

Multiple lines of evidence highlight the dire straits of yellowfin tuna in the Indian Ocean.

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ABSTRACT

Yellowfin tuna (*Thunnus albacares*) are highly valued pelagic fisheries target species. Regional fisheries management organizations (RFMOs) are the principal mechanism that manage yellowfin tuna fisheries. Determining changes in population abundances is crucial for effective conservation and management. We use multiple methods for monitoring biomass trends and evaluating the status of yellowfin tuna in each ocean basin and show how additional, multiple lines of evidence can enhance our understanding of the conservation and exploitation status of this species. Our analysis of regional biomass trajectories and Catch-MSY++ assessments corroborate the findings of the most recent RFMO stock assessments suggesting yellowfin tuna in the Indian Ocean are in critical condition, while the Eastern Pacific yellowfin tuna population shows the lowest levels of exploitation. These results are supported by fisheries-independent data from baited remote underwater video systems (BRUVS), showing that the Indian Ocean yellowfin tuna population is the least common, least abundant, and smallest across all oceans. Our findings support previous claims of systematic and widespread overfishing of yellowfin tuna in the Indian Ocean and thus confirm calls to reduce current fishing levels to ensure the long-term viability of the species.

1. Introduction

Tunas and other highly migratory species are vital to marine ecosystems. They are characterized by rapid growth and high reproductive output (Murua et al., 2017), generally making such species relatively resistant to fisheries exploitation. The seven principal market tuna species, yellowfin (*Thunnus albacares*), skipjack (*Katsuwonus pelamis*), bigeye (*Thunnus obesus*), albacore (*Thunnus alalunga*), southern bluefin (*Thunnus maccoyii*), Atlantic bluefin (*Thunnus thynnus*), and Pacific bluefin tuna (*Thunnus orientalis*) are exploited globally, by small-scale (e.g., Okemwa et al., 2023) and large-scale industrial fisheries (Heidrich et al., 2023) in both developing and developed countries (FAO, 2020). Global tuna fisheries reached an estimated total catch of 4.9 million tonnes in 2020 (ISSF, 2022) contributing more than \$40 billion to the global economy yearly (McKinney et al., 2020). Global tuna assessments

suggest that populations have been declining since the 1950s mainly due to increased fishing mortality (Cox et al., 2002; Juan-Jordá et al., 2011). More recently, overall tuna biomass trajectories have appeared to stabilize around Maximum Sustainable Yield (MSY)-based target reference points, i.e., approaching the biomass that enables the population to deliver MSY (B/B_{MSY}) in response to adjusting global fishing mortalities around target levels, i.e., the fishing mortality that provides MSY in the long term (F/F_{MSY}) (Juan-Jordá et al., 2022). However, some tuna populations, e.g., Indian Ocean yellowfin and Atlantic bigeye tuna remain overfished requiring strengthened management measures (Juan-Jordá et al., 2022). Their overexploitation can have various ecological consequences, including impacts on trophic integrity (Baum and Worm, 2009), reduced ecosystem productivity (Sumaila et al., 2011), and diminished resilience to environmental change (Srinivasan et al., 2010; Ortuño Crespo & Dunn, 2017).

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Table 1

Description of all fisheries-independent metric derived from BRUVS and fisheries-dependent metrics derived from RFMO fish stock assessments.

Dataset	Variable	Description	Years	Data source
RFMO	CPUE index	Abundance indices used in yellowfin tuna stock assessments	2011–2020	IOTC: https://www.iotc.org/data/datasets/latest/nc?order=title&sort=desc (Source datasets: YFT joint longline CPUE series, YFT EU purse seine CPUE series, Standardized CPUE indices for yellowfin) ICCAT: (ICCAT, 2019) WCPFC: https://oceanfish.spc.int/en/ofpsection/sam/sam/216-yellowfin-assessment-results#2020 IATTC: (IATTC, 2022)
	Biomass	Estimates of biomass obtained from stock assessment model runs used for management advice	1950/1975–2020	IOTC: IOTC (2021) ICCAT: (ICCAT, 2019) WCPFC: https://oceanfish.spc.int/en/ofpsection/sam/sam/216-yellowfin-assessment-results#2020 IATTC: (IATTC, 2022)
	Length	Length frequency data of catches provided by RFMOs, used as the basis for length composition input data for stock assessments	2011–2020	IOTC: https://www.iotc.org/data/datasets/latest/SF/YFT (Source dataset: IOTC-DATASETS-LATEST-SF-YFT) ICCAT: https://iccat.int/en/accesingdb.html (Source dataset: T2CS - catch-at-size (estimated) – YFT) WCPFC: https://oceanfish.spc.int/en/ofpsection/sam/sam/216-yellowfin-assessment-results#2020 IATTC: (IATTC, 2022)
	B/B _{MSY}	The ratio of observed biomass to the biomass that would provide maximum sustainable yield obtained from all stock assessment model runs used for management advice	2011–2020	IOTC: (IOTC, 2013, 2014a, 2015a, 2016, 2017, 2018, 2019a, 2020, 2021a) ICCAT: (ICCAT, 2019) WCPFC: https://oceanfish.spc.int/en/ofpsection/sam/sam/216-yellowfin-assessment-results#2020 IATTC: (IATTC, 2013; 2014, 2015, 2016, 2017, 2018, 2019a, 2019b, 2020, 2021)
	F/F _{MSY}	The ratio of observed fishing mortality to the fishing mortality that would provide maximum sustainable yield obtained from all stock assessment model runs used for management advice	2011–2020	IOTC: (IOTC, 2013, 2014a, 2015a, 2019a, 2016, 2017, 2018, 2020, 2021a) ICCAT: (ICCAT, 2019) WCPFC: https://oceanfish.spc.int/en/ofpsection/sam/sam/216-yellowfin-assessment-results#2020 IATTC: (IATTC, 2013; 2014, 2015, 2016, 2017, 2018, 2019a, 2019b, 2020, 2021)
	Catch	Catch time series publicly available from tuna RFMO database	1950–2020	IOTC: https://www.iotc.org/data/datasets/latest/NC-ALL (Source dataset: IOTC-DATASETS-LATEST-NC-ALL) ICCAT: https://iccat.int/en/accesingdb.html (Source dataset: T2CE) WCPFC: https://www.wcpfc.int/doc/annual-catch-estimates-data-files (Source datasets: XLS WCPFC) IATTC: https://www.iattc.org/en-US/Data/Public-domain (Source dataset: CatchBYMGOLoLa)
BRUVS	MSY	Maximum sustainable yield obtained as output from stock assessment model runs used for management advice	2011–2020	IOTC: (IOTC, 2013, 2014a, 2015a, 2016, 2017, 2018, 2019a, 2020, 2021a) ICCAT: (ICCAT, 2019) WCPFC: https://oceanfish.spc.int/en/ofpsection/sam/sam/216-yellowfin-assessment-results#2020 IATTC: (IATTC, 2013; 2014, 2015, 2016, 2017, 2018, 2019a, 2019b, 2020, 2021)
	Abundance	Mean relative abundance (MaxN) of yellowfin tuna recorded within each RFMO Convention Area averaged across all sample sites (set) and study locations.	2012–2022	Marine Futures Lab (https://www.fishbase.se/bruvsv/search.php)
	Biomass	Mean biomass calculated as weight * MaxN (weight = a*Length ^b) of yellowfin tuna recorded within each RFMO Convention Area averaged across all sample sites (set) and study locations.	2012–2022	Marine Futures Lab (https://www.fishbase.se/bruvsv/search.php)
	Fork length	Mean fork length of yellowfin tuna recorded within each RFMO Convention Area averaged across all sample sites (set) and study locations.	2012–2022	Marine Futures Lab (https://www.fishbase.se/bruvsv/search.php)
	Prevalence	Presence/absence data of yellowfin tuna from mid-water BRUVS	2012–2022	Marine Futures Lab (https://www.fishbase.se/bruvsv/search.php)

Tuna are capable of large trans-oceanic migrations, traversing multiple coastal countries' waters and the High Seas, making them vulnerable to small-scale and large-scale industrial fishing operations (Maguire, 2006). This transboundary range is reflected in the international cooperation for their conservation and management. Five tuna Regional Fisheries Management Organizations (RFMOs), are tasked with the management of tuna populations (De Bruyn et al., 2013). These are: the Commission for the Conservation of Southern Bluefin Tuna in the Southern Ocean (CCSBT), the International Commission for the Conservation of Atlantic Tunas (ICCAT) in the Atlantic Ocean, the Indian Ocean Tuna Commission (IOTC) in the Indian Ocean, the Western and Central Pacific Fisheries Commission (WCPFC) and the Inter-American Tropical Tuna Commission (IATTC) in the Western and Eastern Pacific Ocean, respectively. Yellowfin tuna are of considerable ecological and

commercial importance to numerous communities in developed and developing countries, and remote islands worldwide (Bell et al., 2015; Duggan and Kochen, 2016; McCluney et al., 2019). They are apex predators, mainly inhabiting tropical and subtropical waters where they form large schools (Block et al., 1997; Reygondeau et al., 2012). Globally they are primarily caught by industrial purse seine and baited-hook longline fisheries, which support the cannery and sashimi markets (Collette & Graves, 2019; Miyake et al., 2010). Yellowfin tuna also support small-scale and recreational fisheries in many locations (Bell et al., 2018; Coulter et al., 2020; Okemwa et al., 2023). This multi-billion dollar common resource is one of the key species of the Indian Ocean tuna fisheries and is subject to increasing fishing pressure (Pecoraro et al., 2017; ICCAT, 2019; Minte-Vera et al., 2020; Vincent et al., 2020; Wu et al., 2020). Stock assessments are fundamental for

effective management advice to achieve fisheries and conservation objectives (Juan-Jordá et al., 2011; Aranda et al., 2012; Pecoraro et al., 2017). Yellowfin tuna, as a major commercial target species, are regularly assessed by four tuna RFMOs. Integrated stock assessments, such as statistical age-structured assessments have become the dominant method for assessing data-rich tuna stocks in tuna RFMOs (Maunder et al., 2006). These models are used to estimate fisheries reference points and evaluate current stock status with respect to these reference points (Maunder et al., 2006). These methods reflect population dynamics using information on relative abundance, length of the catch, biology of the stock, and tag recaptures. Fisheries-dependent commercial catch per unit effort (CPUE), remains the main source of abundance information available for fishery stock assessments. The most recent assessments found that yellowfin tuna is overfished ($B < B_{MSY}$), and subject to overfishing ($F > F_{MSY}$) in the Indian Ocean, while the stocks in the Atlantic and Pacific Oceans are not overfished and are not experiencing overfishing (ISSF, 2022, 2023).

Most tuna fisheries are operating at or close to optimum yields (B_{MSY}), due to unprecedented increases in fishing capacity with no expected room for further growth (Juan-Jordá et al., 2022). Yellowfin tuna biomass has declined globally by ~58% between the 1950s and 2006 (Juan-Jordá et al., 2011), with the most recent assessments suggesting that populations are still decreasing globally, except for stabilizing trends in the Western Pacific Ocean (Collette et al., 2021a; ICCAT, 2019; Minte-Vera et al., 2020; Vincent et al., 2020; IOTC, 2021a; IOTC, 2022a, b). Moreover, the most recent IUCN Red List assessment has downgraded global yellowfin tuna from globally “Near Threatened” in 2011 to “Least Concern” in 2021 (Collette et al., 2011, 2021a), whereas the Indian Ocean yellowfin tuna population remains “Vulnerable”, with greater risk of extinction (Juan-Jordá et al., 2022).

Integrated fishery assessments are based on the amount and quality of data for which substantial data input challenges and uncertainties often remain, including biased size and abundance sampling (Maunder et al., 2006; Pecoraro et al., 2020; IOTC, 2021b). Therefore, additional sources of information on populations are an important consideration and can complement core approaches when providing management advice, even for relatively data-rich and regularly assessed stocks such as yellowfin tuna (IOTC, 2021a). Data-limited fisheries-dependent stock assessment methods, such as the CMSY⁺⁺ method (Froese et al., 2017, 2021), are increasingly recognized within tuna RFMOs, as they provide an objective way to evaluate the impact of different assumptions on stock status estimates and the value of information in the data, life history parameters, and expert knowledge (Palomares et al., 2020). Regional CMSY⁺⁺ assessments have the advantage of providing reasonable predictions of relative stock biomass status (B/B_{MSY}) and exploitation status (F/F_{MSY}) based on limited data availability compared with the formal integrated fish stock assessments (Froese et al., 2018). Fisheries-independent, non-destructive techniques such as baited remote underwater video systems (BRUVS) are another potential source of additional information on populations. Stereo-BRUVS record biological and ecological data such as relative abundance, size, biomass, and prevalence of pelagic species and have been utilized in survey locations worldwide (Meeuwig et al., 2021). Data collected with BRUVS have been used to investigate direct and indirect effects of fishing (Langlois et al., 2012b) and the effects of fisheries closures (McLean et al., 2011) and could potentially yield a more holistic and unbiased picture of the status of the populations when combined with fisheries-dependent data and analyses.

In this analysis, we explore a range of methods for evaluating the status of yellowfin tuna populations and evaluate to what extent they corroborate or contradict the RFMO-derived stock status. The use of multiple lines of evidence reduces bias and strengthens the confidence in the scientific conclusions that are drawn. Scientific advice can be based on a range of data sources and assessment methods. The combination of experimental, observational, and modelling data can provide a more comprehensive understanding of the phenomenon under investigation.

Moreover, the replication of results using different methods, techniques or equipment can help to validate or contradict original findings and thereby also confirm or deny the validity of additional methods tested and their potential for application in data-limited situations. We use three methods to provide additional lines of evidence to enhance our understanding of the conservation and exploitations status of yellowfin tuna, which include estimating the overall rates and extent of declines in biomass using Bayesian generalized linear models (Juan-Jordá et al., 2011), conducting CMSY⁺⁺ assessments based on RFMO catch and CPUE data (Froese et al., 2021), and estimating video-derived prevalence, abundance, biomass, and size data from a large-scale global dataset of mid-water BRUVS (<https://www.fishbase.se/bruvs/search.php>). We expect strong positive correlations between biomass metrics (e.g., total abundance, biomass, B/B_{MSY}) derived from official RFMO stock assessments and the multiple lines of evidence. Furthermore, we expect strong negative correlations between exploitation metrics (i.e., catch, F/F_{MSY}) from traditional assessments and biomass metrics derived from the additional lines of evidence. The inclusion of multiple lines of evidence aims to provide more robust insights into the status of the exploited species. Recommendations to improve outcomes for yellowfin tuna, based on the insights gained from these multiple lines of evidence, are also provided.

2. Methods

2.1. RFMO fishery data and stock assessment compilation

We compiled the most recent yellowfin tuna stock assessments and assessment reports from the four relevant tuna RFMOs and extracted the trajectories of catch, length of catches, CPUEs and the estimates of MSY, biomass, B/B_{MSY} , and F/F_{MSY} from their model runs (Table 1). Some assessments generated various biomass trajectories from different models or model scenarios, and multiple CPUE (i.e., abundance indices) were available for single yellowfin tuna populations, when data were collected with different gears. In those cases, we standardized time series using the BCRUMB method in R (Winker et al., 2020, <https://github.com/henning-winker/Jara>). The use of this Bayesian population state-space model is a standard approach for averaging relative abundance indices for IUCN Red List assessments (Sherley et al., 2020) and has been used for the estimation of global declines in oceanic sharks and rays (Pacoureau et al., 2021), as well as demersal fish and invertebrates (Tsikliras et al., 2021). We then averaged biomass values for each yellowfin tuna population across ten years to match the BRUVS dataset. The stock assessments compiled here assume a single yellowfin tuna stock for each tuna RFMO, although distinct spawning areas and genetic differences may imply individual stocks or significant heterogeneity in yellowfin tuna distributions (Pecoraro et al., 2018; Vincent et al., 2020; Muñoz-Abril et al., 2022; Relano and Pauly, 2022).

2.2. Analysis and additional lines of evidence for evaluating the status of yellowfin tuna

We applied three methods to provide additional lines of evidence into the stock status of yellowfin tuna, which included (1) an analysis of regional biomass trajectories with the objective of estimating the overall rates and extent of declines in biomass of yellowfin tuna between 1950 and 2020, (2) a CMSY⁺⁺ assessment based on RFMO catch and catch per unit effort (CPUE) data with the objective of testing the performance of data-limited stock assessment methods to data-rich large pelagic species such as yellowfin tuna and the potential of providing a complementary estimate of stock status to the current RFMO fishery stock assessments, and (3) an analysis using a large-scale global dataset of mid-water BRUVS with the objective of providing fishery-independent estimates of prevalence, abundance, biomass, and size data of the yellowfin tuna populations for the most current period (2010–2020).

Table 2

BRUVS sampling data. Metrics at each sample location all univariate metrics are shown as untransformed mean values. Sampling effort (Number of sets), mean abundance, biomass, fork length, and prevalence of yellowfin tuna with associated standard error (SE) for all locations sampled.

Yellowfin tuna population	RFMO	Location	Number of Sets	mean TA	TA SE	mean TB	TB SE	mean FL	FL SE	mean Prevalence
Indian	IOTC	Bremer Canyon	40	0	0	0	0	0	0	0%
		British Indian Ocean Territory	109	0.003	0.003	0.029	0.029	79.295	0	1%
		Cocos Island - Australia	22	0	0	0	0	0	0	0%
		Geographe Bay	67	0	0	0	0	0	0	0%
		Gracetown	60	0	0	0	0	0	0	0%
		Maldives	39	0	0	0	0	0	0	0%
		Montebello Islands	40	0.165	0	0.289	0	41.541	0	5%
		Ningaloo Reef	56	0.061	0.057	0.122	0.114	43.027	2.163	3%
		Ashmore Reef – NW Australia	40	0	0	0	0	0	0	0%
		Long Reef – NW Australia	39	0	0	0	0	0	0	0%
		Perth Canyon	82	0	0	0	0	0	0	0%
		Pilbara	106	0	0	0	0	0	0	0%
		Recherche Archipelago - East	22	0	0	0	0	0	0	0%
		Recherche Archipelago - Central	22	0	0	0	0	0	0	0%
		Recherche Archipelago - West	22	0	0	0	0	0	0	0%
		Rowley Shoals	11	0	0	0	0	0	0	0%
		Shark Bay	69	0.011	0.011	0.114	0.114	79.295	0	1%
		Mean IOTC		0.013	0.009	0.029	0.017	60.799	10.689	1%
Atlantic	ICCAT	St Helena and Ascension Islands	131	0.338	0.134	4.423	1.859	92.134	0.873	11%
		Azores Islands	31	0	0	0	0	0	0	0%
		Ilhas Selvagen	19	0	0	0	0	0	0	0%
		Tristan da Cunha Islands	27	0	0	0	0	0	0	0%
		Uruguay	5	0.050	0	0.536	0	79.295	0	20%
		Mean ICCAT		0.078	0.066	0.992	0.864	85.715	6.419	6%
Western Pacific	WCPFC	Far North Queensland	33	0.006	0.006	0.063	0.063	79.295	0	3%
		French Polynesia	10	0	0	0	0	0	0	0%
		Gambier Islands	10	0	0	0	0	0	0	0%
		New Caledonia	32	0	0	0	0	0	0	0%
		Niue	20	0.030	0	0.592	0	98.655	0	5%
		Palau	30	0	0	0	0	0	0	0%
		Rapa Iti and Marotiri	18	0.185	0	1.985	0	79.295	0	6%
		Timor	24	0	0	0	0	0	0	0%
		Tonga	9	0	0	0	0	0	0	0%
		Mean WCPFC		0.017	0.014	0.203	0.155	85.748	6.453	2%
Eastern Pacific	IATTC	Clipperton Island	17	0.147	0	8.134	0	101.654	0	18%
		Galapagos	50	1.253	0	24.506	0	110.169	0	22%
		Malpelo	16	2.700	0	58.170	0	107.111	0	56%
		Osa Peninsula	34	0.047	0	0.178	0	59.260	0	6%
		Revillagigedo	25	2.880	0	45.476	0	103.779	0	28%
		Mean IATTC		1.004	0.491	19.495	9.074	96.3955	9.396	26%

2.2.1. Analysis of biomass trajectories

We estimated the annual rate of biomass change from 1950 to 2020 and the overall reduction in biomass as a percentage of 1950 estimates using the methodology of Juan- Jordá et al. (2022, for more detail see Supplementary Information). We used the available time series of yellowfin tuna biomass for the ICCAT ($n = 4$ series), the IOTC ($n = 48$ series), the WCPFC ($n = 72$ series), and the IATTC assessment models ($n = 92$ series, Table 1). We ran this analysis from the earliest to the latest available biomass value and also from 2006 onwards, to compare trends with the trends analysis performed in Juan-Jordá et al. (2011). Knowledge about trends in biomass and catch time series, as provided alongside management advice by tuna RFMOs are an important consideration when presenting scientific understanding of the status of stocks (ICCAT, 2019; Mente-Vera et al., 2020; Vincent et al., 2020; Collette et al., 2021b; IOTC, 2021a; Magnusson et al., 2023).

2.2.2. CMSY⁺⁺ assessments

We applied the updated Monte Carlo method of Catch-MSY (CMSY⁺⁺) of Froese et al. (2021) to estimate biomass, exploitation rate, MSY, and related fisheries reference points from catch, resilience, and qualitative stock status information for data-rich yellowfin tuna stocks in each RFMO area. CMSY⁺⁺ was used to evaluate the degree to which consistent results can be achieved across a suite of different assessment methods. Furthermore, the evaluation of data-rich pelagic

stocks with data-limited methods such as CMSY⁺⁺ can provide insights into the potential effectiveness of data-poor methods in situations where data are indeed limited (Kokkalis et al., 2017; Wiedenmann et al., 2019). This method relies on catch and abundance (i.e., CPUE) time series, prior ranges of resilience (r) and carrying capacity (K), and possible ranges of stock sizes in the first and final years of the time series. Prior input parameters for the CMSY⁺⁺ runs were defined using expert opinion and were informed by official tuna RFMO assessments to reduce potential bias and imprecision.

2.2.3. Analysis of fisheries-independent data using BRUVS

We analysed video-derived prevalence, abundance, biomass, and size data from a large-scale global dataset of stereo-baited remote underwater video systems (BRUVS) curated by the Marine Futures Lab. Mid-water BRUVS are deployed in longline configurations of sets of 3–5 rigs at 10 m depth with 200 m of surface line between them and are deployed in water with seabed depths of 20 m to 5000 m. Methods on calculating the parameters are given in the Supplementary Information. This dataset contained 955 records of yellowfin tuna across 1387 sets from a total of 106,347 records of pelagic animals from 5 global surveys at 36 locations (Table 2, <https://www.fishbase.se/bruvs/search.php>).

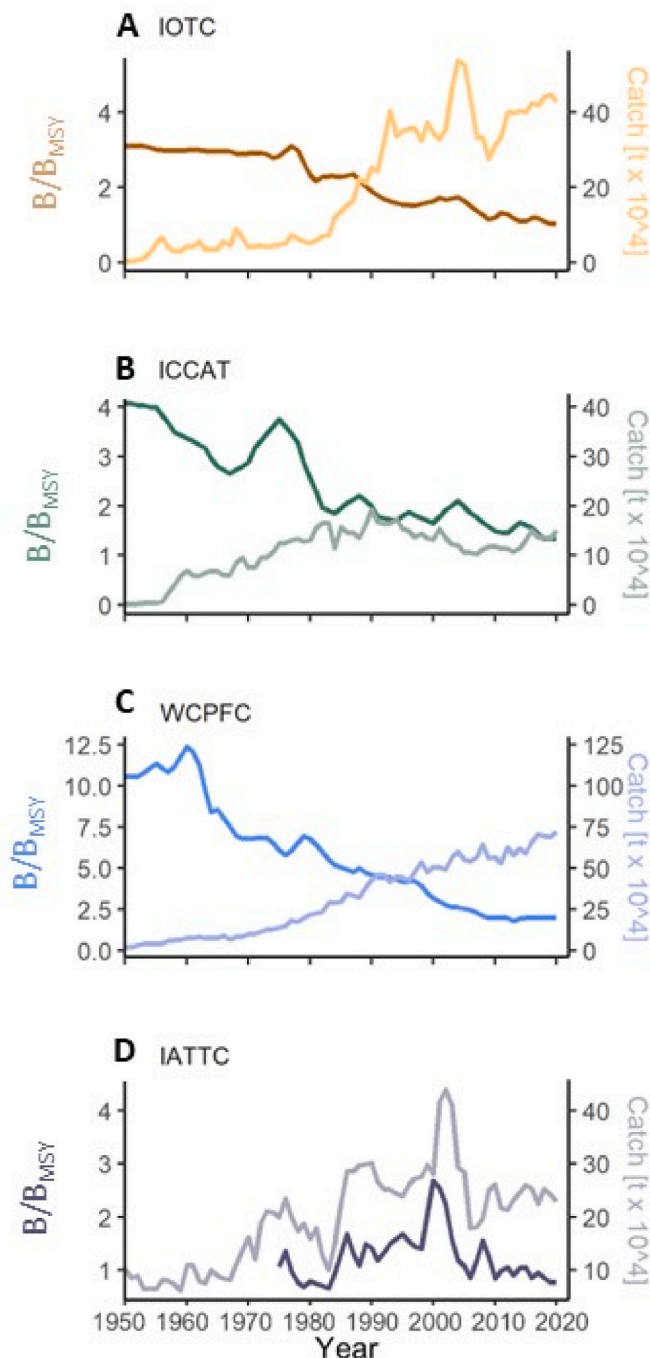


Fig. 1. Catch and biomass time series (B/B_{MSY}) for (A) the Indian Ocean Tuna Commission (IOTC), (B) the International Commission for the Conservation of Atlantic Tunas (ICCAT), (C) the Western Central Pacific Fisheries Commission (WCPFC), and (D) the Inter-American Tropical Tuna Commission (IATTC) from 1950 to 2020. The biomass time series displayed here are outputs from the JARA model, which used raw biomass time series sourced from the individual tuna RFMOs as input values.

2.3. Comparative analysis of fishery assessment metrics and BRUVS metrics across RFMO convention areas

We plotted biomass and catch of yellowfin tuna by year for each RFMO to examine trends between 1950 and 2011, and between 2011 and 2021 to match the BRUVS dataset. We further plotted B/B_{MSY} , F/F_{MSY} , and reported catch relative to MSY by year for each RFMO over the ten years covered by the BRUVS dataset. A traffic light system indicated

whether the ratio of estimated B/B_{MSY} and F/F_{MSY} was sustainable (green), on the MSY mark (yellow), or unsustainable (red) regarding the assumed sustainability ratio of B/B_{MSY} and F/F_{MSY} of 1. Similarly, the traffic system highlighted when the reported catch was less than (green), equal to (yellow), or greater than (red) the recommended MSY. Furthermore, we tested for differences between yellowfin tuna populations for each of the univariate metrics of TA, TB, and FL derived from BRUVS using Permutational Analysis of Variance (PERMANOVA) based on Euclidean distance resemblance matrices of $\log_{10}(x+1)$ (Oksanen, 2010). Numerous studies demonstrate the advantages of PERMANOVAs for extracting ecological patterns from BRUVS-based sampling carried out under various habitat circumstances and water column positions (e.g., Zintzen et al., 2012; Santana-Garcon et al., 2014).

2.4. Correlation analysis between multiple lines of evidence

We calculated the Pearson correlation coefficient (r) between yellowfin tuna stock status metrics derived from RFMO fishery stock assessment (i.e., B/B_{MSY} , F/F_{MSY} , MSY, CPUE, length, biomass), IUCN Red List assessments, biomass trend analysis (i.e., the average rate of change and the extent of decline), CMSY⁺⁺ assessments (i.e., B/B_{MSY} , F/F_{MSY} , MSY, CPUE, biomass), and BRUVS data (i.e., biomass, abundance, prevalence, length) to determine how well they corroborated each other (stats package, R Core Team, 2022). We used average values of catch, MSY, B/B_{MSY} , and F/F_{MSY} , and biomass over the ten years of interest (2010–2020). Correlation coefficients were assigned to three categories “strong” ($\text{abs}(r) > 0.6$), “moderate” ($0.2 < \text{abs}(r) \leq 0.6$), and “weak” ($\text{abs}(r) \leq 0.2$) based on the rule-of-thumb of collinearity between independent variables, set at $r = 0.6$ (Havlicek and Peterson, 1976). Subsequently, strong and moderate significant correlations were assessed based on consistencies with expectations. We used a p-value of 0.10 as guidance rather than as a test of significance, given the small sample size of four RFMOs (significance values were set at 0.1*, 0.05**, 0.01**).

3. Results

3.1. Catch and biomass trends analysis between 1950 and 2020

All four tuna populations showed varying patterns of declining yellowfin tuna biomass with increasing reported catch (Fig. 1A–D). Yellowfin tuna biomass, on average, declined by ~54% globally between 1950 and 2020, with an average annual rate of change of $-1.3\% \text{ y}^{-1}$ (Table 3). The Indian Ocean yellowfin tuna stock experienced the greatest decline in biomass among all the stocks, with a 70.3% decline from 1950 to 2020, compared to a 65.3% decline in the Western Pacific and a 64.4% decline in the Atlantic Ocean. The Eastern Pacific Ocean experienced the least severe decline in adult biomass since 1950, with a decrease of 17.6%

(Fig. 1 A–D, Table 3). The fastest annual rates of decline within the 69 years analysed here occurred in the Indian Ocean ($-1.7\% \text{ y}^{-1}$), followed by the Western Pacific Ocean ($-1.6\% \text{ y}^{-1}$) (Table 3). We compared our updated biomass trend analysis results with those reported by Juan-Jordá et al. (2011). We found that the annual rate and extent of biomass change since 1950 varied between areas (Table 3). This may suggest that the biomass for the various ocean basin-scale stocks of yellowfin tuna may be slowly stabilizing in many of the ocean basins, often around the general management objective defined in the present study as B_{MSY} .

In recent years (Table 3). Most ocean basins suggest biomass levels above or slightly above the B_{MSY} level as measured here, except for the Indian Ocean stock, which suggests biomass levels below the presently used B_{MSY} measure (Fig. 2). The most severe declines in adult yellowfin tuna biomass since 2006 occurred in the Indian Ocean (-18.4%), followed by the Atlantic Ocean (-16.6%). The Eastern Pacific Ocean

Table 3

Comparison of the average yearly rate of change and the extent of decline in biomass between 1950 and 2020 of yellowfin tuna populations derived in this study and those derived in Juan Jorda et al. (2011) only including data from 1950 to 2006.

Yellowfin tuna populations	Average yearly rate of change [%]		Difference between studies [%]	Average extent of change [%]		Difference between studies [%]	Average yearly rate of change between 2006 and 2020 [%]	Average extent of change between 2006 and 2020 [%]
	Between 1950 and 2020 This study	Between 1950 and 2006 Juan-Jordá et al. (2011)		Between 1950 and 2020 This study	Between 1950 and 2006 Juan-Jordá et al. (2011)			
Atlantic population	−1.5	−1.8	16.7	−64.4	−62.9	−2	−1.5%	−16.6
Western Pacific population	−1.6	−1.3	−21.5	−65.3	−52.1	−25	0.6%	7.4
Indian population	−1.7	−2	15.6	−70.3	−66.7	−5	−1.5%	−18.4
Eastern Pacific population	−0.5	−0.6	16.7	−17.6	−29.6	12	−0.3%	−4.7
Average	−1.3	−1.4	6.9	−54.4	−53	−1.5	−0.7	−8.1

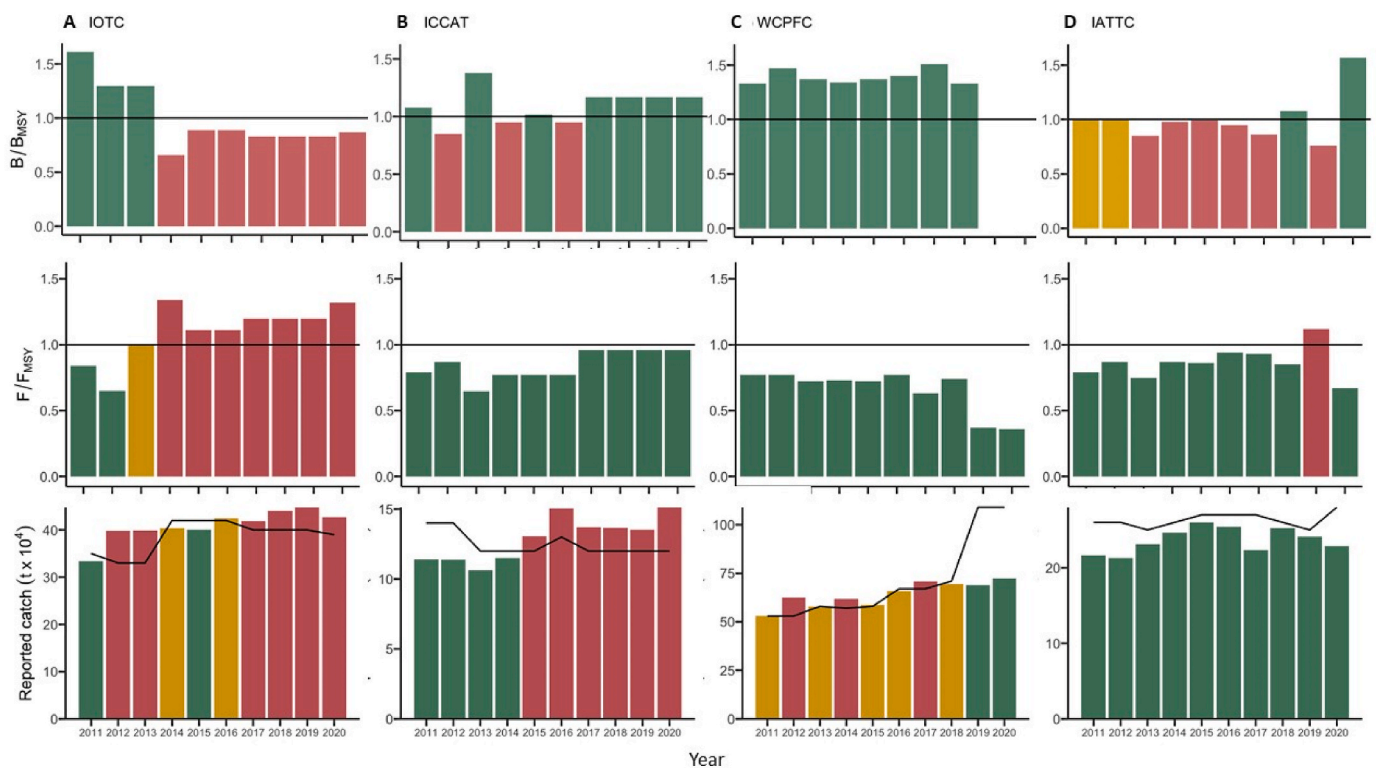


Fig. 2. Traffic light plots for fisheries thresholds of current biomass (B) relative to biomass at maximum sustainable yield (B_{MSY}), current fishing mortality (F) relative to fishing mortality at maximum sustainable yield (F_{MSY}), and reported catch relative to maximum sustainable yield (MSY , black line) by tuna RFMO: (A) IOTC, (B) ICCAT, (C) WCPFC, and (D) IATTC. Red, yellow, and green indicate below (red), met (yellow), or above threshold (green) for B/B_{MSY} and above (red), met (yellow), or below threshold (green) for F/F_{MSY} and reported catch vs. MSY . Black lines indicate limits of 1 for the B/B_{MSY} and F/F_{MSY} graphs and MSY extracted from official RFMO stock assessment reports.

experienced the least severe declines since 2006 (−4.7%) compared to the other tuna RFMOs. In contrast, adult yellowfin tuna biomass has increased by 7.4% in the Western Pacific Ocean since 2006 (Table 3).

3.2. Traffic lights for biomasses, fishing mortalities, and catches vs. fisheries reference points

We summarized the current exploitation status for the four yellowfin tuna populations over the last ten years based on the biological reference points B/B_{MSY} and F/F_{MSY} and reported catch derived from tuna RFMO stock assessment reports to match the temporal scale of the available BRUVS data (Fig. 2). Our traffic light classification indicated that the

ratio of B/B_{MSY} generally fell below the B_{MSY} limit of one 70% of the time in the evaluated ten-year period for the IOTC, 30% of the time for the ICCAT, and 60% of the time for the IATTC, but remained above the B_{MSY} level for the WCPFC throughout the period considered (Fig. 2A–D). The ratio of current fishing mortality F/F_{MSY} consistently exceeded the level of F_{MSY} in the IOTC for the last 6–7 years but remained below the threshold in the other three RFMOs for all but one year in the IATTC (Fig. 2A–D). The reported catch also consistently exceeded MSY in most years for the Indian Ocean yellowfin tuna population (Fig. 2A), with the yellowfin tuna in the Atlantic showing similar patterns of catches having exceeded.

The estimated MSY since 2017 (Fig. 2 B). Annual catches typically

Table 4

Comparison of fishery metrics and stock status derived from catch-based assessments (CMSY) and the fishery stocks assessment adopted in each tuna RFMO.

Yellowfin tuna populations	Fishery Metric	CMSY assessment	RFMO fishery stock assessments	Difference	CMSY stock status	RFMO stock status
Indian population	B/B _{MSY}	0.83	0.87	5%	Stock is overfished and experiencing overfishing	
	F/F _{MSY}	1.37	1.32	4%		
	MSY	382,000	394,000			
	B _{MSY}	1,486,000	1,333,000			
Atlantic population	B/B _{MSY}	1.17	1.17	0%	Stock is not overfished and not experiencing overfishing	
	F/F _{MSY}	0.89	0.96	7%		
	MSY	822,000	121,298			
	B _{MSY}	3,529,000	814,000			
Western Pacific population*	B/B _{MSY}	1.1	2.43	55%	Stock is not overfished but experiencing overfishing	Stock is not overfished and not experiencing overfishing
	F/F _{MSY}	1.07	0.36	197%		
	MSY	598,000	1,091,000			
	B _{MSY}	2,168,000	858,700			
Eastern Pacific population	B/B _{MSY}	1.35	1.57	14%	Stock is not overfished and not experiencing overfishing	
	F/F _{MSY}	0.53	0.67	21%		
	MSY	329,000	288,000			
	B _{MSY}	1,332,000	371,787			

met or slightly exceeded MSY levels of catch until 2019 in the Western Pacific yellowfin tuna population, when MSY levels were suddenly increased by ~35% (<https://oceanfish.spc.int/en/ofpsection/sam/sam/216-yellowfin-assessment-results#2020>, Fig. 2C). In contrast, the catch in the Eastern Pacific yellowfin tuna population has not exceeded RFMO stock assessment derived MSY levels during the past decade (Fig. 2D).

3.3. CMSY⁺⁺ assessments

The fisheries metrics and stock status derived from the CMSY⁺⁺ assessments were the most optimistic for the yellowfin tuna stock in the IATTC convention Area, with B/B_{MSY} at 1.35 and F/F_{MSY} at 0.53,

indicating that the stock is not overfished and not experiencing overfishing (Table 4, Fig. S1). Similarly, yellowfin tuna in the Atlantic Ocean is not overfished (B/B_{MSY} = 1.17) and not subject to overfishing (F/F_{MSY} = 0.89) (Table 4, Fig. S1). In contrast, Indian Ocean yellowfin tuna is overfished (B/B_{MSY} = 0.83) and experiencing overfishing (F/F_{MSY} = 1.37, Table 4, Fig. S1). The Western Pacific yellowfin tuna is not overfished (B/B_{MSY} = 1.1) but experiencing overfishing (F/F_{MSY} = 1.07, Table 4, Fig. S1).

3.4. Regional variation in yellowfin tuna population metrics derived from mid-water BRUVS

Yellowfin tuna were observed at 14 (29%) of the 44 global locations

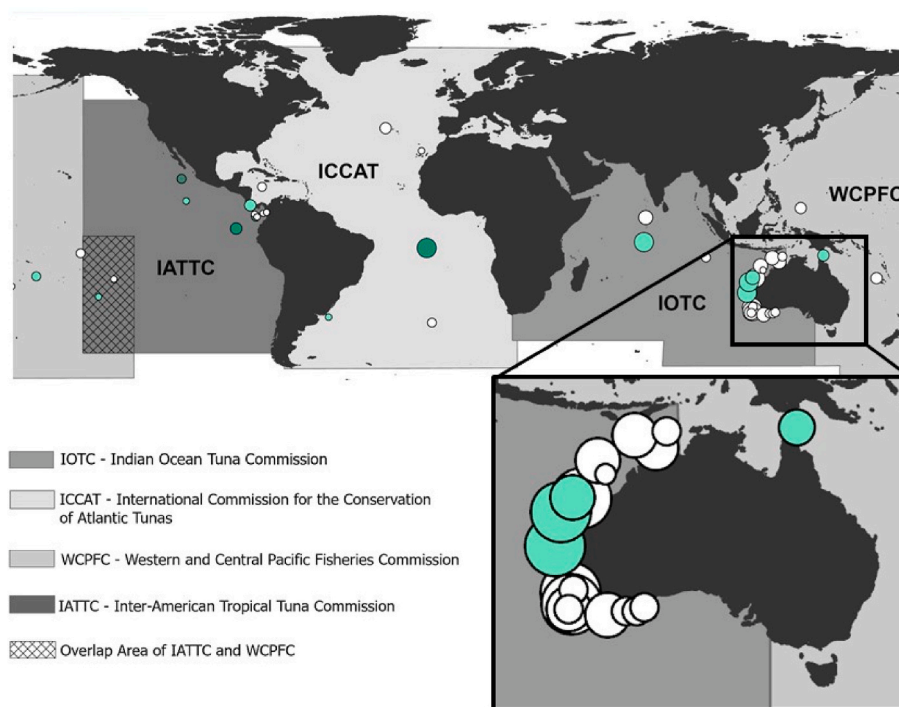


Fig. 3. Observed distribution of yellowfin tuna (*Thunnus albacares*) as sampled with BRUVS across the four tuna Regional Fisheries Management Organization convention areas. Green circles indicate mid-water BRUVS records with yellowfin tuna present, with light green indicating low abundance, medium green indicating moderate abundance, and dark green indicating high abundance; white circles indicate BRUVS records without yellowfin tuna. Sampling effort is indicated by the diameter of each location marker and represents the number of mid-water stereo-BRUVS deployments (range: 17–655).

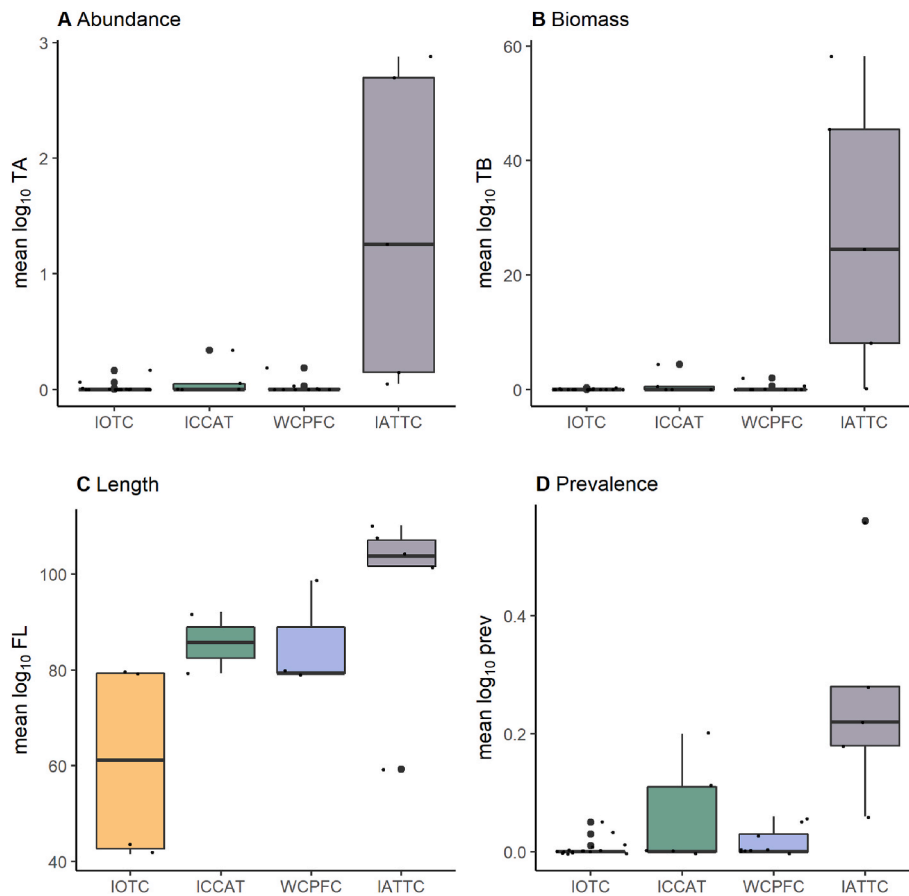


Fig. 4. Mean values for \log_{10} transformed values of BRUVS-derived metrics of yellowfin tuna (A) total abundance (TA), (B) total biomass (TB), (C) fork length (FL), and (D) prevalence by RFMO Convention Area. The horizontal line in the middle of the box indicates the median value of the scores; the box itself marks the interquartile range (IQR; 25th (Q1) and 75th (Q3) percentile around the median). The vertical lines mark the maximum and minimum values (expressed as $Q3 \pm 1.5 \times \text{IQR}$). Values more than 1.5 box-lengths from the lower edge of the box, so-called outliers, are designated with a circle.

surveyed by the Marine Futures Lab since 2014 (Fig. 3; Table 2, Table S1). The mean sampling depth over which BRUVS sampling occurred was 694 m. Yellowfin tuna were observed in locations with seabed depth ranges from 37 m to 2400 m, with no yellowfin tuna observed in samples with seabed depths >2500 m. This fisheries-independent BRUVS dataset suggests that yellowfin tuna in the Indian Ocean are the least common, least abundant, have the lowest biomass, and are the smallest yellowfin tuna in the currently limited global BRUVS dataset, whereas yellowfin tuna in the Eastern Pacific are the most common, most abundant, have the largest biomass, and largest individuals in the global BRUVS dataset (Fig. 4). Future expansion of BRUVS sampling locations will enhance these fisheries-independent surveys to enable further confirmation or revision.

The RFMO populations differed significantly in relative abundance (MaxN) (PERMANOVA: $R^2 = 0.43$, p -value = 0.001) and largely fell into three groups of relatively high, medium, and low abundance. The IOTC and WCPFC showed the lowest relative abundances, with 0.013 and 0.017 individuals per BRUVS set, respectively, and mean prevalence of 1% and 2%, respectively. The ICCAT recorded a mean relative abundance of yellowfin tuna of 0.078 per BRUVS set and a 6% prevalence (Table 2). The IATTC, recorded the most yellowfin tuna with a mean MaxN of 1.004 and a 26% prevalence (Table 2).

Pairwise comparisons indicated that mean abundance was significantly greater at IATTC than IOTC (pairwise PERMANOVA: $R^2 = 0.41$, p -value = 0.002), and WCPFC locations (pairwise PERMANOVA: $R^2 = 0.36$, p -value = 0.011), all other pairwise comparisons were non-significant (Table S2).

IATTC locations had the highest mean biomass of $19.5 \text{ t} \pm 9.074 \text{ SE}$,

followed by ICCAT locations with a mean biomass of $0.992 \text{ t} \pm 0.864 \text{ SE}$ per sample (Table 2). The lowest mean biomass was detected in the IOTC, with a mean of $0.029 \text{ t} \pm 0.017 \text{ SE}$. Pairwise comparisons indicated that the mean biomass of yellowfin tuna was significantly higher in the IATTC than in the IOTC (pairwise PERMANOVA: $R^2 = 0.45$, p -value = 0.001), and the WCPFC (pairwise PERMANOVA: $R^2 = 0.39$, p -value = 0.005). Additionally, we found significantly higher mean biomass of yellowfin tuna in the ICCAT than in the IOTC (pairwise PERMANOVA: $R^2 = 0.2$, p -value = 0.042). All other pairwise comparisons were non-significant (Table S2). The BRUVS database contains 195 yellowfin tuna length measurements at the point of MaxN. The overall length distribution ranged from 23.1 to 220.2 cm, with an overall mean of $81.8 \pm 2.85 \text{ SE cm}$. The largest mean FL was $96.4 \text{ cm} \pm 9.4 \text{ SE}$ in the IATTC and the smallest mean FL was $60.8 \text{ cm} \pm 10.7 \text{ SE cm}$ in the IOTC (Table 2). The greatest range in FL was 35.8 cm–201.9 cm in the IATTC. Mean FL varied significantly among locations (PERMANOVA: $R^2 = 0.31$, p -value = 0.003). Pairwise comparison indicated that mean FL was significantly larger in the IATTC than in both the IOTC (pairwise PERMANOVA: $R^2 = 0.49$, p -value = 0.001), and the WCPFC (pairwise PERMANOVA: $R^2 = 0.31$, p -value = 0.019). All other pairwise comparisons were non-significant (Table S2).

3.5. Comparative analysis of multiple lines of evidence

We found good agreement between the F/F_{MSY} ratios estimated by the CMSY⁺⁺ assessments and those estimated by the respective stock assessments performed by working groups in tuna RFMOs, with three out of four CMSY⁺⁺ estimates reaching the same conclusion regarding

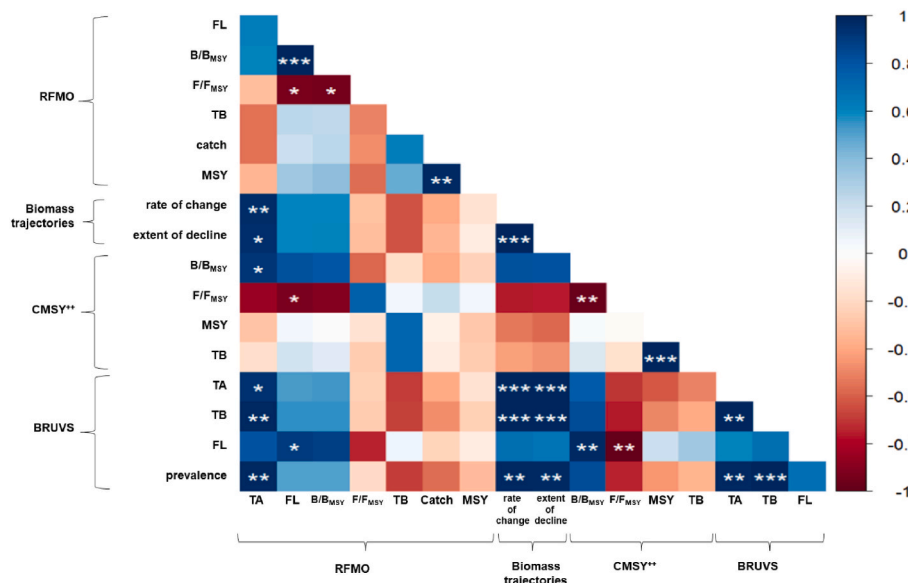


Fig. 5. Pearson's correlation coefficients between and within fisheries-independent population metrics (derived from BRUVS analysis) and fisheries-dependent population metrics (derived from RFMO fishery assessments, CMSY assessments, and biomass trend analysis) of yellowfin tuna populations. Positive correlations between variables are displayed in blue (0.1–1), negative correlations in red (–0.1 to –1), with strong correlations in opaque and moderate correlations in transparent. No correlation between variables is shown as a white square. Only significant correlations are displayed with: $p < 0.01^{***}$, $p < 0.05^{**}$, $p < 0.1^{*}$. Metrics include fork length (FL), relative stock biomass status (B/B_{MSY}), exploitation status (F/F_{MSY}), total biomass (TB), Maximum Sustainably Yield (MSY), total abundance, (TA).

overfishing ($F/F_{MSY} > 1$), deviating less than 25% from the RFMO assessments (Table 4). Similarly, a comparison of the CMSY⁺⁺ and RFMO assessment estimates of B/B_{MSY} ratios revealed good agreement, with 100% of the CMSY⁺⁺ estimates reaching the same conclusion as the RFMO assessment estimates regarding overfished stock status ($B/B_{MSY} < 1$) and three out of four CMSY⁺⁺ estimates deviating less than 15% from the working group's estimates (Table 4, Fig. S1). Thus, we considered these results comparable to the official RFMO.

Assessment estimates used to provide fisheries management advice and used them as fishery-dependent variables in our correlation analysis. Kobe plots from the CMSY⁺⁺ assessments used to evaluate the status of a stock based on the fishing mortality (F) and biomass (B) associated with MSY (i.e., F_{MSY} and B_{MSY}) are provided in the supplementary information (Fig. S1).

Generally, we observed the predicted positive and negative correlations between the outcomes of the methods used to assess the conservation and fishery status of yellowfin tuna (Table S3). We found highly significant positive correlations between biomass trends metrics (i.e., the annual rate of change and extent of decline) and RFMO total abundance (CPUE, $r = 0.96$, $p = 0.04$ and $r = 0.65$, $p = 0.05$, respectively, Fig. 5, Tables S4 and S5). Biomass.

Trends from 2006 to 2020 derived from our analyses were also significantly and highly correlated with BRUVS-derived abundance, biomass, and prevalence ($r = 1.0$, $p = 0.001$, $r = 1.0$, $p = 0.01$, $r = 0.98$, $p = 0.02$, respectively, Fig. 5, Tables S4 and S5). Similarly, CMSY⁺⁺-derived B/B_{MSY} was significantly highly correlated with RFMO-derived total abundance ($r = 0.92$, $p = 0.08$, Fig. 5, Tables S4 and S5).

Additionally, three metrics derived from the fishery-independent BRUVS method were significantly highly correlated with RFMO-derived total abundance: BRUVS abundance ($r = 0.94$, $p = 0.06$), BRUVS biomass ($r = 0.98$, $p = 0.02$), and BRUVS prevalence ($r = 0.99$, $p = 0.01$, Fig. 5, Tables S4 and S5). We also found highly significant positive correlations between metrics derived for fork length from RFMO assessments and BRUVS sampling ($r = 0.9$, $p = 0.1$, Fig. 5, Tables S4 and S5). Furthermore, we found significant negative correlations between CMSY⁺⁺-derived F/F_{MSY} and RFMO-derived fork length ($r = -0.92$, $p = 0.08$), and BRUVS-derived fork length ($r = -0.99$, $p =$

0.01). We confirmed this trend with RFMO F/F_{MSY} data; however, it was only marginally significant for RFMO-derived fork length ($r = -0.94$, $p = 0.06$) (Fig. 5, Tables S4 and S5).

4. Discussion

4.1. The dire straits of Indian Ocean yellowfin tuna

Our analysis found that since 1950, the biomass of all global yellowfin tuna stocks combined has decreased, on average, by 54 % across the four globally assessed populations. The exploitation status of yellowfin tuna populations across ocean basins ranges from not-fully exploited (IATTC, ICCAT) to fully exploited (IOTC, WCPFC), where any further increase in fishing effort would lead to overfishing. Tuna biomass has declined largely due to overexploitation (Juan-Jordá et al., 2022). However, concerns around perceived reliability of data in the early years if fisheries may complicate the differentiation of fishery-related declines in biomass and declines caused by non-fishery factors. For instance, there is some evidence that sustained poor recruitment and variability in recruitment may also lead to low spawning stock biomass and consequently affect the productivity of fish stocks (Sharma et al., 2020; Hampton and Fournier, 2001; Maunder et al., 2006; Kolody et al., 2019). However, reduced catch levels can lead to stabilized biomass trends, such as in the case of the WCPFC yellowfin tuna population.

The yellowfin tuna population in the Indian Ocean basin, on the other hand, is in critical condition, with current biomass and fishing mortality levels well outside the levels supporting MSY (i.e., B_{MSY} and F_{MSY}). This implies that the Indian Ocean yellowfin tuna population is both overfished (B_{MSY}) and experiencing overfishing (F_{MSY}), yet IOTC fisheries thresholds have consistently been exceeded in the last decade. We found that yellowfin tuna biomass in the Indian Ocean, has declined by ~70% since 1950, at an annual rate of decline of ~1.7%. This yellowfin tuna population has declined by a further 18% since the last biomass trend analysis in 2011 (Juan-Jordá et al., 2011). From a conservation perspective, this decline is alarming and highlights the threat to this population's future health and productivity. Furthermore, the

CMSY⁺⁺ assessment corroborated RFMO stock assessment results and confirmed the Indian Ocean population is overfished and subject to overfishing and the BRUVS analysis indicates that yellowfin tuna in the Indian Ocean are the least common, least abundant, and the smallest compared to other RFMO management regions. CMSY⁺⁺ assessments may overestimate fishing mortality in some cases (Bouch et al., 2021) and may not be ideal as a stand-alone measure for implementing management control (Kell et al., 2003) in situations where conventional assessments can be undertaken. Yet, many of the world's exploited fish stocks, particularly vulnerable shark and ray species lack established fisheries reference points (Froese et al., 2012; Zhou et al., 2012; Ortuño Crespo et al., 2019). This absence of reference points makes it challenging to determine the extent of exploitation and the current status of the stocks. It is not always economically feasible to conduct traditional stock assessments for currently unassessed or unmonitored species or stocks, necessitating the use of other methods to provide preliminary estimates of abundance and status. Tuna RFMOs are mandated to monitor, report, and manage all species under their legislation and they have made progress in implementing stock assessments for functionally important non-target species such as sharks using quantitative methods for data-limited situations, including surplus production models (CMSY⁺⁺, Froese et al., 2017; Heidrich et al., 2022). Here we treated the CMSY⁺⁺ assessments as a complementary rather than competing approach to official RFMO assessments, alongside other lines of evidence such as the biomass trajectory and BRUVS analyses. This study indicates that results from CMSY⁺⁺ assessments of data rich yellowfin tuna stocks mirror official tuna RFMO stock assessment results, thus confirming the applicability of data-limited assessment methods to the large number of currently unassessed stocks and species. Our findings support previous claims of systematic and widespread overfishing of yellowfin tuna in the Indian Ocean threatening its future productivity (ISSF, 2022, 2023). We support calls to adapt management strategies accordingly to reduce the current level of fishing of this valuable resource to ensure its long-term sustainability (Chassot et al., 2019; Rattle, 2021).

The most recent IUCN Red List assessment downlisted yellowfin tuna from globally “Near Threatened” in 2011 to “Least Concern” in 2021 (Collette et al., 2011, 2021a). Yet, the risk of extinction varies regionally for yellowfin tuna populations: Atlantic and Pacific populations of yellowfin tuna are classified as “Least Concern”, but the Indian yellowfin tuna population is listed as “Vulnerable”, with recent steep declines in biomass (Collette et al., 2021a). Both RFMO fishery stock assessments and regional Red List assessments suggest the status of the Indian Ocean yellowfin tuna population to be in worse condition than those in other oceans (IOTC, 2021a; Juan-Jordá et al., 2022). Fisheries stock assessments determine stock status comparing current biomasses of the stocks to B_{MSY} levels, which are already based on exploited stocks (i.e., IATTC, ICCAT), or based on spawning biomass depletion ratios (i.e., IOTC, WCPFC). IUCN Red List assessments, on the other hand, measure population declines within the last three generations lengths of the species, to determine its risk of extinction (Collette et al., 2021a). As such, any large historical declines in biomass are not accounted for in both fishery and extinction risk assessments. We recommend quantifying and monitoring declines ideally from unexploited status, to account for shifting baselines (Pauly, 1995), to avoid loss of ecological knowledge, and assess progress towards conservation goals. Furthermore, sampling in ‘pristine’ locations alongside fished locations could mitigate potential bias.

4.2. Challenges of formal stock assessments and the use of fisheries independent methods

Estimating the status of fish stocks can be very challenging, not least due to biases in fisheries-dependent input data, i.e., nominal catch, size frequency data, and abundance indices (i.e., CPUE), such as sampling error in data collection, e.g., sample size, location and frequency, and

large uncertainties around biological processes, i.e., growth and natural mortality still exist (Geehan & Pierre, 2015; Pecoraro et al., 2017; Heidrich et al., 2022). Consequently, there are increasing number of studies developing and testing the use of fisheries-independent data derived from acoustic and aerial surveys to examine the spatial and temporal distribution of tropical tuna and non-tuna-like species associated with FADs (Lopez et al., 2017; Orue et al., 2020) and develop indices of abundance for tropical tuna stock assessments (Melvin et al., 2018; Santiago et al., 2020).

Here we add BRUVS to this suite of fisheries-independent methodologies. Our findings support previous research that identified BRUVS as a suitable, standardized, and non-extractive fishery-independent method for characterizing fish assemblages (Langlois et al., 2012b; White et al., 2013; Cappo et al., 2006; Langlois et al., 2012b; Santana-Garcon et al., 2014b; Brooks et al., 2011; Goetze & Fullwood, 2013). We confirm that surveys using mid-water BRUVS can yield information on the relative abundance and size composition of migratory species such as yellowfin tuna that complements and confirms results from fisheries-dependent datasets. This fisheries-independent method has the potential to support large scale sampling of finer-scale population structures for widely distributed species at targeted locations decoupled from fishing operations. This will be particularly important, because, despite the documentation of genetic differentiation within the Pacific (Grewe et al., 2015), Atlantic (Pecoraro et al., 2018), and Indian oceans (Grewe et al., 2020; Artetxe-Arrate et al., 2021), current species evaluation at the ocean basin scale might mask exacerbated declines in sub-populations that exhibit varying responses to fishing and may require separate evaluations and management measures (Pecoraro et al., 2017; Artetxe-Arrate et al., 2021; Muñoz-Abril et al., 2022). Mid-water BRUVS may enable finer-scale management to more effectively accommodate the development, response to fishing pressures, and recovery potential of various subpopulations. Non-lethal methods such as BRUVS are also appropriate for areas where the use of fisheries-dependent methods is constrained, such as in marine protected areas (Langlois et al., 2012a, 2012b). The 2022 agreement at the Conference of Parties (COP15) of the Convention on Biological Diversity to place 30% of the oceans in marine protected areas by 2030 will drive the need for fisheries-independent monitoring of marine populations.

Mid-water BRUVS have limitations. The current limited sampling area of BRUVS may not be representative of the wide-ranging distributions of yellowfin tuna populations and may not accurately reflect global populations. Sampling effort was mainly restricted to EEZ waters and excludes key locations, such as the Western Indian Ocean, where, most recently, the majority of industrial fishing effort for large pelagic species such as yellowfin tuna is concentrated (ICCAT, 2019; Mente-Vera et al., 2020; Collette et al., 2021a; IOTC, 2021a; Magnusson et al., 2023). However, prior to the 1970s, yellowfin tuna and other large pelagic species were also targeted and caught by fishing vessels in coastal waters, and there remains recreational fishing of yellowfin tuna within 50 km from shore in many places in the world (IOTC, 2009; Patterson, 2021). That we are finding low to no abundances of yellowfin tuna in these near-coastal pelagic EEZ waters where this species once was present or even abundant may be a sign of shrinking areas of occupancy with associated declining population sizes as per IUCN RedList Criteria (Collette et al., 2011, 2021a; IUCN, 2012). Current BRUVS sampling locations do not provide a comprehensive and representative coverage of the entire current distribution area of yellowfin tuna, however, our analysis showed that patterns of stock status provided by tuna RFMO assessments were confirmed. Future expansions of BRUVS sampling locations will improve these independent surveys of abundance. Furthermore, the BRUVS deployed here are limited to the epipelagic zone, a trade-off between ease of use and capturing a broader range of vertical habitat. Considering these challenges, the data used here must be treated with caution. However, mid-water BRUVS retain all the characteristics that have made camera-based sampling a versatile and efficient method for non-destructive marine monitoring and should be

considered in future management measures to strengthen the scientific advice for data-rich and data-limited large pelagic species. Future widespread application of this technology across diverse biological and anthropogenic gradients can provide enough data to detect trends in biomass and the abundance of widely-distributed species with large migration patterns and will further increase the utility of this approach (Letessier et al., 2017).

4.3. The stalled management of Indian Ocean yellowfin tuna

Indian Ocean yellowfin tuna have been overfished at least since 2015, and scientists have repeatedly warned that if fishing pressure is not reduced, the population might collapse within a few years (Winker et al., 2019; Rattle, 2021). The IOTC started to develop and adopt conservation and management measures to recover yellowfin tuna, including catch limits (IOTC, 2017), mandatory statistical reporting requirements (Res. 15/02), target and limit reference points (Res. 15/10), and a ban on discards (Res. 19/05) (IOTC, 2011, 2014, 2015a, 2015b, 2015c, 2019a, 2019b). Yet the RFMO assessments, together with our findings from multiple lines of evidence, indicate that the yellowfin tuna in the Indian Ocean is still not being managed to ensure the sustainability of the fishery. At its 25th session in 2021, the IOTC agreed on an interim rebuilding plan for the species and established a catch limit of 401,011 MT (Hillary et al., 2021). However, even that catch limit exceeded the 2021 estimated MSY of 349,000 MT (IOTC, 2021b). According to a new more reliable assessment, a catch reduction of at least 30% from 2020 levels is required to be confident in the Indian Ocean population's recovery (Sinan and Bailey, 2020; IOTC, 2021b), more than double the largest reductions outlined in 2017 (IOTC, 2017).

Europe, as the larger contributor to yellowfin catches, has a key responsibility to lead the recovery of the species, yet, the EU refuses to comply with any further catch reductions until a number of IOTC objects comply with the measure, risking further declines of the population (Global Tuna Alliance, 2021; Walker, 2021). The EU has also recently decided to object the implementation of an annual 72-day prohibition of drifting FADs in the Indian Ocean, proposed by member countries due to the increasing use of FADs over the past two decades which has raised serious concerns about their effects on the environment. This decision jeopardizes the long-term health of the fishery, and decisive actions need to be taken to ensure the successful implementation of the much-needed temporary ban. Moreover, the EU Commission calls for the relaxation of so-called margins of tolerance, i.e., the difference between logbook catches and landing declaration, to 25% (European Commission, 2021), which could foster misreporting (IOTC, 2021a) and further jeopardize the reliability of species-specific catch data necessary for reliable stock assessments and adequate management advice. However, differentiating between small yellowfin and bigeye tuna caught by purse seine fleets can be challenging and misidentification can be as high as 30% (Pedrosa-Gerasmio et al., 2012; Pecoraro et al., 2017, 2020).

4.4. The strength of using multiple lines of evidence to provide scientific advice and recommendations to improve the management of Indian Ocean yellowfin tuna

In this study we combined quantitative and qualitative data (i.e., CMSY⁺⁺), integrated different types of data sources (i.e., fisheries-dependent and fisheries-independent), replicated and validated original findings using different modelling methods (i.e., CMSY⁺⁺ stock assessments) to strengthen the scientific advice for yellowfin tuna. Multiple lines of evidence are often used to provide more robust and reliable scientific advice and we showed that the additional methods presented in this manuscript, i.e., biomass trend analysis, CMSY⁺⁺ assessments, and BRUVS assessments cross-validate each other and the official tuna RFMO stock assessment results. We further note that these methods can improve confidence, accuracy, transparency, and

understanding of the complex large pelagic fishery and population dynamics. The fisheries-dependent and fisheries-independent data, analyses, and assessments in our study can therefore be used to strengthen the scientific advice for yellowfin tuna. However, improvements in scientific research are insufficient on their own to ensure advancements in the long-term management and sustainability of yellowfin tuna populations. This can only be achieved by strong governance based on the best available scientific advice. Stricter management measures may include reduction in fishing capacity, the treatment of MSY as a limit reference point, and the implementation of effective catch limits (Kell et al., 2003; Maunder and Harley, 2006; Mooney-Seus and Rosenberg, 2007; Caddy, 1995). Total allowable catches (TACs) are highly effective in rebuilding overfished populations (Pons et al., 2017). Yet, only the ICCAT has applied TACs for the regionally-managed yellowfin tuna populations in the Atlantic Ocean (ICCAT, 2021) while managers in other tuna RFMOs continue to debate how to allocate catch quotas (Seto et al., 2021). We emphasize the urgency of finding a way to reduce Indian Ocean yellowfin tuna catches by at least the recommended 22% to halt and reverse their decline.

Reduced TACs should be complemented with further management measures, i.e., minimum size regulations and seasonal and spatial dynamic closures to ensure recovery to sustainable levels (Pons et al., 2017). Positive effects of marine protected areas (MPAs) have been documented for many species, including large pelagics, both for the recovery of species within reserves as well as increased catches in adjacent fisheries (Dueri and Maury, 2013; Di Lorenzo et al., 2016; Medoff et al., 2022). However, larval dispersal and increased mobility of species may limit these benefits (Hampton et al., 2023). We further recommend that the IOTC member countries prioritize the implementation of appropriate control systems and the improvement of the IOTC management framework to manage tropical tuna populations sustainably in the long term by de-incentivizing FAD fishing, investing in far higher levels of on-board monitoring and sampling (Banks et al., 2016), and enhancing controls at landing sites instead of relaxing the margin of tolerance to 25%, as demanded by the EU tropical purse seine fishing fleets. More stringent management practices must be implemented to reduce overall fishing capacity, rebuild overfished populations, and enforce other regulations to reduce the collateral damage these fisheries cause to marine ecosystems and ensure the recovery and long-term viability of large pelagic species.

5. Conclusion

Thomas Huxley was wrong. Clearly, one of the “great sea fisheries”, the yellowfin tuna in the Indian Ocean, is in dire straits. Multiple lines of evidence corroborate that yellowfin tuna in the Indian Ocean is in poor status being exploited unsustainably. We highlight the urgency of implementing and enforcing management measures that reduce catches and fishing mortality and aid biomass recovery. High value and global demand coupled with rising fishing capacity and fishing mortality are exacerbating the pressure on yellowfin tuna populations that are at best, already fully exploited or, in the case of the Indian Ocean, overexploited (ISSF, 2022). Now more than ever, robust, urgent, and strict measures and actions are required to ensure that yellowfin tuna overfishing is stopped and that binding precautionary total catch limits are put in place to improve the Indian Ocean yellowfin tuna resources.

Statements

Author contributions

KH completed the data synthesis and analysis and drafted, reviewed and edited the manuscript. JJM advised on methods, reviewed and edited the manuscript. All authors reviewed and edited the manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ocecoaman.2023.106902>.

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