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Effects of biological, economic and management factors on tuna and billfish stock status

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Abstract

Commercial tunas and billfishes (swordfish, marlins and sailfish) provide considerable catches and income in both developed and developing countries. These stocks vary in status from lightly exploited to rebuilding to severely depleted. Previous studies suggested that this variability could result from differences in life-history characteristics and economic incentives, but differences in exploitation histories and management measures also have a strong effect on current stock status. Although the status (biomass and fishing mortality rate) of major tuna and billfish stocks is well documented, the effect of these diverse factors on current stock status and the effect of management measures in rebuilding stocks have not been analysed at the global level. Here, we show that, particularly for tunas, stocks were more depleted if they had high commercial value, were long-lived species, had small pre-fishing biomass and were subject to intense fishing pressure for a long time. In addition, implementing and enforcing total allowable catches (TACs) had the strongest positive influence on rebuilding overfished tuna and billfish stocks. Other control rules such as minimum size regulations or seasonal closures were also important in reducing fishing pressure, but stocks under TAC implementations showed the fastest increase of biomass. Lessons learned from this study can be applied in managing large industrial fisheries around the world. In particular, tuna regional fisheries management organizations should consider the relative effectiveness of management measures observed in this study for rebuilding depleted large pelagic stocks.

Keywords Fisheries management, marine conservation, stock assessment, stock status, tuna fisheries

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Introduction

The oceans have been subjected to intensive fishing pressure over the past 60 years, with fisheries expanding to new geographical areas, shifting from coastal to pelagic environments (Swartz *et al.* 2010). As a result, an estimated 28–33% of the large well-assessed fisheries of the world are overfished (Branch *et al.* 2011; FAO 2014), while many smaller unassessed fisheries in poorer countries are likely in worse shape (Costello *et al.* 2012). These depleted fisheries have negatively affected food security, fishing-dependent communities and marine ecosystems globally (Scheffer *et al.* 2005).

Tunas and billfishes are important contributors to food security and income in both developed and developing countries, and some of these stocks have experienced high exploitation rates for decades (Collette *et al.* 2011; Juan-Jordá *et al.* 2011; FAO 2014). While tunas and swordfish are the main target species of many fisheries, marlins are a common by-catch, particularly in commercial longline fisheries. Throughout the study, 'tunas' were defined as the following commercially important species, often called the principal market tunas: southern bluefin (*Thunnus maccoyii*), Atlantic bluefin (*T. thynnus*), Pacific bluefin (*T. orientalis*), bigeye (*T. obesus*), albacore (*T. alalunga*), yellowfin (*T. albacares*) and skipjack (*Katsuwonus pelamis*). Also, 'Billfishes' includes not only marlins (*Istiompax indica, Makaira nigricans, Kajikia albidus* and *K. audax*) and sailfish (*Istiophorus albicans*) but also swordfish (*Xiphias gladius*).

A substantial proportion of these stocks has been categorized as overfished (Restrepo *et al.* 2003; Collette *et al.* 2011; Juan-Jordá *et al.* 2011; Punt *et al.* 2015). In 2003, catch-per-unit-effort data were used to suggest that industrial fishing pressure had reduced the abundance of tunas and billfishes (and other ocean predators) by 90% from pre-industrial levels (Myers and Worm 2003). More recent studies based on biomass trends estimated from stock assessment models found that tunas and their relatives had actually declined by an average of 60% from unfished levels (Juan-Jordá *et al.* 2011), for which most stocks were above the biomass level that would produce maximum sustainable yield (MSY), and only a few were fished intensively enough to be classified as experiencing overfishing (Hampton *et al.* 2005; Polacheck 2006; Sibert *et al.* 2006).

Although the status of tunas and billfishes is well documented in the literature, the factors that drive the current status of these stocks are often not jointly analysed. For example, life-history strategies can affect the probability of stock collapse of many fish species (Reynolds *et al.* 2005). Tunas and billfishes range from small tunas and marlins with rapid growth rates and short lifespans to big tunas and swordfish with larger body sizes and longer lifespans (Fromentin and Fonteneau 2001; Juan-Jordá *et al.* 2012). Some tuna studies suggest that attributes such as short lifespan, wide geographical distribution and opportunistic behaviour make tropical tunas more productive and less susceptible to collapse than temperate tunas (Majkowski 2007; Collette *et al.* 2011; Juan-Jordá *et al.* 2011). Also, Sadovy (2001) suggested that, in long-lived species, the probability of extinction is related to limited geographical range, being part of mixed-species fisheries or being distributed mainly in areas of intense fishing activity.

Moreover, economic factors may be equally or more important in determining stock status. Fishery profits, and not the trophic levels and associated characteristics of the target species, were found to be the dominant driver of historical fishery development patterns in a study that covered a wide range of stocks (Sethi *et al.* 2010). High market values drive exploitation far below MSY biomass levels and have increased the risk of stock collapse (Collette *et al.* 2011). Notably, while Pacific bluefin tuna and albacore tuna are both temperate species, albacore is used mostly for the cheaper canned tuna market, while Pacific bluefin serves the high-end sashimi market (Majkowski 2007). It may therefore not be surprising that Pacific bluefin is overfished, while some albacore stocks are not.

In addition to life history and economic value, exploitation history and management measures drive the status of tuna and billfish resources. Exploitation history is an important factor affecting the conservation status of many exploited stocks (Melnychuk *et al.* 2013; Neubauer *et al.* 2013) including tuna species. Atlantic bluefin tuna has been fished in the Mediterranean since the 7th century BC and reconstructed bluefin tuna trap catches date back to the 16th century (Fromentin and Powers 2005). On the other hand, skipjack and yellowfin tuna in the Indian Ocean were not targeted until the development of large-scale commercial purse seine fisheries in the 1980s (Parks 1991), and these stocks are currently considered to be healthy (Juan-Jordá *et al.* 2011). In general, the development of commercial fisheries started earlier for species that were easily accessible, abundant and valuable and then expanded to less valuable species (Sethi *et al.* 2010).

We also expect that highly regulated stocks are those that have been experiencing overfishing, where strict management measures are placed to rebuild them, while stocks that lack strong regulations are more often not over-exploited. Tuna and billfish stocks are managed by tuna Regional Fisheries Management Organizations (tRFMOs), including: 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). As an example, international management has clearly failed to keep some bluefin tuna stocks near target reference points despite their high commercial value (Fromentin and Powers 2005; Worm *et al.* 2009), and the ability of tRFMOs to prevent stock depletion and overfishing has been questioned (Cullis-Suzuki and Pauly 2010). The exploitation history and management actions taken vary greatly by tRFMO, and this may have a strong impact on the status of tuna and billfish stocks (Parma *et al.* 2006). Many tRFMOs have implemented a variety of input (or effort) controls, while others have implemented also output (or quota) controls.

Although there has been considerable discussion about what elements are required for successful fisheries management (Hilborn 2007; Beddington *et al.* 2007), the effectiveness of specific management measures for tunas and billfishes has not been analysed on a global scale. The purpose of this study was two-fold: (i) to evaluate the effect of different factors (management measures, life history, economic values and exploitation history) on the current biological status of major tuna and billfish stocks of the world and (ii) to identify which management measures have promoted the recovery of depleted stocks.

Methods

In general, among tRFMOs, the stock status is summarized using two biological reference points, B/B_{MSY} (current biomass, B, in relation to the B that produces MSY) and F/F_{MSY} (current fishing mortality, F, in relation to the F that produces MSY). Thus, these reference points were considered in this study to define tuna and billfish stock status. Throughout the manuscript, we defined stocks as 'overfished' if the biomass was reduced to a level less than what would provide MSY ($B < B_{\mathrm{MSY}}$) and 'overfishing' if the stock is subjected to a fishing mortality rate greater than that expected to produce the MSY ($F > F_{\mathrm{MSY}}$). Stocks that had $B > B_{\mathrm{MSY}}$ and $F < F_{\mathrm{MSY}}$ were considered 'healthy'.

Data

Data used to assess the status of tunas and billfishes were obtained from stock assessment outputs compiled in the RAM Legacy Stock

Assessment Database (Ricard *et al.* 2012). Most reference points, time series, available from assessments were current through 2012. We found data for 40 stocks of 13 species, 7 species of major commercial tunas and 6 species of billfishes (Figs. S1 and S2) from at least 48 stocks defined globally (Table 1).

Data for management variables were compiled from information available on the websites and reports of different tRFMOs and through personal communication with their staff. Only regulations that existed during the 5- to 10-year period leading up to the last stock assessment were considered for each stock, although in some cases new management measures are currently in place. Table 2 summarizes all management measures in place by stock, and Table S1 lists the relevant Web references.

Effect of different factors on the current biological status of major tuna and billfish stocks

To evaluate our first objective in analysing which factors can predict the biological status of tuna and billfish stocks, we assessed the effect and importance of each predictor (Fig. S3) on the geometric mean of the last 10 years of each time series of the two stock performance measures considered (B/B_{MSY} and F/F_{MSY}) using a random forest analysis (Breiman 2001). This approach was used previously to analyse similar data (Melnychuk *et al.* 2013) and has been increasingly used in ecology and fisheries studies (Lennert-Cody and Berk 2007; Gutiérrez *et al.* 2011). The main advantages of this method are that the nonparametric approach does not assume any particular distribution of error, it allows the use of many predictors in relation to the total number of observations, and it allows for visualization of nonlinear relationships. It is an ensemble method that aggregates *K* trees (forming the forest), each tree similar to ones constructed with CART (Classification and Regression Trees) and grown using a bootstrapped sample of the original data set. Each tree in the forest uses at each node only a number of variables randomly sampled as candidates from a subset of the explanatory variables (*mtry*), which in our case was equal to a third of the predictor variables (Liaw and Wiener 2002). To stabilize the mean square error, we used 10 000 trees. We used the 'randomForest' package (version 4.6-7) (Liaw and Wiener 2002) in R (version 3.0.1) (R Core Team 2014) for this analysis. We presented variable importance plots for both performance measures as the decrease in mean accuracy resulting from the removal of each variable and presented partial dependence plots to show the effect of the main continuous predictors on the response variables (Liaw and Wiener 2002). We showed the results of partial dependence plots for tunas and billfishes independently, to show the differences between these taxonomic groups, as well as combined.

The predictors considered (Fig. S3) include:

1. Taxa (factor): consisting of two categories, tunas or billfishes.
2. Year of fishery development (continuous): defined as the first year in which the total catch reached 25% of the maximum historical catch for the full time series available since 1950. Those stocks with a maximum catch in 1950 were considered as developed in this year, although we know that some of them developed earlier (Sethi *et al.* 2010). Catch data do not necessarily include discards, unregulated artisanal catches or illegal, unreported and unregulated (IUU) catches.
3. MSY (continuous): used on a log scale as a measure of the size of each stock.
4. Generation time (GT, continuous): we used the values estimated by Collette *et al.* (2011) on a log scale as a biological predictor, because life-history parameters such as growth, longevity and age of maturity are considered to be uncertain for most stocks of billfishes, if available (Kopf *et al.* 2009). In the supplemental material of Collette *et al.* (2011), there is a detailed explanation of how GT was calculated for each stock and/or species. The range of this variable is from 1 year for skipjack to 17.2 years for southern bluefin tuna (Table S2).
5. Market price (continuous): we obtained market price for tunas and billfishes from different sources. For all tunas, stocks we used the data available in the FAO economic trade and markets database. However, for billfishes, detailed information by species was not available in this database. Therefore, US market price database for all billfish stocks was considered. In all cases, we used the average price for the last 10 years, from 2003 to 2012. Prices range from \$0.96 dollars/kg for skipjack tuna to \$14.49 dollars/kg for southern bluefin tuna (Table S3).
6. Number of countries fishing each stock (continuous): we considered the smallest number of countries that cumulatively reported more

Table 1 Stock status (B/B_{MSY} and F/F_{MSY}) of tuna and billfish stocks assessed up to December 2014.

Species	Ocean	tRFMO	Stock common name	Code	B/B_{MSY}	F/F_{MSY}	References
Tunas							
Katsuwonus pelamis	Pacific	WCPFC	Skipjack tuna central western Pacific	SKJ-WCPO	1.71	0.62	Rice *et al.* (2014)
	Atlantic	ICCAT	Skipjack tuna eastern Atlantic	SKJ-E-AO	1.708	0.27	ICCAT (2009)
	Indian	IOTC	Skipjack tuna Indian Ocean	SKJ-IO	1.15	0.62	Sharma and Herrera (2014b)
	Atlantic	ICCAT	Skipjack tuna western Atlantic	SKJ-W-AO	1.31	0.83	ICCAT (2015b)
	Pacific	IATTC	Skipjack tuna eastern Pacific Ocean	SKJ-EPO	No reference points		Maunder (2011)
Thunnus alalunga	Indian	IOTC	Albacore tuna Indian Ocean	ALB-IO	1.08	0.69	Hoyle *et al.* (2014)
	Atlantic	ICCAT	Albacore tuna Mediterranean	ALB-MED	1.91	0.99	ICCAT (2012b)
	Atlantic	ICCAT	Albacore tuna North Atlantic	ALB-N-AO	0.76	0.75	ICCAT (2014b)
	Pacific	WCPFC-IATTC	Albacore tuna North Pacific	ALB-N-PO	2.21	0.52	ISC (2014c)
	Atlantic	ICCAT	Albacore tuna South Atlantic	ALB-S-AO	0.84	1.09	ICCAT (2014b)
	Pacific	WCPFC	Albacore tuna South Pacific Ocean	ALB-S-PO	2.6	0.21	Hoyle *et al.* (2012)
Thunnus albacares	Atlantic	ICCAT	Yellowfin tuna Atlantic	YFT-AO	0.67	1.15	ICCAT (2012c)
	Pacific	WCPFC	Yellowfin tuna central western Pacific	YFT-WCPO	1.37	0.72	Davies *et al.* (2014)
	Pacific	IATTC	Yellowfin tuna eastern Pacific	YFT-EPO	0.85	0.99	Minte-Vera *et al.* (2014)
	Indian	IOTC	Yellowfin tuna Indian Ocean	YFT-IO	1.15	0.61	Lee *et al.* (2013b)
Thunnus maccoyii	Indian	CCSBT	Southern bluefin tuna	SBT	0.23	0.76	CCSBT (2014)
Thunnus obesus	Atlantic	ICCAT	Bigeye tuna Atlantic	BET-AO	1.01	0.95	ICCAT (2010b)
	Pacific	IATTC	Bigeye tuna eastern Pacific	BET-EPO	1.05	0.95	Aires-da-Silva and Maunder (2014)
	Indian	IOTC	Bigeye tuna Indian Ocean	BET-IO	1.20	0.79	Langley *et al.* (2013)
	Pacific	WCPFC	Bigeye tuna western Pacific Ocean	BET-WCPO	0.94	1.57	Harley *et al.* (2014)
Thunnus orientalis	Pacific	WCPFC-IATTC	Pacific bluefin tuna Pacific Ocean	PBF	0.42	2.72	ISC (2014b)
Thunnus thynnus	Atlantic	ICCAT	Bluefin tuna eastern Atlantic	BFT-E-AO	1.73	0.24	ICCAT (2015a)
	Atlantic	ICCAT	Bluefin tuna western Atlantic	BFT-W-AO	0.48	0.85	ICCAT (2015a)
Billfishes							
Xiphias gladius	Pacific	IATTC	Swordfish south-eastern Pacific	SWO-EPO	8.96	0.06	Hinton and Maunder (2011b)
	Indian	IOTC	Swordfish Indian Ocean	SWO-IO	1.81	0.70	Sharma and Herrera (2014a)
	Atlantic	ICCAT	Swordfish Mediterranean Sea	SWO-MED	0.96	0.89	ICCAT (2011)
	Atlantic	ICCAT	Swordfish North Atlantic	SWO-N-AO	1.14	0.81	ICCAT (2014a)
	Pacific	WCPFC-IATTC	Swordfish North Pacific	SWO-N-PO	1.2	0.58	ISC (2014a)
	Atlantic	ICCAT	Swordfish South Atlantic	SWO-S-AO	0.98	0.84	ICCAT (2014a)
	Pacific	WCPFC	Swordfish south-west Pacific	SWO-SWPO	1.52	0.40	Davies *et al.* (2013)

Table 1 Continued.

Species	Ocean	tRFMO	Stock common name	Code	B/B_{MSY}	F/F_{MSY}	References
Istiophorus albicans	Atlantic	ICCAT	Sailfish eastern Atlantic	SAI-E-AO	0.26	3.08	ICCAT (2010a)
	Atlantic	ICCAT	Sailfish western Atlantic	SAI-W-AO	0.28	2.20	ICCAT (2010a)
	Indian	IOTC	Indo-Pacific sailfish Indian Ocean	SFA-IO	Not assessed		–
Istiophorus platypterus	Pacific	IATTC	Indo-Pacific sailfish Pacific Ocean	SFA-PO	No reference points		Hinton and Maunder (2011a)
Istiompax indica	Indian	IOTC	Black marlin Indian Ocean	BLM-IO	1.17	1.03	Sharma (2013)
	Pacific	WCPFC	Black marlin western Pacific	BLM-WCPO	Not assessed		–
Makaira nigricans	Atlantic	ICCAT	Blue marlin Atlantic	BUM-AO	0.52	2.19	ICCAT (2012a)
	Indian	IOTC	Blue marlin Indian Ocean	BUM-IO	1.03	1.05	Sharma (2013)
	Pacific	WCPFC-IATTC	Blue marlin Pacific Ocean	BUM-PO	1.29	0.72	ISC (2013)
Kajikia albidus	Atlantic	ICCAT	White marlin Atlantic	WHM	0.40	0.84	ICCAT (2013)
Kajikia audax	Indian	IOTC	Striped marlin Indian Ocean	MLS-IO	0.52	1.12	Sharma (2013)
	Pacific	IATTC	Striped marlin north-east Pacific	MLS-EPO	1.52	0.08	Hinton and Maunder (2010)
	Pacific	WCPFC	Striped marlin south-west Pacific Ocean	MLS-SWPO	0.83	0.81	Davies *et al.* (2012)
	Pacific	WCPFC	Striped marlin western and central North Pacific	MLS-WCPO	0.35	1.24	Lee *et al.* (2013a)
Tetrapturus angustirostris	Indo-Pacific	IOTC	Indo-Pacific shortbill spearfish	SSP	Not assessed		–
Tetrapturus belone	Atlantic	ICCAT	Mediterranean spearfish	MSP	Not assessed		–
Tetrapturus georgii	Atlantic	ICCAT	Roundscale spearfish	RSP	Not assessed		–
Tetrapturus pfluegeri	Atlantic	ICCAT	Longbill spearfish	SPF	Not assessed		–

Table 2 Summary of management measures by stock. The stock codes are listed in Table 1.

Code	Year of fishery development	# Countries reporting >75% catches	Year of formal TAC Implementation	Seasonal closures	Catch restrictions, other than TACs	Minimum size regulations	Fishing capacity limits	Description	Reference to Table S1 in the supporting information
SBT	1957	3	2006	No	No	No	No	Although voluntary quotas were put in place in 1985 by the main fishing countries at the time, the first global TACs including all current CCSBT members was agreed in 2007. However, starting in 2006, more effective TAC compliance measures were implemented In 2011, CCSBT adopted a formal rebuilding plan for SBT*	1
BET-EPO	1961	19	No quota	Yes	No	No	Yes	IATTC C-02-03, reduction in fishing capacity in purse seine fisheries; C-02-04,C-03-12,C-04-09, C-10-01, A seasonal closure of the purse seine fishery in an area known as ‘El Corralito’, near Galapagos. C-13-01, annual catch limits*	2–7
MLS-EPO	1962	16	No quota	No	No	No	No	No management measures in effect	
SWO-EPO	1987	18	No quota	No	No	No	No	No management measures in effect	
YFT-EPO	1950	19	No quota	Yes	No	No	Yes	IATTC C-02-03, reduction in fishing capacity in purse seine fisheries; C-02-04, C-03-12, C-04-09, C-10-01, A seasonal closure of the purse seine fishery in an area known as ‘El Corralito’, near Galapagos	2–6
ALB-MED	1984	11	No quota	No	No	No	No	No management measures in effect	
ALB-N-AO	1950	30	2001	No	No	No	Yes	ICCAT Rec. 98-08, limits on number of fishing vessels to 1993–1995 average	8
ALB-S-AO	1960	24	1998	No	No	No	No	No other management measures in effect rather than TAC	
BET-AO	1965	42	2005	Yes	No	No	Yes	ICCAT Rec. 09-01, Rec. 06-01, limits on numbers of fishing vessels less than average 1991–1992; limits of number of longline and purse seine boats for some countries; ICCAT Rec. 04-01, No purse seine and baitboat fishing during November in the area encompassed by 0–5° N and 10° W–20° W	9–11

Table 2 Continued.

Code	Year of fishery development	# Countries reporting >75% catches	Year of formal TAC Implementation	Seasonal closures	Catch restrictions, other than TACs	Minimum size regulations	Fishing capacity limits	Description	Reference to Table S1 in the supporting information
BUM-AO	1960	32	2013*	No	Yes	Yes	No	ICCAT Rec. 02-13, stock under a formal rebuilding plan since 2003, which includes minimum size regulation for recreational fisheries and catch limits	12
BFT-E-AO	1950	23	1999	Yes	No	Yes	Yes	Formal Rebuilding plan since 2007; Rec. 06-05, Rec. 08-05, Rec. 13-08, which includes minimum size regulation and limits in fishing capacity; Rec. 09-06, calls for a seasonal closure for purse seiners in the eastern Atlantic and Mediterranean between May 15 and June 15	13–16
BFT-W-AO	1962	9	1982	Yes	No	Yes	Yes	ICCAT Rec. 98-07, Rec. 13-09, formal Rebuilding plan since 1999, with minimum regulation sizes and limits in fishing capacity. ICCAT Rec. 06-06: no directed fishery on bluefin tuna in spawning areas such as the Gulf of Mexico	17–19
SAI-E-AO	1974	20	No quota	No	No	No	No	No management measures in effect	
SAI-W-AO	1964	19	No quota	No	No	No	No	No management measures in effect	
SKJ-E-AO	1970	27	No quota	Yes	No	No	No	ICCAT Rec. 04-01, no purse seine and baitboat fishing during November in the area encompassed by 0–5° N and 10° W–20° W	11
SKJ-W-AO	1980	21	No quota	No	No	No	No	No management measures in effect	
SWO-MED	1972	14	No quota	No	No	Yes	No	ICCAT Rec. 03-04, reduction of juvenile swordfish mortality and driftnet ban	20
SWO-N-AO	1959	30	1997	No	No	Yes	No	ICCAT Rec. 01-04, Rec. 06-02, Rec. 11-02, Formal Rebuilding Plan since 1999, including minimum size regulations and TAC	21–23
SWO-S-AO	1970	22	1998	No	No	Yes	No	ICCAT Rec 01-04, minimum size regulations	21
WHM	1962	24	2013*	No	Yes	Yes	No	ICCAT Rec. 02-13, stock under a formal rebuilding plan since 2003, which includes minimum size regulation for recreational fisheries and catch limits	12

Table 2 Continued.

Code	Year of fishery development	# Countries reporting >75% catches	Year of formal TAC Implementation	Seasonal closures	Catch restrictions, other than TACs	Minimum size regulations	Fishing capacity limits	Description	Reference to Table S1 in the supporting information
YFT-AO	1959	49	2013*	Yes	No	No	Yes	ICCAT Rec. 09-01, Rec. 06-01, Limits on numbers of fishing vessels less than average 1991–1992; limits of number of longline and purse seine boats for some countries; ICCAT Rec. 04-01, No purse seine and baitboat fishing during November in the area encompassed by 0–5° N and 10° W–20° W	9–11
ALB-IO	1959	30	No quota	No	No	No	Yes	IOTC CMM. 12-11: limits in fishing capacity. CMM. 12–13, 1-month closure for purse seiners and longliners in an area of size 10 × 20^1	24–25
BET-IO	1975	33	No quota	No	Yes	No	Yes	IOTC CMM. 12-11: limits in fishing capacity. CMM. 05-01. Catch limits. CMM. 12–13, 1-month closure for purse seiners and longliners in an area of size 10 × 20^1	24–26
BUM-IO	1983	25	No quota	No	No	No	Yes	IOTC CMM. 12-11: limits in fishing capacity. CMM. 12–13, 1-month closure for purse seiners and longliners in an area of size 10 × 20^1	24–25
SKJ-IO	1956	33	No quota	No	No	No	Yes	IOTC CMM. 12-11: limits in fishing capacity. CMM. 12–13, 1-month closure for purse seiners and longliners in an area of size 10 × 20^1	24–25
MLS-IO	1985	25	No quota	No	No	No	Yes	IOTC CMM. 12-11: limits in fishing capacity. CMM. 12–13, 1-month closure for purse seiners and longliners in an area of size 10 × 20^1	24–25
SWO-IO	1956	30	No quota	No	No	No	Yes	IOTC CMM. 12-11: limits in fishing capacity. CMM. 12–13, 1-month closure for purse seiners and longliners in an area of size 10 × 20^1	24–25
YFT-IO	1992	39	No quota	No	No	No	Yes	IOTC CMM. 12–11: limits in fishing capacity. CMM. 12–13, 1-month closure for purse seiners and longliners in an area of size 10 × 20^1	24–25
ALB-N-PO	1985	15	No quota	No	No	No	Yes	WCPFC CMM 2005-03 and IATTC C-05-02 called for members not to increase fishing effort directed at North Albacore	27–28

Table 2 Continued.

Code	Year of fishery development	# Countries reporting >75% catches	Year of formal TAC Implementation	Seasonal closures	Catch restrictions, other than TACs	Minimum size regulations	Fishing capacity limits	Description	Reference to Table S1 in the supporting information
ALB-S-PO	1950	25	No quota	No	No	No	Yes	WCPFC CMM 2005-02, no increase of number of vessels south of 20S from 2000–2004 levels	29
BET-WCPO	1960	35	No quota	No	Yes	No	Yes	WCPFC CMM-2005-01, CMM-2008-01, catch limits and reduction of fishing effort. Also, CMM-2013-01, calls for a 3 months (July, August and September) prohibition of setting on FADs for all purse seine vessels[1]	30–31
BUM-PO	1957	35	No quota	No	No	No	No	No management measures in effect	
PBF	1953	5	2014[1]	No	No	No	No	CMM 2009-07, total fishing effort in the area north of the 20° north shall not be increased from the 2002–2004 level for 2010[1]; IATTC C-13-02, implementation of TAC[1]	32–33
SKJ-WCPO	1952	35	No quota	No	No	No	No	No management measures in effect	
MLS-SWPO	1978	25	No quota	No	No	No	Yes	CMM-2006-04, shall limit the number of their fishing vessels fishing for striped marlin in the Convention Area south of 150° S, to the number in any 1 year between the period 2000 and 2004	34
MLS-WCPO	1954	35	No quota	No	No	No	No	CMM 2010-01, total catch of North Pacific Striped Marlin will be subject to a phased reduction such that by 1 January 2013 the catch is 80% of the levels caught in 2000 to 2003[1]	35
SWO-N-PO	1951	15	No quota	No	No	No	No	No management measures in effect	
YFT-WCPO	1952	35	No quota	No	Yes	No	Yes	WCPFC CMM-2005-01, CMM-2008-01, catch limits and reduction of fishing effort. Also, CMM-2013-01, calls for a 3 months (July, August and September) prohibition of setting on FADs for all purse seine vessels[1]	30–31
BLM-IO	1977	25	No quota	No	No	No	Yes	IOTC CMM. 12–11: limits in fishing capacity. CMM. 12–13, 1-month closure for purse seiners and longliners in an area of size 10 × 20[1]	24–25
SWO-SWPO	1988	18	No quota	No	No	No	No	No management measures in effect	

[1] Management measures in effect in recent years (less than 5 years from the last assessment); it is too early to see the effects.

than 75% of the total catch during the past 10 years (2003–2012) as a measure of how the total catch for each stock is allocated among countries (Table 2).

7. Total allowable catch (TAC in years, continuous): this was used to take into account the number of years under TAC enforcement. We used a continuous variable ranging from 0 for stocks with no TACs to 31 for western Atlantic bluefin tuna. TACs have been set and enforced for almost all Atlantic tuna stocks and southern bluefin tuna, although, for some of them, there have been problems with underreporting of catches (Polacheck and Davies 2008; Polacheck 2012). A quota was implemented for white and blue marlins, as well as Pacific bluefin tuna in 2013, but we did not consider these species as having a quota in this study, as it is too early to see the effects of this measure on stock status (Table 2).
8. Input management measures were also considered (factor: presence/absence):
    a). seasonal closures, for specific areas and seasons;
    b). minimum size regulations, such as limits in captured length for some species;
    c). fishing capacity limits, for some stocks, ICCAT refers to limits in the number of vessels that were considered here as a limit in fishing capacity. The only tRFMO that specifically refers to 'non-increase or reduction in fishing effort' is the WCPFC, but this is measured as number of licences authorized so, it was interpreted also as limits in fishing capacity;
    d). catch restrictions, caps in relation to some previous catch level, but not as a formal TAC derived from a stock assessment (i.e. catch should not exceed some average historical level).

Some of the stocks, such as the two stocks of Atlantic bluefin tuna, are currently under a formal rebuilding plan that includes at least one of these input measures or a combination of them. In addition, some of the management measures in place can affect several stocks. For example, seasonal closures of purse seine fisheries in the Atlantic Ocean for bigeye tuna also affect the yellowfin tuna stock (Table 2), In this case, both stocks were considered as having seasonal closures.

Before conducting random forest analyses, predictors were tested for collinearity using variance inflation factors (VIF) (see supporting information, Table S4). We presented, in the main text, the results from the average of the 10 years leading up to the last assessment for both performance measures (B/B_{MSY} and F/F_{MSY}). However, we also considered the last year assessed and a period of 5 years leading up to the last assessment for sensitivity analyses in the random forest analysis finding that the results were not sensitive to the period of time selected (Fig. S4).

Effect of management regulations on depleted stocks

The same type of statistical analysis was used to identify which management measures have the strongest effect on the recovery of previously depleted stocks. We selected those stocks that showed $B < B_{\text{MSY}}$ or $F > F_{\text{MSY}}$ 10 years before the final assessment year. We used as a response variable the geometric mean of the annual rate of change of B and F during this period. We considered biomass levels increasing towards B_{MSY} and fishing mortality rates decreasing towards F_{MSY} as positive signs of stock rebuilding. The same input and output management measures as in the previous analysis were used as predictors.

We conducted two sensitivity analyses, one removing the bluefin tuna stock from the eastern Atlantic, as it is an outlier in the rate-of-change data (Fig. S5), and another one removing the western Atlantic bluefin tuna stock, as it has 31 years of TAC implementation and could bias the results. In terms of variable importance, removing these data did not change the main results observed using the complete data set (Fig. S6).

Results and discussion

We collected stock assessment information for 22 tunas and 18 billfish stocks covering all oceans (Fig. 1). There are still some billfishes, such as longbill, Mediterranean, roundscale and shortbill spearfishes, that remain unassessed because they are not commercially important species. These species cannot easily be assessed, as their catch statistics are generally aggregated with other species (Punt *et al.* 2015).

Tuna catches increased steadily from 1950 to 2000 and then stabilized in the last 10 years (Fig. 2a), with greatest catches coming from

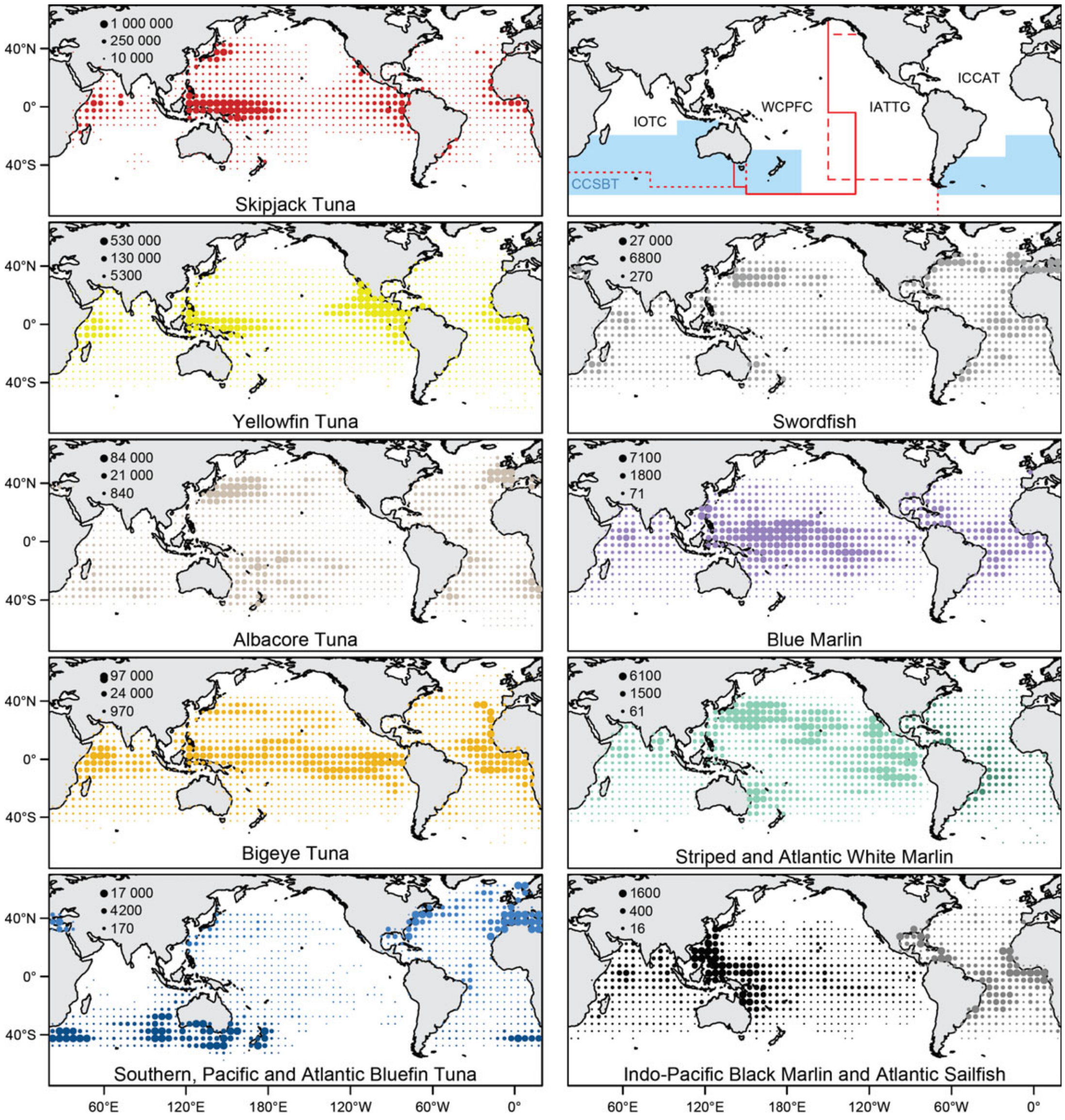

Figure 1 Geographical patterns of total cumulative catch (1950–2012) in tones by 5 × 5° of major tuna and billfish species. Within each panel, different colour shading is used to represent individual species. The top right panel shows the areas governed by the five tuna regional fisheries management organizations: ICCAT = International Commission for the Conservation of Atlantic Tunas; IOTC = Indian Ocean Tuna Commission; IATTC = Inter-American Tropical Tuna Commission (dashed red lines); WCPFC = Western and Central Pacific Fisheries Commission (solid red line); and CCSBT = Commission for the Conservation of Southern Bluefin Tuna (blue shading). [Colour figure can be viewed at wileyonlinelibrary.com]

skipjack, particularly from the western and central Pacific Ocean, followed by yellowfin, bigeye, albacore, and bluefin. Billfish catches also increased before declining in recent years (Fig. 2b). The most important billfish stock by volume during the 1950–1960s was Pacific blue marlin, while swordfish presently dominate catches in all oceans. However, it should be noted that, because most marlin and sailfish stocks are over-exploited, some of these stocks cannot longer be retained, and some artisanal catches remain under- or unreported.

In general, tunas have sustainable biomass and fishing mortality rates, with a median B/B_{MSY} of 1.12 and F/F_{MSY} of 0.81 (Fig. 2c). Bluefin tuna in the western Atlantic and southern bluefin tuna are not showing signs of overfishing ($F < F_{\mathrm{MSY}}$),

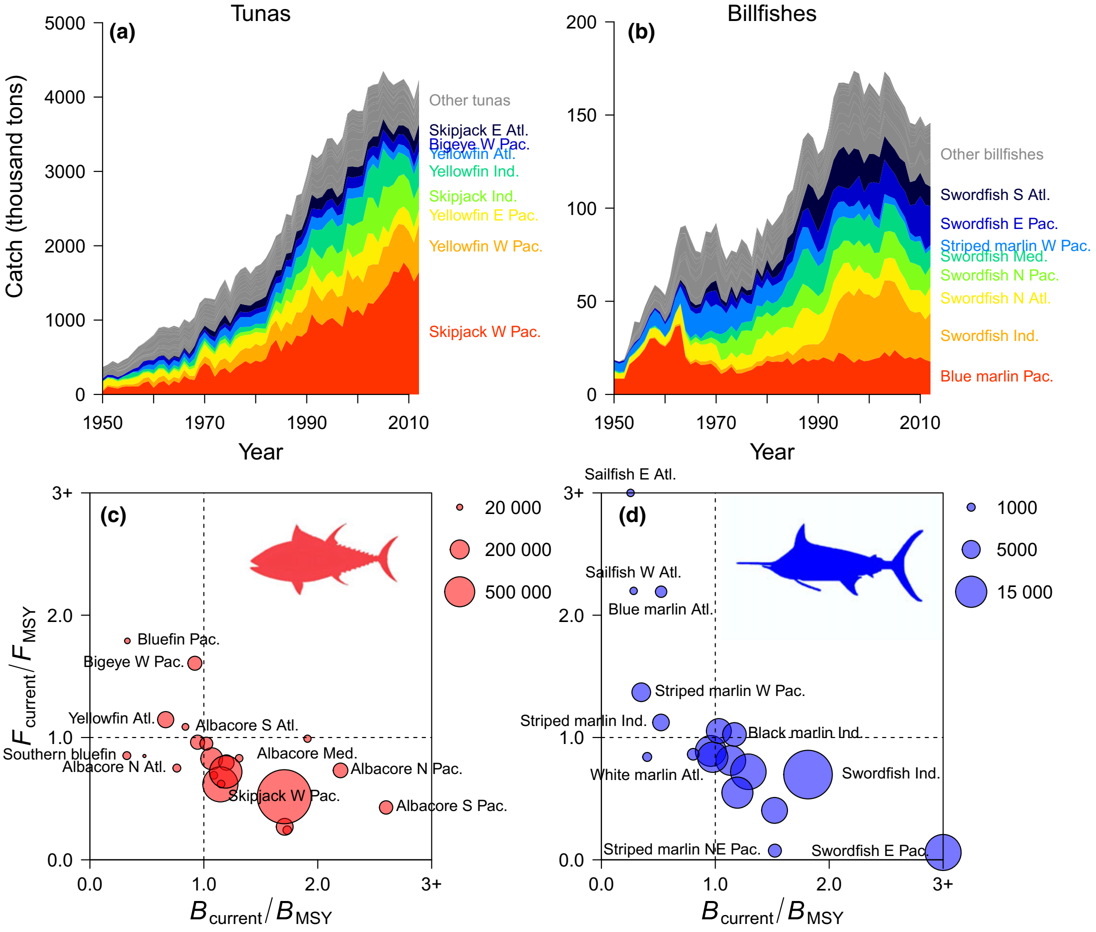

Figure 2 Global catches and current status of tuna and billfish stocks. (a**)** Time trends of tuna catches by stock. The eight with greatest catches are highlighted in colour. (b**)** Time trends in billfish catches by stock. Stock status relative to target reference points (dashed lines) for fishing mortality (F_{MSY}) and biomass (B_{MSY}) for (c) tunas and (d) billfishes. Horizontal and vertical dashed lines show MSY target reference points commonly used among tRFMOs. The area of circles within each plot is proportional to MSY (mt). [Colour figure can be viewed at wileyonlinelibrary.com]

but they are still overfished ($B < B_{MSY}$) due to past over-exploitation. Pacific bluefin tuna and bigeye tuna in the western and central Pacific Ocean are still experiencing overfishing with mortality rates exceeding 1.5 F_{MSY} (Fig. 2c), although substantial management measures have recently been adopted for Pacific bluefin (ISC 2014b). Overall, 64% of tuna stocks have healthy biomass levels, with B above B_{MSY}.

Billfishes are in slightly worse shape than tunas (Fig. 2d), with a median B/B_{MSY} of 0.85 and F/F_{MSY} of 1.01. Sailfish in the eastern and western Atlantic Ocean, and Atlantic blue marlin, are experiencing the highest exploitation rates (with $F > 1.5F_{MSY}$), while swordfish in the eastern Pacific and Indian Ocean are above target biomass levels (Fig. 2d). For billfishes, only 39% have healthy biomass levels and 22% are still experiencing overfishing.

Overall, most tunas and billfish stocks are in healthy conditions, neither overfished nor subjected to excessive fishing pressure. However, 23% of tunas and billfish stocks are still experiencing overfishing and the four stocks of most concern are both heavily depleted ($B < 0.5\ B_{MSY}$) and have high fishing mortality rates ($F > F_{MSY}$). These stocks are Pacific bluefin tuna, eastern and western Atlantic sailfish and Atlantic blue marlin.

Effect of different factors on the current biological status of major tuna and billfish stocks

In general, the status of tuna and billfish stocks is the product of diverse exploitation histories,

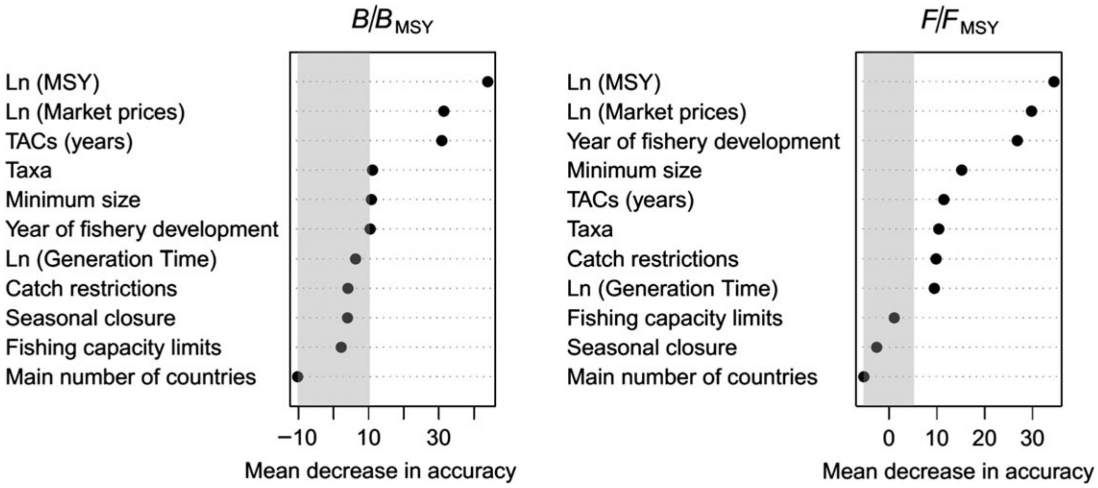

Figure 3 Variable importance score of different predictors on the current stock status (B/B_{MSY} and F/F_{MSY}) of tunas and billfishes. The most influential variables are those with the greatest decrease in accuracy. Variables in the grey-shaded area are considered as not influential. They are significant if their importance value is above the absolute value of the lowest negative-scoring variable. Log refers to the natural logarithm.

biological characteristics, economic incentives and management strategies (Fig. 3). The most important predictor variables affecting both performance measures were MSY and market price. The year of fishery development also affected the F/F_{MSY} ratio and the implementation of quotas, the B/B_{MSY} ratio (Fig. 3). Overall, depletion was greater for less abundant and highly marketable stocks that were subjected to intense fishing pressure for a long time. For both tunas and billfishes, larger stocks had higher values of B/B_{MSY} and lower values of F/F_{MSY} than smaller stocks. Later-developing fisheries had lower values of F/F_{MSY} than earlier-developing fisheries and although not significant, higher values of B/B_{MSY} (Fig. 4). The same pattern was observed in the western north American groundfish fisheries (Melnychuk *et al.* 2013).

Tunas and billfishes showed opposite influences of GT and market price. For tunas, higher market price and longer GT were associated with higher rates of overfishing (higher F/F_{MSY}). Regarding the trends in biomass, a lower B/B_{MSY} was observed for highly valuable tunas; however, the trend for GT was not as clear (Fig. 4). On the contrary, for billfishes, lower market price and shorter GT were associated with higher F/F_{MSY} and lower B/B_{MSY} (Fig. 4). These differences could be because billfishes, except for swordfish, are typically by-catch species and not primary targets of industrial tuna fisheries and therefore might not respond in the same way to market price (Gentner 2007). In addition, marlins have shorter GT compared to swordfish and nevertheless they showed higher fishing pressure. This is probably not associated directly with GT but with the fact that marlins have a more restricted distribution, with much smaller population sizes by far smaller than swordfish and can endure lower fishing mortality. Also, unlike on land, Pinsky *et al.* (2011) suggested that long-lived marine fish species have a lower probability of collapse than short-lived species, although there are certainly exceptions to this overall pattern.

Effect of management regulations on depleted stocks

Twelve stocks (30%) had no management measures in place in the last 10-year period (Table 2). The other 28 stocks had at least one management measure in place during the past 10 years. Most of these 28 stocks are under input management measures to control fishing mortality, such as seasonal closures, minimum size regulations, input restrictions on catch and/or fishing capacity. Only eight stocks have a formal TAC, and, except for southern bluefin tuna, all of the stocks are managed by ICCAT (Table 2).

Fisheries under different types of management differed in status: TAC-managed fisheries had low biomass and high fishing mortality; input-controlled fisheries had a wide range of biomass and fishing mortality; and those with no management measures generally had high biomass and low

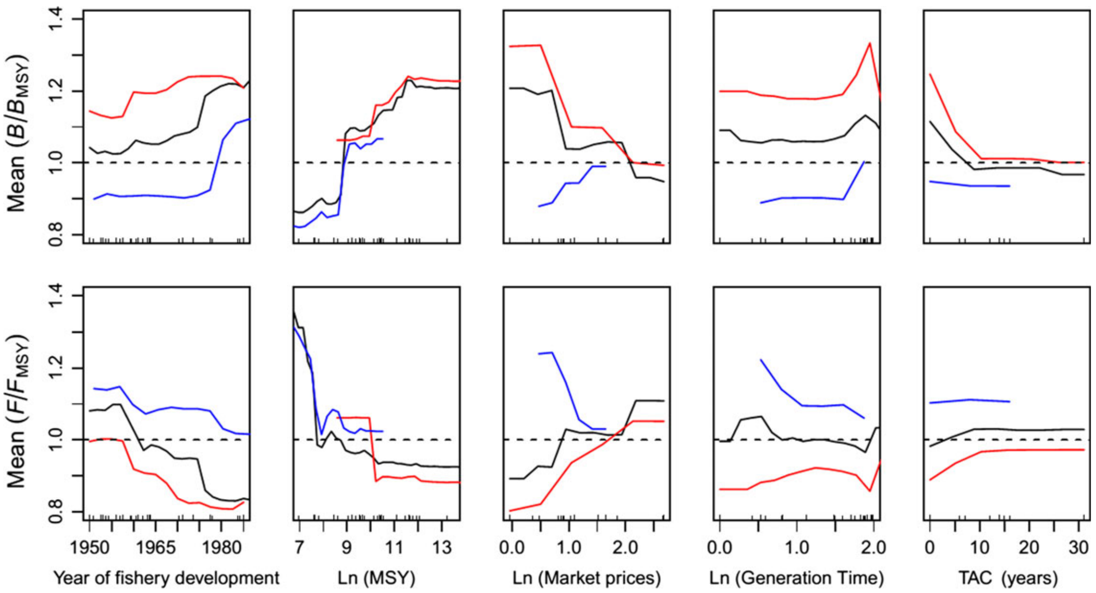

Figure 4 Partial dependence plots of the most important continuous predictors of stock status. The geometric mean of B/B_{MSY} and F/F_{MSY} corresponds to the 10 years prior to the last assessment for each stock. Red lines represent tunas, blue lines billfishes and black lines both combined. Dashed lines show general management targets. Ln refers to the natural logarithm and the tic marks on the *x*-axis represent the data available. [Colour figure can be viewed at wileyonlinelibrary.com]

mortality rates (Fig. 5a and b). Notably, TACs generally have been implemented on less abundant stocks that are already overfished (Fig. 5a and b). For example, the eastern and western stocks of Atlantic bluefin tuna have been managed with TACs for 15 and >30 years, respectively. However, the effect of the TAC implementation on these stocks could be more recent because ICCAT did not follow the scientific advice at the begging and recommended catches that exceeded the scientific recommendations (Fromentin *et al.* 2014). When we take a look at the rate of change over the last 10 years, the biomass of TAC-managed stocks is increasing, and fishing mortality is declining, unlike those managed by input controls or with no controls (Fig. 5c and d).

Using a random forest analysis, we identified management measures influencing the recovery of stocks that were below B_{MSY} (17 stocks) or were experiencing fishing mortality above F_{MSY} (19 stocks) 10 years before the last assessment. We found that previously depleted tuna and billfish stocks that were under some type of management measure showed improvements over the 10-year period leading up to the last stock assessment, with biomass increasing and fishing mortality decreasing over time (Fig. S4). Of all management measures considered, the number of years since TAC implementation had the strongest effect on stock rebuilding, especially on increasing biomass, but also to some extent on decreasing fishing mortality (Fig. 6), as expected from other studies showing the impact of TACs (Melnychuk *et al.* 2012; Neubauer *et al.* 2013; Hilborn and Ovando 2014). Although not possible to determine from our analyses, the success of quotas over other management measures may simply be that quotas result from a more serious effort to manage a stock. While TACs were most important in rebuilding biomass and did decrease fishing mortality, input management measures such as minimum size regulations and seasonal closures were also important in reducing fishing mortality (Fig. 6), as was suggested particularly for the eastern Atlantic bluefin tuna stock (Fromentin *et al.* 2014). In particular for IOTC stocks, one possible confounding effect regarding the reduction in fishing mortality could be associated with Somali piracy in the western Indian Ocean starting ~2007 (Dueri *et al.* 2014). This could be considered as a controversial spatial closure that it was not taken into account in this study.

We plotted changes in status for stocks that were below target reference levels ($B < B_{MSY}$ and

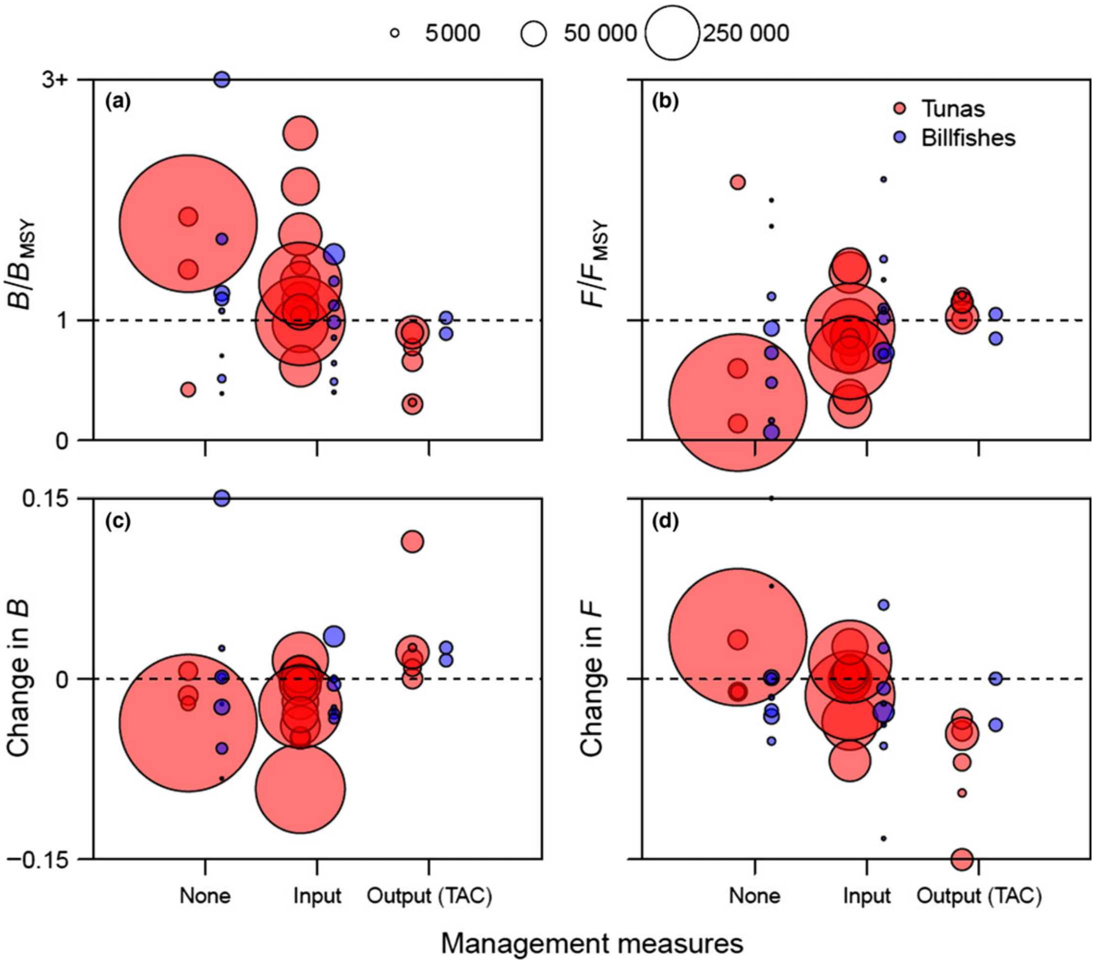

Figure 5 Effect of current management measures on tuna and billfish stocks. Geometric means of (a) B/B_{MSY} and (b) F/F_{MSY} over the final 10 years from the latest stock assessment. Dashed lines represent target reference points (B_{MSY} and F_{MSY}). Annual mean rates of change of (c) biomass and (d) fishing mortality. Dashed lines represent no changes in B or F. In all panels, stocks are categorized by whether there are no management measures in effect, some input management measures, or output measures (TACs), and separated by taxa (tunas or billfishes). The area of circles within each plot is proportional to MSY (mt). [Colour figure can be viewed at wileyonlinelibrary.com]

$F > F_{MSY}$) 10 years before the last assessment, highlighting stocks with and without TACs (Fig. 7) to show the change in status. Stocks with TACs showed a decrease in fishing mortality (arrows moving from the upper left to the lower left quadrant) and an increase in biomass (arrows moving from the left to the right) (Fig. 7). This is a clear signal of rebuilding; fishing mortality is reduced and thus biomass increases. Although fishing mortality was reduced for most stocks without TACs, most of these stocks still show a decrease in biomass, consistent with the results from the random forest analysis (Fig. 6).

Only ICCAT and CCSBT have applied TACs for regionally managed tuna and billfish stocks. National TACs have been proposed as a possible method to harvest resources in the eastern Pacific Ocean, but there is a debate among IATTC scientists and managers about how such a quota should be allocated. This tRFMO faces different obstacles to the adoption of allocation systems for tropical tuna fisheries because of the lack of clarity regarding which criteria to apply for assigning fishing rights in the light of the considerable heterogeneity of the participants in the fishery (Allen 2010). However, IATTC implemented a TAC of 5000 t for Pacific bluefin tuna in 2014, although the success of this measure remains to be seen. ICCAT also implemented quotas on yellowfin tuna and blue and white marlin in 2013 (Table 2).

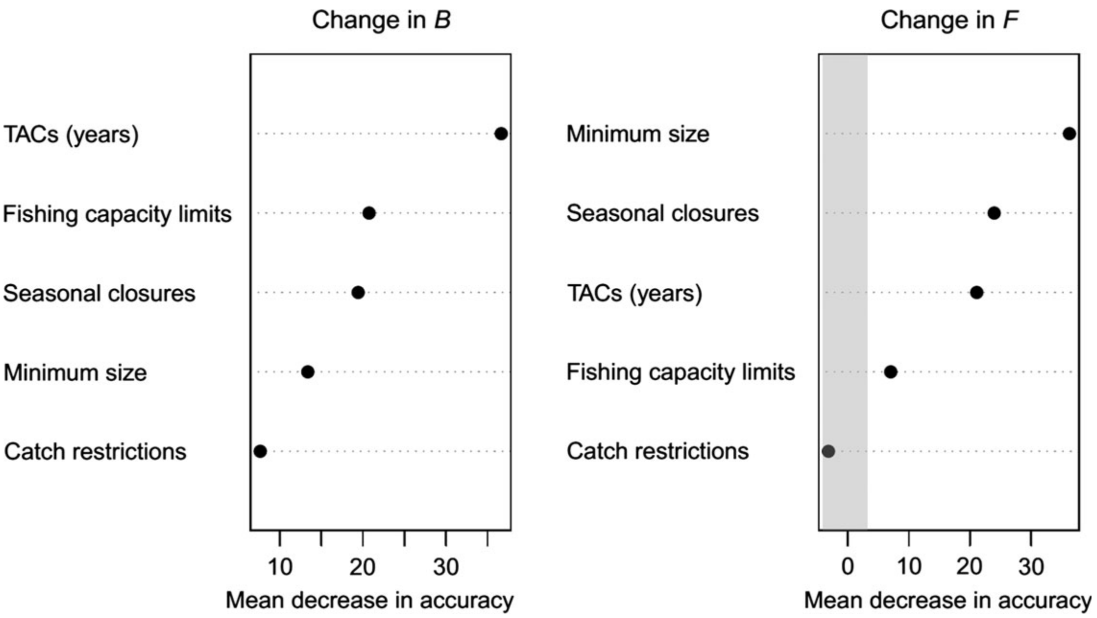

Figure 6 Variable importance scores of different management measures on stock rebuilding. The response variables are the geometric mean of the annual rates of change of biomass (*B*) and fishing mortality rates (*F*) for stocks declared overfished or experiencing overfishing 10 years before the last assessment. The most influential variables are those with the greatest decrease in accuracy. Variables in the grey-shaded area are considered not influential. They are significant if their important value is above the absolute value of the lowest negative-scoring variable. [Colour figure can be viewed at wileyonlinelibrary.com]

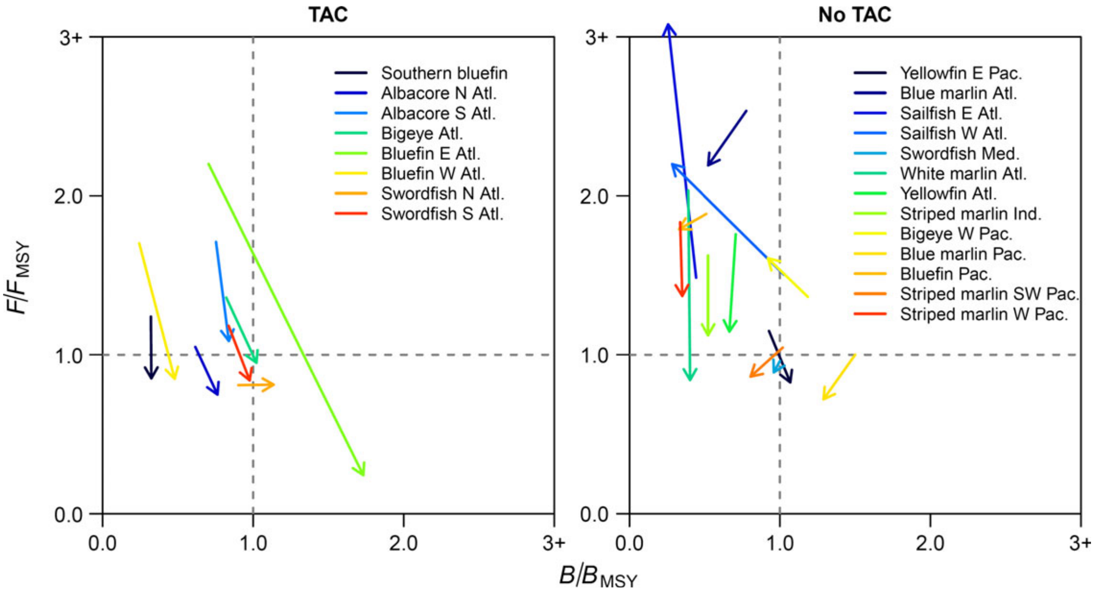

Figure 7 Change in status (B/B_{MSY} and F/F_{MSY}) for stocks declared overfished or experiencing overfishing 10 years before the last assessment to the present. Results are shown for stocks with and without TAC regulations. Vertical and horizontal lines represent target reference points (for B_{MSY} and F_{MSY}, respectively).

Input management measures are relatively easy to implement, but difficult to enforce without an appropriate monitoring and surveillance system (Cochrane and Garcia 2009). Also, effort regulations can be affected by 'effort creep' and uncertainty in the relationship between fishing effort and fishing mortality (Punt and Donovan 2007). We know that TACs can also be circumvented by underreporting or illegal fishing, if they are not effectively enforced by authorities. Catches reported to tRFMOs that applied TACs seldom exceed target TACs (Fromentin *et al.* 2014). However, ICCAT has suggested that bluefin catches from the eastern Atlantic and Mediterranean were seriously underreported from 1998 to 2007, and the CCSBT has found evidence that southern bluefin catches may have been substantially underreported since at least the early 1990s (Polacheck 2012). The latest Atlantic bluefin tuna stock assessments took underreporting into account, and underreporting is thought to have declined in recent years in these fisheries (ICCAT 2015a).

Lessons learned from managing tuna and billfish can be applied to manage other large industrial fisheries. Large targeted stocks that receive direct management attention are generally better managed than small stocks that are caught incidentally, such as marlins and sailfish. When fisheries management is weak, high-value species such as bluefin and bigeye tuna are the most likely to be over-exploited. Strong management measures such as TACs could prevent the over-exploitation of these species, but TACs have not typically been applied until stocks are heavily overfished (Fig. 5a). On the other hand, TACs alone are, in some cases, insufficient to ensure sustainable fisheries. For example, over-exploitation of bigeye tuna is in part due to the by-catch of small individuals by purse seiners targeting other tuna species, that is skipjack and yellowfin. So, other management measures such as seasonal closures or minimum size regulations are also needed to protect this part of the population and avoid overfishing.

Can these lessons about tuna be applied elsewhere? In many regions and fisheries, TACs are not easy to apply, particularly where fleets are small, diverse and target a range of species. In such fisheries, other management tools may be more appropriate (Worm *et al.* 2009; Gutiérrez *et al.* 2011)· Input controls, for instance, may have a higher probability of being accepted by the fishing industry. Nevertheless, where applicable, TACs should be considered as a primary tool for managing depleted stocks as they could lead to faster stock rebuilding. This can be explore using approaches like management strategy evaluation (MSE) to examine both input (effort) and output (catch quota) controls in each fishery (Carruthers *et al.* 2014).

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. List of references from Table 2. Some of the regulations are not currently active but were active during the last 10 years.

Table S2. Generation Time (GT, from Collette et al. 2011). The stock codes are listed in Table 1.

Table S3. Market price used for the analysis (average price from 2003 to 2012). The price is species specific not by stock.

Table S4. Variance inflation factors (VIF) for continuous predictors used in the random forest analysis. Ln refers to the natural logarithm.

Fig. S1. Yearly trends in F/F_{MSY} by stock. Values for $F>F_{\mathrm{MSY}}$ are in red. The stock codes are listed in Table S1.

Fig. S2. Yearly trends in B/B_{MSY} by stock. Values for $B<B_{\mathrm{MSY}}$ are in red. The stock codes are listed in Table S1.

Fig. S3. Variables considered for the random forest analysis of the prediction of the current status of tuna and billfish stocks. Continuous variables are shown with boxplots and categorical variables with barplots for tunas and billfishes separately. In the barplots the y-axis represents frequency in numbers and in the continuos plots the variable itself. Log refers to the natural logarithm.

Fig. S4. Sensitivity analysis on the partial dependence plots of the most important continuous predictors of stock status. Partial dependence plots are similar to those in Fig. S6, with the exception that in (a) and (b), the geometric means of B/B_{MSY} and F/F_{MSY} were calculated for the 5 years prior to the last assessment instead of 10 years, and in (c) and (d), only the final year stock status of B/B_{MSY} and F/F_{MSY} was considered (no averaging). Red lines represent tunas, blue lines billfishes, black lines both combined and dashed lines general management targets. Log refers to the natural logarithm.

Fig. S5. Effect of management measures on rebuilding previously depleted tuna and billfish stocks. (a) Annual change in biomass, *B*, and (b) annual change in fishing mortality, *F*, versus management measures. The rate of change was calculated as the geometric mean of the differences in B/B_{MSY} or F/F_{MSY} from one year to the next over the 10-year period leading up to the year of the latest stock assessment. Red dashed lines represent levels of no change. Grey dashed lines are linear trend lines between the rate of change in *B* and *F* against years under TACs.

Fig. S6. Sensitivity analysis on variable importance scores of management measures after removing outlying stocks. Variable importance plots are similar to those in Fig. S8, with the exception that in (a) the Eastern Atlantic bluefin tuna stock is removed, and in (b) the Western Atlantic bluefin tuna stock is removed.