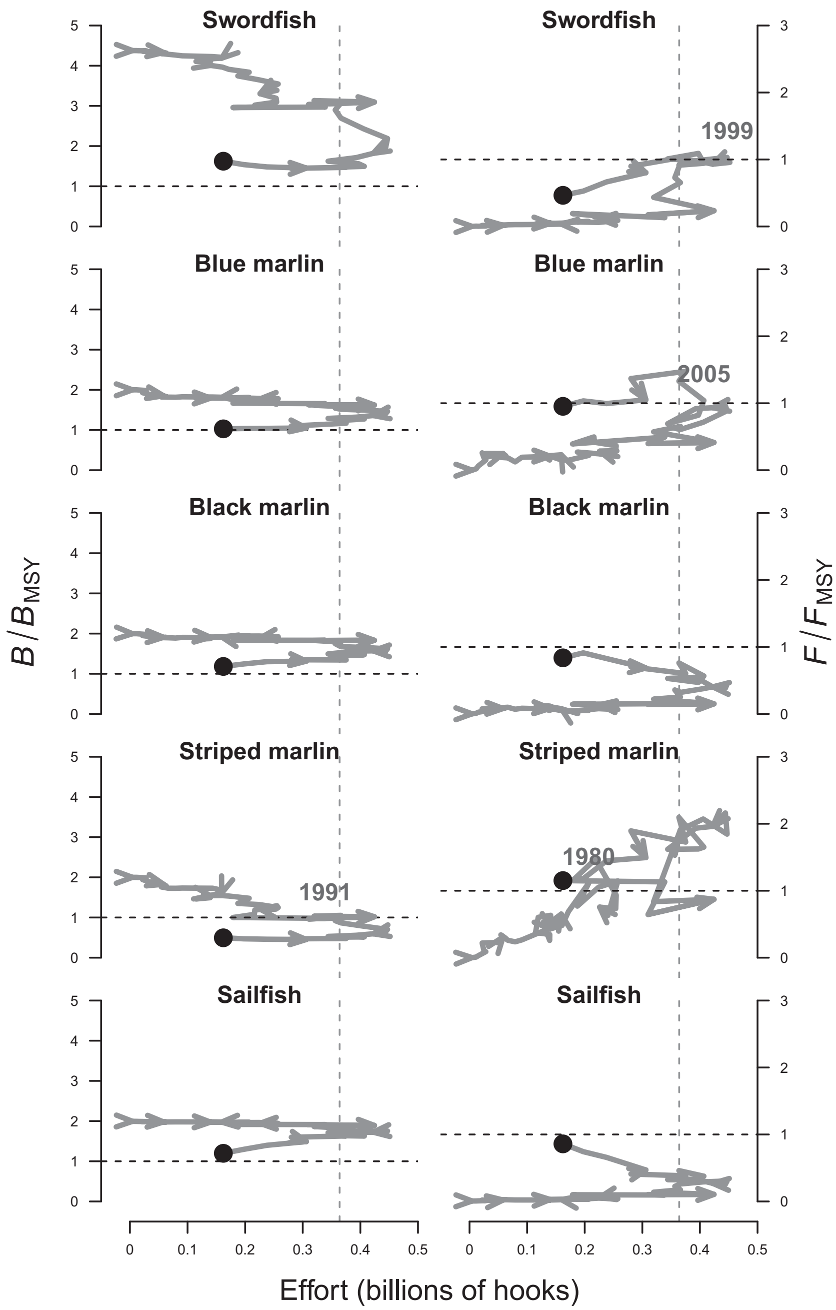

Figure 4. Indian Ocean stock status trajectories for biomass and fishing mortality with respect to effort (in billions of hooks). Horizontal lines indicate where the stocks should not be below with respect to biomass (*B*, left panel), and above with respect to fishing mortality (*F*, right panels). Vertical lines indicate where the suggested threshold effort lies. The trajectory displayed starts in 1952 and goes to 2014 (the left-most point in each graph is 1952, and the last point is 2014, where the time-series ends). The year in which the thresholds are exceeded with respect to a threshold is displayed on the graph. Vertical lines are where threshold effort sizes are estimated. Note: swordfish in the Indian Ocean has SSB/SSB_{MSY} as a reference point. Vertical lines indicate where threshold effort sizes are estimated.

institutional commitment and governance capacity to maintain catch levels corresponding to commission objectives often takes longer to achieve. Nevertheless, for catches of nontarget species that are not necessarily retained, output controls may be insufficient in isolation of other measures (Pons *et al.*, 2017).

Table 4 highlights the fact that the bulk of the catch in the Indian Ocean comes from less developed countries such as Indonesia, India, Sri Lanka, and Pakistan compared with the Atlantic Ocean where the largest proportion of catch is from the EU followed by the United States. The nature of these fisheries is also very different; in the coastal, developing countries of the Indian Ocean, billfish are not considered incidental catch, but are often targeted through a directed-take fishery using gillnets, drift gillnets, and other troll and longline gear (IOTC, 2016b). In such cases, governance is even more important, as direct management measures are necessary to control these fisheries, although

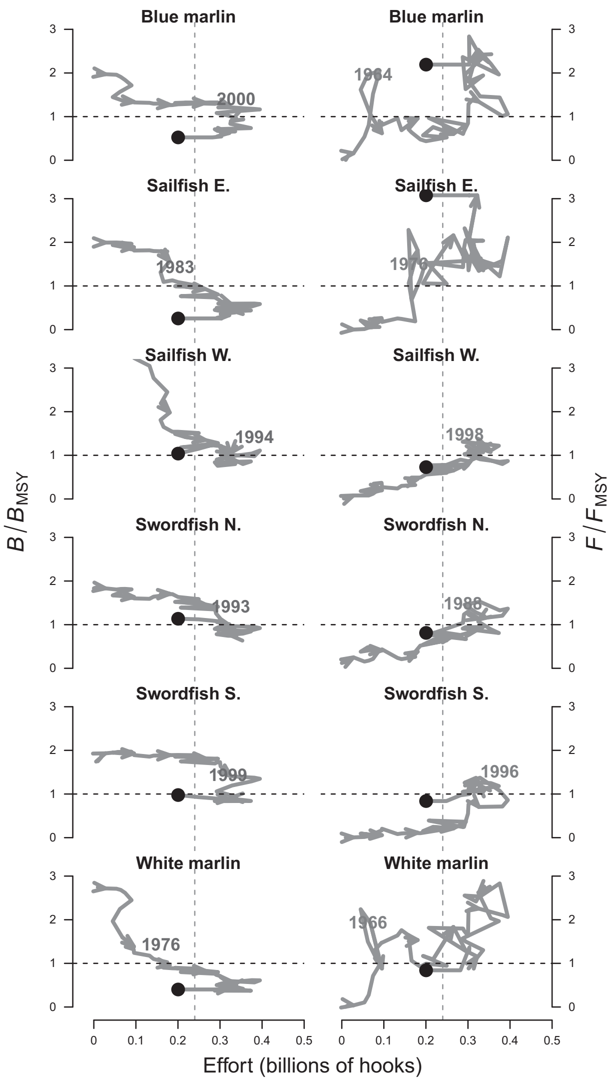

Figure 5. Atlantic Ocean stock status trajectories for biomass and fishing mortality with respect to effort (in billions of hooks). Horizontal lines indicate where the stocks should not be below with respect to biomass (*B*, left panel), and above with respect to fishing mortality (*F*, right panels). Vertical lines indicate where the suggested threshold effort lies. The trajectory displayed starts in 1952 and goes to 2014 (the left-most point in each graph is 1952, and the last point is 2014, where the time-series ends). The year in which the thresholds are exceeded with respect to a threshold is displayed on the graph. Note: Mediterranean swordfish is not used or displayed as it is a different stock and affected differently by Mediterranean effort only. Vertical lines are where threshold effort sizes are estimated.

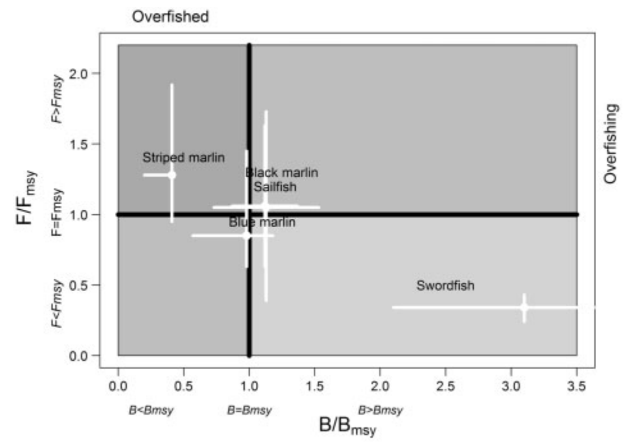

Figure 6. Current stock status using a Kobe plot for Indian Ocean billfish stocks. The vertical and horizontal bars indicate the uncertainty in the assessment results with respect to B/B_{MSY} and F/F_{MSY}. The point where they intersect indicates the point estimate reported to the IOTC based on the last evaluated assessment year for the stock.

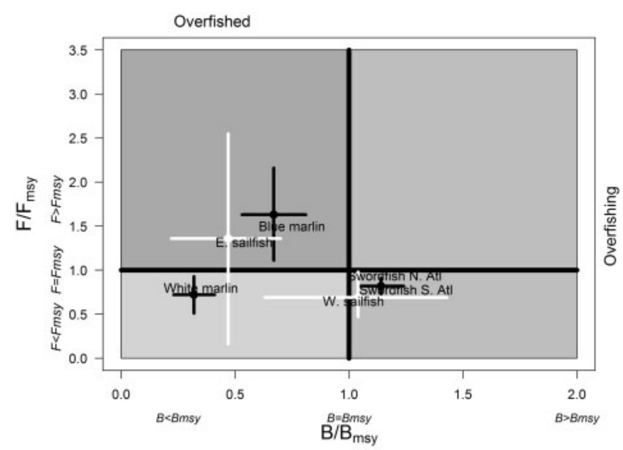

Figure 7. Current stock status using a Kobe plot for Atlantic Ocean billfish stocks. The vertical and horizontal bars indicate the uncertainty in the assessment results with respect to B/B_{MSY} and F/F_{MSY}. The point where they intersect indicates the point estimate reported to ICCAT based on the last evaluated assessment year for the stock.

overcapacity would eventually lead to a decline in effort (unless subsidies are provided for some of these fleets or they are the primary source of food for coastal fishing communities). In the case of countries fishing in the Atlantic, other than possibly Brazil and Morocco (which take a small portion of the catch compared with the developed countries, Table 4), this is not a serious consideration. Furthermore, we note that basic geopolitical instability in several IOTC jurisdictional areas and ongoing violent conflicts remain as factors influencing fishery dynamics, as evidenced by Somali piracy, but also weaken the potential for effective fisheries management.

Pons *et al.* (2017) have shown that, among different management measures considered, the implementation of TACs had the greatest effect on stock rebuilding, the measurement most credited by Neilson *et al.* (2013) for recovering Atlantic swordfish. While IOTC has only recently implemented catch limits for the yellowfin tunas fisheries, catch controls in ICCAT have been implemented for swordfish, Atlantic bluefin, bigeye, and albacore, and recently as well for yellowfin, white marlin, and blue marlin (ICCAT, 2016). The most effective catch controls also have country-specific quota levels so that individual countries must comply with an individual quota, e.g. ICCAT bluefin tuna, swordfish, and albacore, rather than sharing one overall quota. The only other tRFMO that has an effective management control,

Table 1. Correlations between estimated effort in the Indian Ocean and F/F_{MSY} and B/B_{MSY} for all billfish stocks.

Indian Ocean	Effort	Swordfish B/B_{MSY}	Blue marlin B/B_{MSY}	Black marlin B/B_{MSY}	Striped marlin B/B_{MSY}	Sailfish ind. B/B_{MSY}
Effort	1.00					
Swordfish B/B_{MSY}	−0.92	1.00				
Blue marlin B/B_{MSY}	−0.81	0.94	1.00			
Black marlin B/B_{MSY}	−0.76	0.91	0.99	1.00		
Striped marlin B/B_{MSY}	−0.94	0.99	0.92	0.88	1.00	
Sailfish ind. B/B_{MSY}	−0.70	0.87	0.96	0.97	0.85	1.00

F trajectory—with no lag

Indian Ocean	Effort	Swordfish F/F_{MSY}	Blue marlin F/F_{MSY}	Black marlin F/F_{MSY}	Striped marlin F/F_{MSY}	Sailfish ind. F/F_{MSY}
Effort	1.00					
Swordfish F/F_{MSY}	0.82	1.00				
Blue marlin F/F_{MSY}	0.69	0.89	1.00			
Black marlin F/F_{MSY}	0.52	0.80	0.92	1.00		
Striped marlin F/F_{MSY}	0.86	0.89	0.83	0.69	1.00	
Sailfish ind. F/F_{MSY}	0.47	0.72	0.85	0.97	0.64	1.00

Values greater than the absolute value of 0.7 are shaded showing a high correlation between effort and fishing mortality or stock status.

Table 2. Correlations between estimated effort in the Atlantic Ocean and F/F_{MSY} and B/B_{MSY} for all billfish stocks.

Atlantic Ocean	Effort	Blue marlin B/B_{MSY}	Sailfish E B/B_{MSY}	Sailfish W B/B_{MSY}	Swordfish N B/B_{MSY}	Swordfish S B/B_{MSY}	White marlin B/B_{MSY}
Effort	1.00						
Blue marlin B/B_{MSY}	−0.78	1.00					
Sailfish E B/B_{MSY}	−0.95	0.79	1.00				
Sailfish W B/B_{MSY}	−0.90	0.74	0.92	1.00			
Swordfish N B/B_{MSY}	−0.93	0.75	0.89	0.77	1.00		
Swordfish S B/B_{MSY}	−0.85	0.88	0.84	0.67	0.91	1.00	
White marlin B/B_{MSY}	−0.85	0.84	0.86	0.95	0.77	0.70	1.00

F trajectory – with no lag

Atlantic Ocean	Effort	Blue marlin F/F_{MSY}	Sailfish E F/F_{MSY}	Sailfish W F/F_{MSY}	Swordfish N F/F_{MSY}	Swordfish S F/F_{MSY}	White marlin F/F_{MSY}
Effort	1.00						
Blue marlin F/F_{MSY}	0.52	1.00					
Sailfish E F/F_{MSY}	0.78	0.50	1.00				
Sailfish W F/F_{MSY}	0.91	0.65	0.76	1.00			
Swordfish N F/F_{MSY}	0.87	0.48	0.63	0.80	1.00		
Swordfish S F/F_{MSY}	0.83	0.78	0.68	0.89	0.80	1.00	
White marlin F/F_{MSY}	0.63	0.46	0.34	0.59	0.71	0.57	1.00

Values greater than the absolute value of 0.7 are shaded showing a high correlation between effort and fishing mortality or stock status.

Table 3. Threshold effort and years when F exceed F_{MSY} for 3 consecutive years in a time-series.

Ocean	Species	Effort threshold (*M*)	Year threshold exceeded	Years of overfishing	Year overfishing stopped
Atlantic	Blue Marlin	300	1990	23	
	Sailfish E	175	1975	38	
	Sailfish W	292	1998	10	2008
	Swordfish N	207	1987	16	2003
	Swordfish S	395	1995	16	2011
	White marlin	74	1964	15 and 30	1979 and 2012
Indian	Swordfish	406	1998, 2002, and 2003	3	2003
	Blue marlin	397	2004	8 (in 2010 dropped)	2012
	Black marlin		Not overfished		
	Striped marlin	254	1986	24 (excl 2 years)	2012
	Sailfish	397	2013	1	

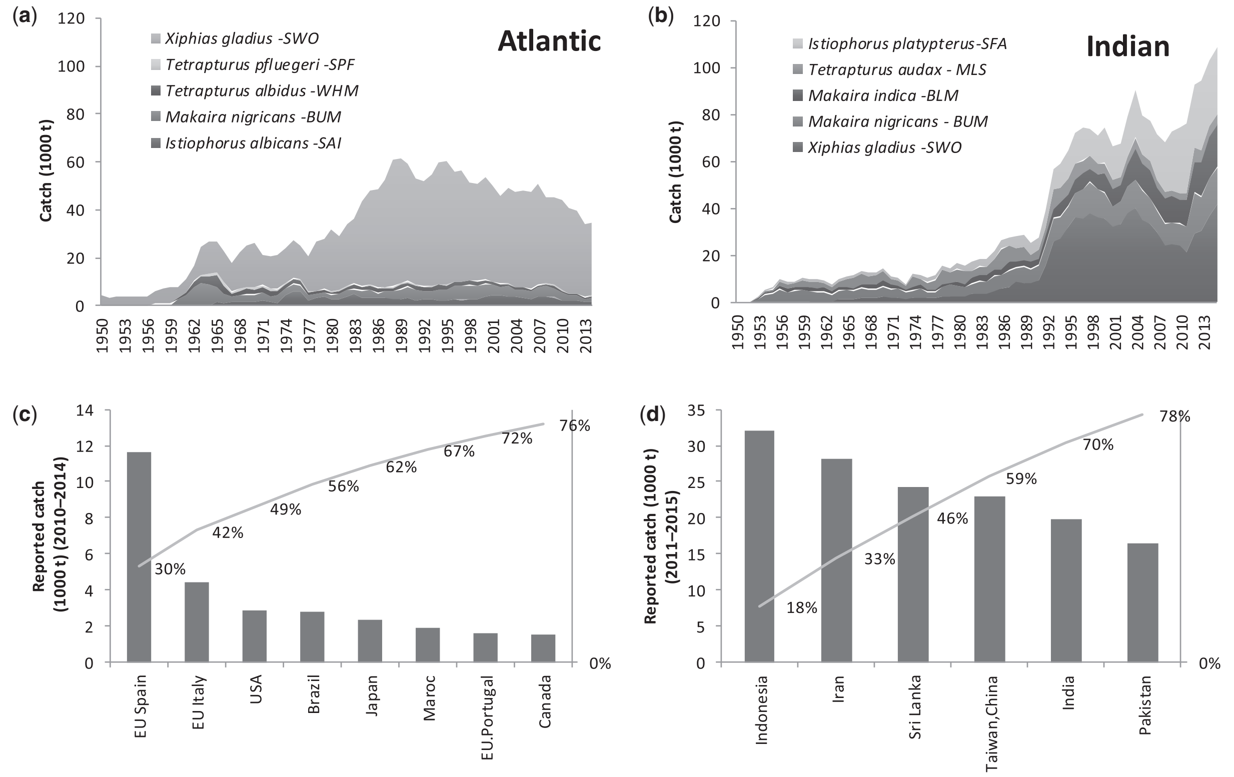

Figure 8. Overall billfish catch by ocean (a and b) and by major contracting parties and cooperating noncontracting parties to the respective commission, and CPCs (>75% of the total billfish catch) (c and d) for the recent 5-year period (2010–2014).

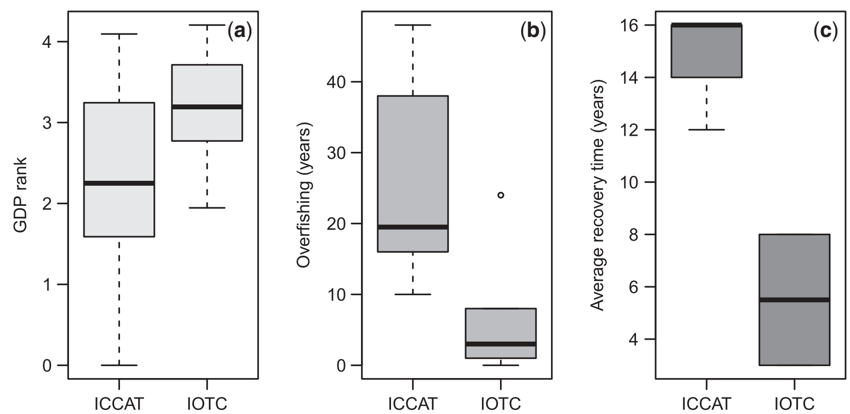

Figure 9. GDP rank (a), years of overfishing (b), and recovery time by tRFMO (c) for ICCAT and IOTC. The shaded areas show the interquartile range, points indicate the outliers, and the horizontal bars in the shaded areas indicate the median values by tRFMO group.

again in the form of catch limits, is CCSBT, and stocks are showing signs of rebuilding. Quota strategies work only if governance, monitoring, and control mechanisms exist, and GDP may be a simple indicator (Figure 9) of why these measures might perform better in some fisheries than in others. Melnychuk *et al.* (2017) found that, over other economic and fishery indicators, GDP is one of the most important variables affecting the intensity of fisheries management systems. In particular, Pons *et al.* (in review) found that tRFMOs with countries having higher GDP tended to perform better in terms of research, management, and enforcement. In these three categories, ICCAT scored higher than IOTC. Nevertheless, the counterintuitive results from this analysis show the complexity of individual fisheries and the range of other factors interacting with them that make intensity of management very different among tRFMOs.

Although IOTC implemented input management controls in the form of an area closure between 2011 and 2012 for some months for certain vessel types off the coast of Somalia (IOTC Resolution10/01), the effect was small, as the number of vessels operating in that time and area strata were relatively few (Martin *et al.*, 2011; IOTC, 2013). Input management measures are relatively easy to implement, but difficult to enforce without an appropriate monitoring and surveillance system (Cochrane and Garcia, 2009), and this was evident from the IOTC experience.

Table 4. GDP ranks of the countries with the highest catch proportions on billfish.

RFMO	Country	Average catch (2010–2015) (*t*)	% catch	% cum	Global GDP rank	GDP in billions ($)
ICCAT	EU Spain	11 605	30	30	14	1252
	EU Italy	4425	12	42	8	1853
	USA	2830	7	49	1	18 562
	Brazil	2819	7	56	9	1770
	Japan	2330	6	62	3	4730
	Morocco	1924	5	67	60	105
	EU Portugal	1569	4	72	47	206
	Canada	1542	4	76	10	1532
	Average				19	3751
IOTC	Indonesia	32 107	18	18	16	941
	Iran	28 223	15	33	27	412
	Sri Lanka	24 274	13	46	67	82
	Taiwan, China	22 971	13	59	22	519
	India	19 803	11	70	7	2 251
	Pakistan	16 386	9	78	41	285
	Average				30	748

In conclusion, we believe that ICCAT has greater capacity than IOTC to implement effective management controls to reduce overall catch and rebuild stocks. This is primarily due to the fact that the ICCAT member countries that take the bulk of the catch or incidental catch of billfishes have stronger governance capacity and the primary fleets are industrial longliners (as incidental catch) or directed sport fisheries which have greater potential for management than artisanal fleets. Nonetheless, the level of reduction in longline effort that may be needed to recover stocks may be very difficult to achieve because it is likely to affect catches of the targeted tunas and swordfish as well as the billfish that are overexploited. Other controls such as changing the gear configuration (J-hooks to circle hooks) may have also helped reduce mortality of the nontargeted species in ICCAT vs. IOTC. Although IOTC has lower capacity in terms of governance, the fact that much of the billfish catches are retained means that output controls, if enforced, could actually limit the total catch.

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All views expressed in this article are the view of the authors and not the agencies they represent.

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