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Equitable pathways for sustainable tuna fisheries management in the Indian Ocean

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A B S T R A C T

Sustainability in fisheries hinges upon a multifaceted approach. It entails an ongoing assessment of fisheries' sustainability across ecological, social, and economic dimensions. This necessitates a comprehensive understanding of the trade-offs inherent in pursuing these diverse goals. Within the Indian Ocean, tuna fisheries management faces challenges due to unsustainable exploitation, uneven access to catch opportunities, and increasing stakeholder tensions. To address some of these challenges and respond to the expressed need for science-based management, our integrated approach combines a stock assessment operating model, several management scenarios used for decadal projections and the resulting inequality metrics across fishing fleets. The application focuses on yellowfin tuna (*Thunnus albacares*), which is the most vulnerable species in the Indian Ocean, targeted equally by both industrial and artisanal fleets. The study explores management options, including restrictions on DFAD (drifting fish aggregating device) sets, operational buoys, seasonal closures, and complete DFAD elimination. Results suggest that DFAD-free and seasonal closures effectively rebuild yellowfin tuna biomass but may also lead to increased inequality, either in catch or revenue distributional terms. Reducing DFAD fishing during the third quarter redistributes fishing opportunities more equitably. The findings underscore the need for effective DFAD control and emphasise considering distributional aspects in tuna fisheries management.

1. Introduction

Tuna and tuna-like species significantly contribute to global fisheries [1], constituting over 8 million tons annually, valued at $41 billion in 2018 [2]. Three tropical tuna species, skipjack (*Katsuwonus pelamis*) (2.90 Mt), yellowfin (*Thunnus albacares*) (1.52 Mt), and bigeye (*Thunnus obesus*) (0.40 Mt), make up approximately 60 % of these catches. Managed by tuna Regional Fisheries Management Organizations (RFMOs), tropical tuna stocks involve various stakeholders, including scientists, NGOs, and representatives of coastal and fishing countries [3]. The management complexity arises from diverse fishing gears, ranging from artisanal methods in coastal developing countries to industrial fleets, mainly associated with developed nations and operating in distant international waters [4].

Tuna RFMO member countries are mandated to work towards sustainable tuna stock exploitation. Management decisions hinge on stock status, assessed through biological reference points like maximum sustainable yield (MSY). Adhering to Ecosystem-Based Fisheries Management [5], decisions extend beyond the target species to address ecological concerns, such as minimising habitat impact and accidental catches. Scientists in dedicated groups develop models and indicators, offering crucial advice to decision-makers [6]. In addition to ecological considerations, equity issues related to stock recovery plans and catch reductions are often discussed during negotiations [7]. Equity within tuna RFMOs relates to a fair distribution of fishing opportunities in the form of fishing rights and benefits among the member states stakeholders, ranging from the least to the most developed countries. Tensions among stakeholders arise within decision-making bodies due to uneven access to catch opportunities and varying dependence levels on tuna fisheries for revenue, food security, employment, and overall social well-being [8]. For instance, equity principles come into play when dividing Total Allowable Catches (TACs) among claimants [9]. In

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tropical tuna fisheries, historical rights may allocate higher quotas to contracting parties (CPCs) involved in the initial development. The impact of management decisions on food-insecure populations and artisanal fishing communities relying on tuna is also debated regarding the legitimacy of historical access rights [10,11]. Despite their significance and influence in decision-making, quantitative approaches addressing biological and distributional aspects of tuna fisheries management still need room for improvement. Most tuna RFMOs have incorporated distributional equity into their allocation guidelines, except for the Indian Ocean Tuna Commission (IOTC) [12]. However, in many cases, the specific weighting or significance assigned to each criterion remains underdeveloped or inconsistently applied [13]. For example, RFMOs may need to implement management measures that can economically impact member countries by reducing fishing opportunities. In the Western and Central Pacific Ocean RFMO, small island developing states (SIDs) with limited economic diversity rely heavily on tuna revenues coming from foreign fleets. These states manage fisheries through access fees, selling fishing days to distant-water fishing nations (DWFNs) while ensuring sustainable management of fishing effort. In contrast, the Atlantic Ocean RFMO, ICCAT, uses similar mechanisms but also considers socio-economic factors when allocating quotas, such as potential job losses, impacts on small-scale fishers, and effects on regional economies [14].

Since the early 1990s, economic studies on distributional aspects in fisheries have explored the trade-off between equity and efficiency, with theoretical models examining the connection between sole ownership and optimal exploitation rates, e.g., [15,16]. Management plans commonly involve reducing effort, implementing capacity decommissioning schemes, and concentrating access rights. Despite being viewed as a direct route to maximise fishing rent, Individual Transferable Quota systems (ITQs) raise equity concerns, creating potential entry barriers and dominant positions [17–19]. Managing high-seas fisheries and transboundary stocks with diverse fleets and contracting parties complicates the definition of fair international agreements, as highlighted by game theory studies [20–22]. To assess the distributional effects of fisheries management plans, inequality metrics, particularly the Gini index, have been introduced [23–25,18]. The Gini index reflects more on equity than fairness, measuring deviation from an egalitarian situation where all participants would receive an equal share of a defined variable (catch, revenue, benefit, etc.).

Tuna RFMOs currently grapple with sustainability and equity concerns surrounding the widespread use of Drifting Fishing Aggregating Devices (DFADs) by industrial purse seine fleets. DFADs are drifting floating objects (FOBs), such as rafts or buoys, constructed and deployed by purse seiners, who exploit tuna's natural associative behaviour by deploying FOBs to enhance their catches. Estimated annual numbers of DFADs were between 81,000 and 121,000 in 2013 [26]. Industrial purse seiners use DFADs equipped with advanced technology, such as satellite-linked echosounder buoys, to remotely locate and track tuna biomass associated with them [27]. The term "operational buoys" denotes echosounder buoys deployed at sea, which remotely transmit their location and acoustic data to purse seine vessels.

While enhancing fishing efficiency [28], DFADs also pose ecological challenges, impacting target and non-target species and habitats [29, 30]. A significant concern is the heightened fishing mortality of juvenile yellowfin tuna, potentially compromising the stock's spawning biomass. Addressing these issues requires the development of specific operating models and indicators tailored to DFAD fisheries to provide adequate scientific advice to managers [31].

The ecological concerns related to the widespread use of DFADs are heightened in the Indian Ocean by the current status of the yellowfin tuna stock, marked by a decade of overfishing and overexploitation [32]. An updated assessment is expected later this year (2024), which could provide crucial insights for future management measures and determine whether more stringent conservation actions are needed. The industrial purse seine fleet in the region comprises approximately 48 vessels, contributing a quarter of the total yellowfin tuna catch in this ocean, which is around 427,000 tons in 2020 [33]. Over three-quarters of this catch was obtained using DFADs [33].

The Indian Ocean Tuna Commission functions as the responsible tuna RFMO for overseeing tuna and tuna-like fishery resources in the Indian Ocean. To restore the yellowfin tuna stock, the IOTC has adopted TAC-based output control rules (IOTC Resolution 16/01). Additionally, since 2013, the IOTC has implemented various measures concerning DFADs, progressively reducing the limits on the number of operational buoys used by purse seine vessels (IOTC Res. 15/08 to IOTC Res. 19/02). Despite these measures, there has been no significant impact on DFAD catches [31].

In a 2023 Special Commission meeting exclusively addressing DFAD management, IOTC member states approved a new resolution implementing a quarterly DFAD closure in the Indian Ocean (IOTC Res. 23/02). This CMM was passed by a vote to adopt the measure, just over two thirds, an unusual process in the IOTC which usually adopts measures by consensus. However, the decision occurred in a tense atmosphere marked by communication breakdown and strained negotiations among delegations. The meeting revealed apparent tensions between some coastal and long-distance fishing nations, emphasising concerns over the status of the yellowfin tuna stock. Owing to the absence of consensus and scientific guidance, the resolution faced objections from numerous fishing countries shortly after the Commission meeting, meaning that measures shall bind none of the IOTC members. Under the manifestation of the United Nations, if one-third of the IOTC member states rejects the resolution within the required 180 days, then a resolution is not binding for anyone.

This study evaluates the impact of various DFAD effort limitation measures on yellowfin tuna, addressing stock status (SSB, recruitment) and equity considerations. A case study focused on the Indian Ocean's industrial purse seine fleet was used. We explore four management scenarios restricting DFAD use. These scenarios are compared against baseline effort levels and a broader scenario involving the quarterly closure of all yellowfin tuna fisheries. Employing efficiency measurement methods [34], we assess the effect of reducing the number of DFAD sets/operational buoys. Incorporating this information into a medium-term forecast through a stock assessment model enables estimating future effects on SSB, recruitment, and catches. Projected catches and revenues are then used to assess equity levels for each scenario, employing inequality metrics like the Lorenz curve and the Gini index [18]. This study aims to pave the way for evaluating input-based measures related to DFAD regulations, contributing to the sustainability and equity of the relevant tuna fisheries.

2. Methods

2.1. Biological operating model

The biological operating model (OM) used in this study consists of an age-structured population dynamics model of the Indian Ocean yellowfin stock. The mortality and annual recruitment of juvenile fish govern the stock dynamics. Both fishing and natural mortality cause the stock numbers to decline as each year class grows older.

The stock dynamics are based on the standard age-structured model:

$$N_{a,\quad t} = \begin{cases} R_t for a = 1 \\ N_{a-1,t-1} e^{-Z_{a-1,t-1}} \quad for 2 \leq a < P \\ N_{a-1,t-1} e^{-Z_{a-1,t-1}} + N_{a,t-1} e^{-Z_{a,t-1}} for a = P \end{cases} \tag{1}$$

Where $N_{a,t}$ is the number (in thousands) of fish of age a (where P is the plus-group) at time t (in quarters), $Z_{a,t}$ is the total mortality at age a and time t, with $Z_{a,t} = M_a + F_{a,t}$, where M_a is the natural mortality at age a and $F_{a,t}$, is the fishing mortality at age a, at time t.

At each time step, the Spawning Stock Biomass (SSB) is calculated as follows:

$$SSB_t = \sum N_{a,t} W_{a,t} O_{a,t} \tag{2}$$

Where $W_{a,t}$ is the fish weight at age in kilogrammes at time *t*, and, $O_{a,t}$ is the proportion of mature fish at age *a* and at time t.

The stock-recruitment relationship is assumed to be of the Beverton and Holt type [35], which implies that there is an asymptotic maximum in recruitment:

$$R_t = \frac{(4hR_0 SSB_{t-1})}{(S_0(1-h) + SSB_{t-1}(5h-1))} \tag{3}$$

Where R_0 represents the unfished virgin recruitment numbers at age 0, S_0 is the unfished virgin SSB, and h is the steepness.

Catch numbers at age $C_{a,t}$ are related to the fishing mortality at age through the Baranov catch equation [36]):

$$C_{a,t} = N_{a,t}\frac{F_{a,t}}{Z_{a,t}}\left(1 - e^{-Z_{a,t}}\right) \tag{4}$$

The catch yield in tonnes $(Y_{a,t})$ is calculated as follows:

$$Y_{a,t} = \sum C_{a,t} W_{a,t} \tag{5}$$

2.2. Model inputs and parametrisation

The Indian Ocean Tuna Commission (IOTC) https://iotc.org/ routinely performs single species assessments for yellowfin using Stock Synthesis (SS3) [37], which provides the basic framework for our study. The basis of the IOTC SS3 stock assessment comprises an age-based (29 age groups, quarterly ages 0–28) model structured along multiple areas, seasonality in the form of a quarterly time step, and combined sexes.

The parametrisation of the OM used in this study relies on the SS3 base model used in the 2020 IOTC assessment for yellowfin tuna (IOTC–2021–WPTT23–12). The IOTC Secretariat provided SS3 input files. For each quarter, stock numbers at age ($N_{a,t}$ in Eq.1) and catch-numbers-at-age ($C_{a,t}$In Eq.4) were extracted from the SS3 files. Since the OM used in this study has no spatial structure, the stock and catch numbers at the age were aggregated, summing over all regions for each age group (0−29) and a quarter.

Biological parameters, such as natural mortality at age (M_a) and weight-at-age ($W_{a,t}$), were also taken from the base model's SS3 files. The parameters for the stock-recruitment relationship (Eq. 3) were estimated using the SS3 estimation of the unfished virgin recruitment at age 0 (R_0=116,231, in thousands) and the unfished virgin SSB (S_0 =3,323,090 tonnes). All data were exported from SS3 output files into the *R* software via the ss3om package (https://github.com/flr/ss3om accessed 1/8/23).

2.3. Estimates of $F_{a,t}$ according to different DFAD management scenarios

Yield variations resulting from changes in the number of DFAD sets were estimated based on findings from a recent study [34]. This study employed a Data Envelopment Approach (DEA) methodology to assess fishing capacity, offering a comprehensive analysis of factors influencing capacity utilisation in the French purse seine fleet. According to the study, a 1 % alteration in the number of DFAD sets corresponds to a 0.29 % change in catch yield for yellowfin tuna (i.e., elasticity). Likewise, a 1 % increase in buoy deployments leads to a 0.05 % decrease in catch.

To project model outcomes incorporating the mentioned elasticities, we initiated the process by deducting the catch numbers-at-age linked to DFAD sets from the overall catch-at-age estimation for all gears in each quarter of 2020. Subsequently, the catch numbers-at-age associated with DFADs were transformed into yields using Eq. 5. Next, we computed the revised DFAD yields, accounting for the expected percentage changes in each scenario based on the described elasticity values. Afterwards, we deduced the revised catch numbers at age for DFADs and integrated them with catch numbers at age for various gears. The new *F*-at-age for each scenario was then determined through a non-linear optimisation of Eq. (4). These updated *F* values were considered constant throughout the forecast period.

2.4. Scenarios

Stock numbers-at-age projections for the period 2021–2030 were assessed under the following scenarios:

- **Scenario 1** (Reference or base case): Fishing mortality induced by DFADs remained constant at 2020 levels (averaged over all quarters).
- **Scenario 2a** (50 % reduction of DFAD sets): Future DFAD effort was halved compared to 2020 levels, with no reallocation to free school (FSC) sets.
- **Scenario 2b** (50 % reduction of operational buoys): A 50 % reduction in the number of operational buoys per vessel impacted fishing mortality at age due to DFAD purse-seine fisheries without reallocating forgone effort to FSC sets.
- **Scenario 3** (Seasonal closure of DFAD fishing during the third quarter): Fishing mortality linked to DFAD fishing in the third quarter of each year was set to zero, maintaining DFAD effort at 2020 levels in other quarters.
- **Scenario 4** (DFAD-free fishery): A scenario assuming a DFAD ban globally, setting fishing mortality induced by DFADs to zero in all quarters.
- **Scenario 5** (Seasonal closure of all fisheries during the third quarter ~biological rest): This scenario explores the consequences of a full closure of yellowfin tuna fisheries during one quarter. All gears fishing mortality was set to zero in Q3, while effort was maintained at the 2020 level for the other quarters.

In all scenarios, the fishing mortality for other fleets remained consistent with 2020 levels, with no reallocation of effort on free school (FSC) for purse seiners. The biological parameters governing the model's variables (weights at age, maturity at age, etc.) were based on 3-year averages preceding 2020 in the projections. Results were assessed as a percentage change (Δ%) in spawning stock biomass (SSB), catch, and recruitment. A yearly percentage rate of change was computed for these variables relative to the baseline stock projection (Scenario 1) over ten years. The mean fishing mortality (*F*) for fully exploited age classes was a constant target for each quarter-time step in every scenario. This mean *F*, calculated by estimating a new *F* using Eqs. (1–5), was employed as the control object for future fishing mortality. Catches were forecasted for each gear/fishing mode, considering nine categories: Baitboat (BB), Gillnet (GI), Purse-seine on DFADs (FA), Small-scale Longline (LF), Purse seine on free schools (FS), Handline (HD), Industrial longline (LL), Trolling line (TR), and Others (OT), aligning with the fisheries groups outlined in the 2020 IOTC assessment base model (IOTC–2021–WPTT23–12). All projections were conducted using FLR (www.flr-project.org accessed 2/2/23).

2.5. Equity indices

The concentration of catches and revenues per gear in the Indian Ocean yellowfin tuna fishery was analysed using standard economic methods for income distribution assessment—the Lorenz curve and the Gini index [38]. The Lorenz curve illustrates the relationship between the cumulative share of a variable (e.g., catch) and the cumulative share of ordered entities (e.g., fleets or countries). The Gini index, a widely employed measure of inequality, ranges from 0 (perfect equality) to 1 (total concentration or maximum inequality). These metrics, commonly found in fisheries distributional studies [18,23], provide valuable insights into the distributional aspects of the fishery.

The Gini index assesses the inequality in catch shares projected by the operating model and the revenue shares by fishing gear. Revenues were estimated by multiplying the projected catch quantity by a specific price for each gear. To estimate original prices by gear, unit values of IO countries were collected from the World Bank international trade database at the HS-6-digit level.[1] Considering the export DFAD price as a good proxy of the national ex-vessel price, we estimated a weighted mean of unit values of the fish products exported by IO countries (Table 1), the weights being the actual catch shares of countries by gear in the IOTC database (average 2019–21). For example, the BB price depends mainly on the Maldivian export values because Maldives represents the bulk (90 %) of BB yellowfin catches in the Indian Ocean. In the GI price, Iran prevails with a weight of 54 %, followed by Oman (16 %), Pakistan (12 %), etc. For the purse-seine prices, the EU (Spain and France) frozen skipjack price was used as a proxy of the small (juvenile) yellowfin price, while the ex-vessel large yellowfin price was estimated by the HS-6 frozen yellowfin product category exported by several countries (Spain, France, Seychelles, Indonesia, Korea…). Catches and revenues from industrial purse seiners obtained through two fishing modes (DFADs and FSC) were amalgamated into a single gear (PS) to conduct the inequality analyses on a gear basis. In summary, while the analysis is conducted per gear, the gears are proxies for entities like countries (flags), regions, or fleets, as shown by catch shares in Table 1.

3. Results

The results of the projections demonstrate contrasting trends between scenarios (Fig. 1, Table 2, and Fig. 1). Scenario 1 (effort levels fixed at the 2020 level for all fleets) predicts higher catches, SSB, and recruitment levels in 2030 than 2020 (Fig. 1). However, the Kobe plot shows that SSB (and *F*) levels are still below (above) the MSY reference points (Fig. 2). A 50 % decline in the number of DFADs sets (Scenario 2a) results in a slight increase in SSB (~+5 % deviation), catch (~+1 %), and recruitment (~+1 %) relative to Scenario 1 (Table 2, Fig. 1). However, biomass and fishing mortality levels remain unsustainable after ten years (Fig. 2). Scenario 2b (50 % reduction of operational buoys) shows the lowest performances, with a decline in SSB by ~-1.4 % relative to the baseline, as well as a slight decrease in recruitment and catches, demonstrating that a 50 % decrease in the number of operational buoys cannot allow the recovery of the stock (Fig. 2). On the other hand, a third quarter closure of the DFAD fishery (Scenario 3) implies higher SSB (~+9.5 % change), catch, and recruitment levels compared to Scenario 1 (Table 2). This scenario just about reaches sustainable biomass levels (SSB_{MSY}) but is still subject to overfishing by an excessive fishing mortality rate (Fig. 2). In the scenario of a complete moratorium of DFADs (Scenario 4), the catch, the SSB, and recruitment of yellowfin tuna are substantially larger than if the fishing effort remains constant from 2020 onwards (Scenario 1) (Fig. 1, Table 2). The stock reaches the green quadrant of the Kobe plot (Fig. 2). Finally, a quarterly closure of all fisheries in Q3 (Scenario 5) provides significant increases in SSB and recruitment (Table 2 and Fig. 1) but lower catch levels (-0.72 % change) relative to the baseline. This scenario also allows sustainable levels for fishing mortality and the SSB (Fig. 2).

Fig. 3 sheds some light on which fleets may benefit or lose from the management scenarios. The catch deviations per gear show more significant changes for Scenarios 4–5, consistent with the global catch trends. Interestingly, contrasting results depend on the Scenario when focusing on the gear-specific level. The large-scale purse-seine DFAD fishery (FA) shows negative percentage changes for all scenarios, apart

[1] HS-6 code 030332 (Fish; yellowfin tunas (*Thunnus albacares*), fresh or chilled (excluding fillets, livers, roes and other fish meat of heading no. 0304)) and 030342 (Fish; yellowfin tunas (*Thunnus albacares*), frozen (excluding fillets, livers, roes and other fish meat of heading no. 0304)). Source: WITS - https://wits.worldbank.org.

Table 1
Export unit values used to calculate catch revenues per gear. Source of data: IOTC for the catch weights and UN Comtrade (through WITS, https://wits.worldbank.org/) for unit values of exports per country. Whenever the unit value of exports for one country was missing and for the 'Others' category, the average unit value of exports for the product categories was retained.

Gear	Unit value of exports per gear (USD/t, avg. 2019–21)	Selected countries (catch shares, 2019–21)	Unit value of exports per country (USD/t, avg 2019–21)	Product categories (HS trade product classification-6 digits)
BB	1796	Maldives (90 %) India (6.5 %) Indonesia (3.5 %)	1761 1847 2695	Frozen yellowfin tuna (030342)
GI	3370	Iran (54 %) Oman (16 %) Pakistan (12.3 %) India (7.8 %) Tanzania (5.7 %) Sri Lanka (2.4 %) Others (1.5 %)	2990 5148 2990 1847 2990 8167 2990	Fresh or chilled (030232) and frozen (030342) yellowfin tuna
FA	1296	EU Spain (84 %) EU France (16 %)	1301 1269	Frozen skipjack (030343) as a proxy of juvenile YFT price
FS	2140	EU Spain (31.5 %) Seychelles (22.4 %) EU France (19.3 %) Indonesia (11.4 %) Mauritius (7.6 %) Korea (4.1 %) Others (3.7 %)	2216 1647 2235 2695 2159 2169 2187	Bangkok frozen yellowfin tuna
PS	1528	FA+LS (72.5 %) FS (27.5 %)	1296 2140	Frozen skipjack (030343) and frozen yellowfin (030342)
FL	9440	Sri Lanka (41 %) Indonesia (30 %) Oman (29 %)	13719 4520 8480	Fresh yellowfin tuna (030232)
HD TR OT	4532	Oman (28.2 %) Sri Lanka (15.6 %) Maldives (13.1 %) India (11.4 %) Yemen (10.4 %) Indonesia (8.8 %) Iran (7.2 %) Comoros (3.2 %) Others (2 %)	5148 8167 1761 1847 2990 7715 2990 2990 2990	fresh (030232) and frozen yellowfin tuna (030342)
LL	4777	Taiwan (26.5 %) Sri Lanka (21.9 %) Seychelles (20.3 %) China PR (9 %) Indonesia	4217 8167 1491 4217 4942 6621 4942 4942	Frozen yellowfin tuna (030342)

(*continued on next page*)

Table 1 (*continued*)

Gear	Unit value of exports per gear (USD/t, avg. 2019–21)	Selected countries (catch shares, 2019–21)	Unit value of exports per country (USD/t, avg 2019–21)	Product categories (HS trade product classification-6 digits)
		(8.9 %) Japan (5 %) Korea (3.5 %) Others (4.9 %)		

from Scenario 2b (50 % operational buoys reduction). HD, FL, FS, GI, and industrial LL fisheries show opposite trends, marked by increased catches for all scenarios but Scenario 2a. TR, BB, and other OT small-scale fisheries follow similar catch changes as the HD, FL, FS, GI, and LL fleets, except under Scenario 5, when their catch slightly decreases in 2030 (Fig. 3).

As far as the distributional aspects of the scenario projections are concerned, the Lorenz curve and the Gini index obtained for the catch shares per gear (Fig. 4) reveal that scenarios are pretty close to each other (Gini values stand in the range of 38–41 % at the end of the period). In other words, any management measure considered in this study may significantly affect some fisheries more than others, but the overall impact on equity may not vary much. The fourth scenario shows significantly higher inequality levels due to removing DFAD catches for the PS fishery. Regarding other scenarios, the Lorenz curves obtained for the 2030 projections almost overlap, whereas interesting gaps appear when inspecting the Gini index. Indeed, Scenario 5 shows the lowest level of inequality at the beginning of the period but monotonously increases after 2022 to exceed the outcomes of Scenarios 2a and 3 in 2030. As shown in Fig. 3, this sharp inequality increase is primarily due to the decline of the purse seine DFAD fishery, benefitting the hand line and longline fleets. Scenario 3 (DFAD closure in Q3), on the other hand, maintains the best equality levels throughout time.

Finally, the Lorenz curve and Gini indices obtained considering the revenue shares for each gear (Fig. 5) demonstrate different rankings among the Scenarios compared to those obtained from the catch. Scenario 4 opposes all other trends by increasing the inequality level within the Indian Ocean yellowfin tuna fishery, with a Gini value close to 50 %, i.e., five points above the initial value. Scenario 5 maintains the same level after ten years, with an initial decrease followed by a growing index value after two years. Unlike the catch inequality observed in Fig. 4, Scenario 3 is no longer the best option to achieve more equal revenue shares. Scenarios 1, 2a, and 2b would do better in that respect. The balanced setting under Scenario 3 obtained by a partial transfer of the PS DFAD catch to the small-scale fisheries (i.e., all types of lines and gillnets) is offset by the price spread between cannery-grade frozen tuna and fresh tuna markets, which amplifies the changes towards a concentration of value shares in a few fisheries (Table 1).

To differentiate the scenarios from the most desirable one (1) to the

Table 2
Percent changes in SSB, recruitment, and catches for Scenarios 2–5 relative to the 2030 baseline projections (Scenario 1). Scenario 1: Reference or base case relating to 2020 effort levels; Scenario 2a: 50 % reduction of FAD/FOB sets*;* Scenario 2b: 50 % reduction in the number of operational buoys; Scenario3: Seasonal closure of FAD fishing in Q3; Scenario 4: FAD-free, zero FAD sets all year; Scenario 5: Seasonal closure of all fisheries in Q3.

variable	Scenario 2a	Scenario 2b	Scenario 3	Scenario 4	Scenario 5
catch	1.04	−0.99	2.69	10.05	−0.72
rec	1.03	−0.27	1.75	6.59	5.32
ssb	5.44	−1.36	9.52	45.64	34.51

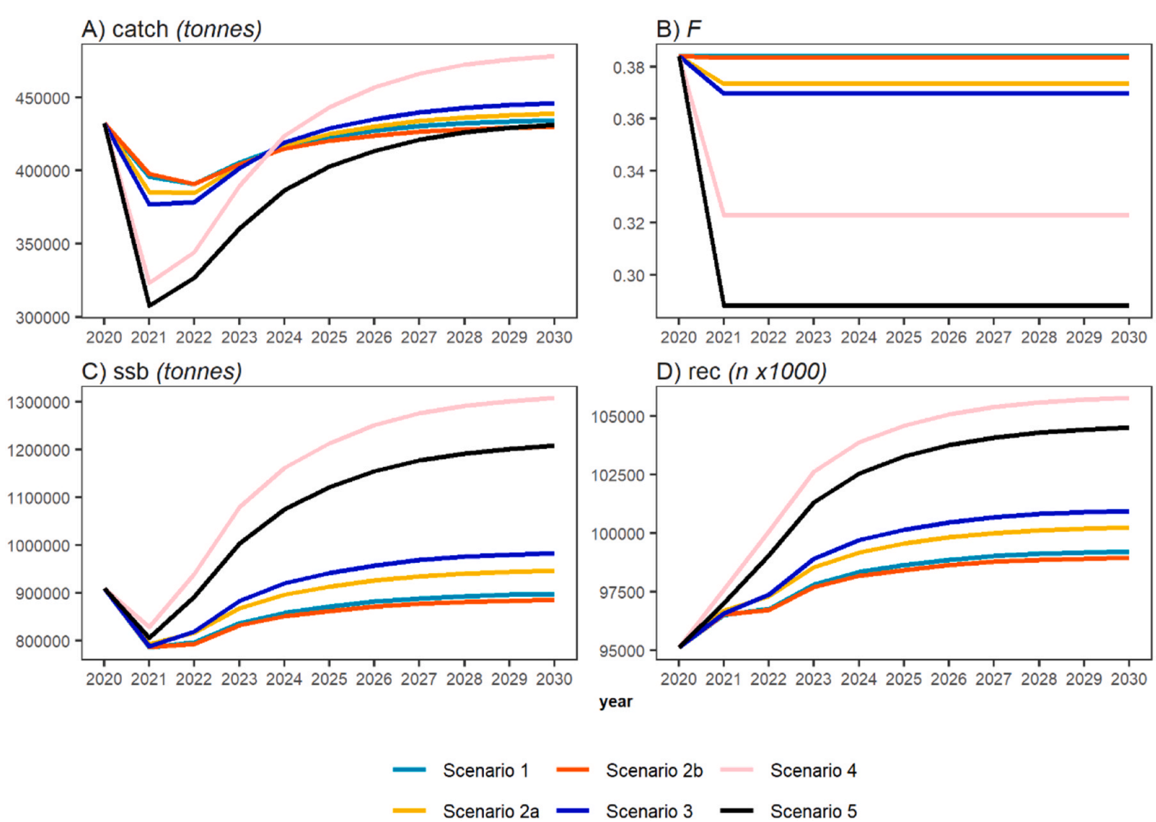

Fig. 1. 10-year projection for catches (A) considering different fishing mortalities (B), SSB (C), and recruitment (D). **Scenario 1**: Reference or base case relating to 2020 effort levels; **Scenario 2a**: 50 % reduction of DFAD/FOB sets; **Scenario 2b**: 50 % reduction of operational buoys; **Scenario 3**: Seasonal closure of DFAD fishing in Q3; **Scenario 4**: FAD-free, zero DFAD sets all year; **Scenario 5**: Seasonal closure of all fisheries in Q3.

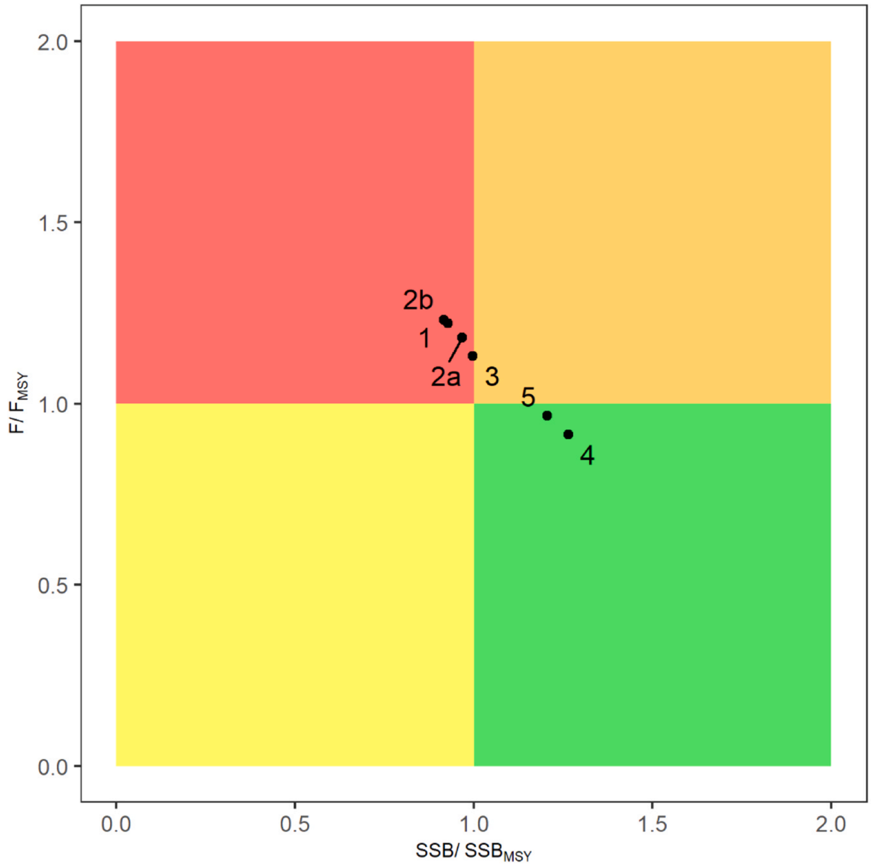

Fig. 2. Kobe plot representation of the yellowfin tuna stock status projections relative to the MSY reference points obtained for Scenarios 1–5 in 2030.

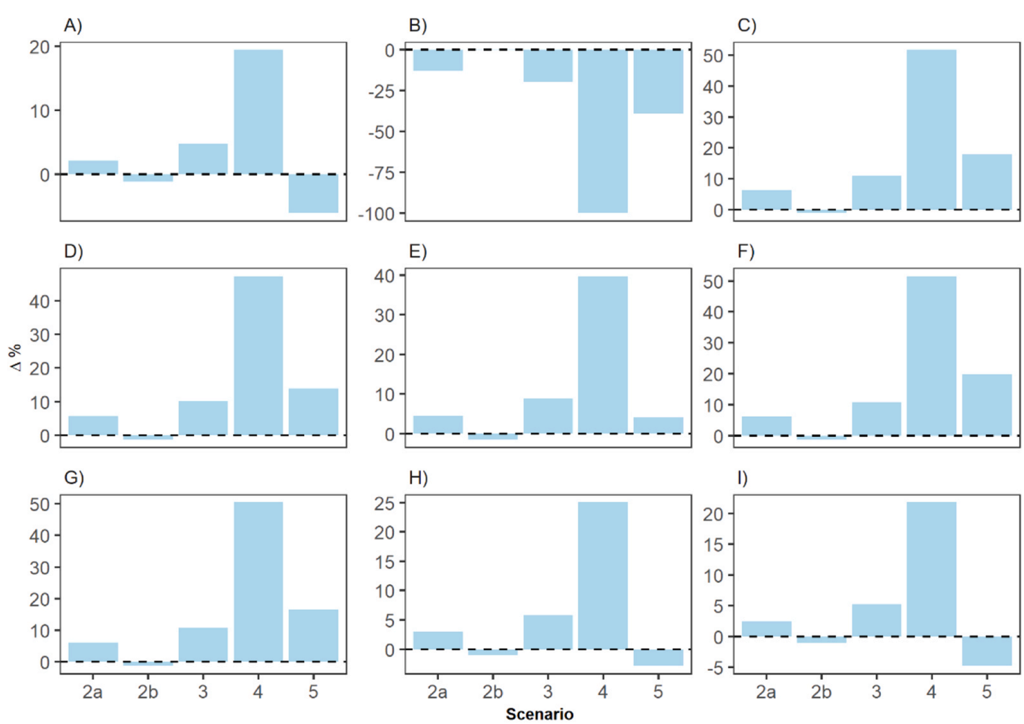

Fig. 3. Estimated percent changes in catches per gear/fishing mode for Scenarios 2–5 relative to the 2030 baseline projections (Scenario 1). Gears and fishing modes (9 groups): **A)** BB = Baitboat, **B)** FA = Purse-seiners on DFADs, **C)** FL = Small-scale Longliner, **D)** FS = Purse seiners on free schools, **E)** GI = Gillnet, **F)** HD = Handliner, **G)** LL = Industrial longliner, **H)** OT = Others, **I)** TR = Trolling line.

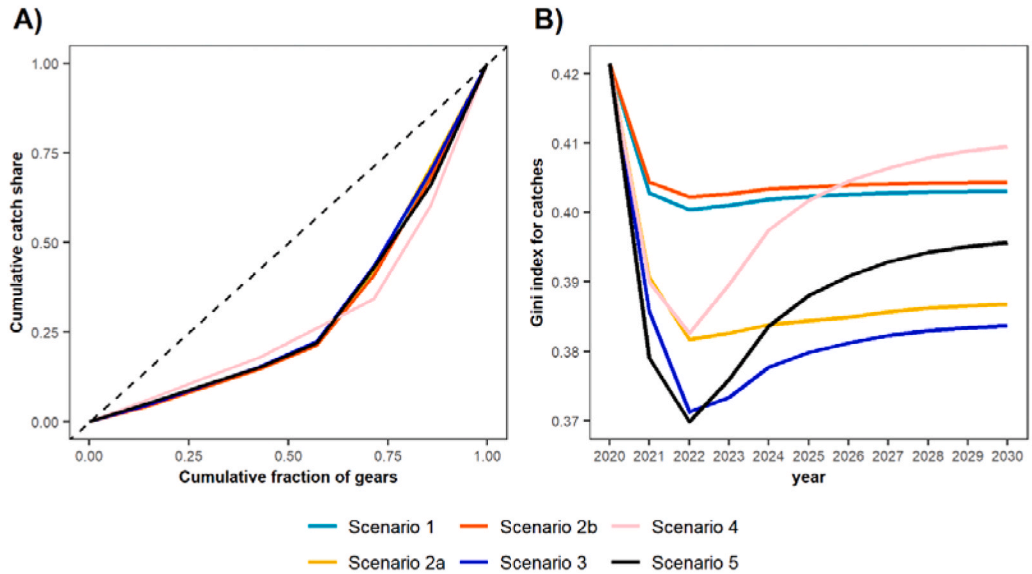

Fig. 4. Lorenz curve (**A**) of the catch per gear projected in 2030 and yearly evolution of the Gini index (**B**) estimated considering the catch per gear for Scenarios 1–5 between 2020 and 2030. Note that the DFAD and FSC fisheries were amalgamated as one unique PS fishery for the calculation.

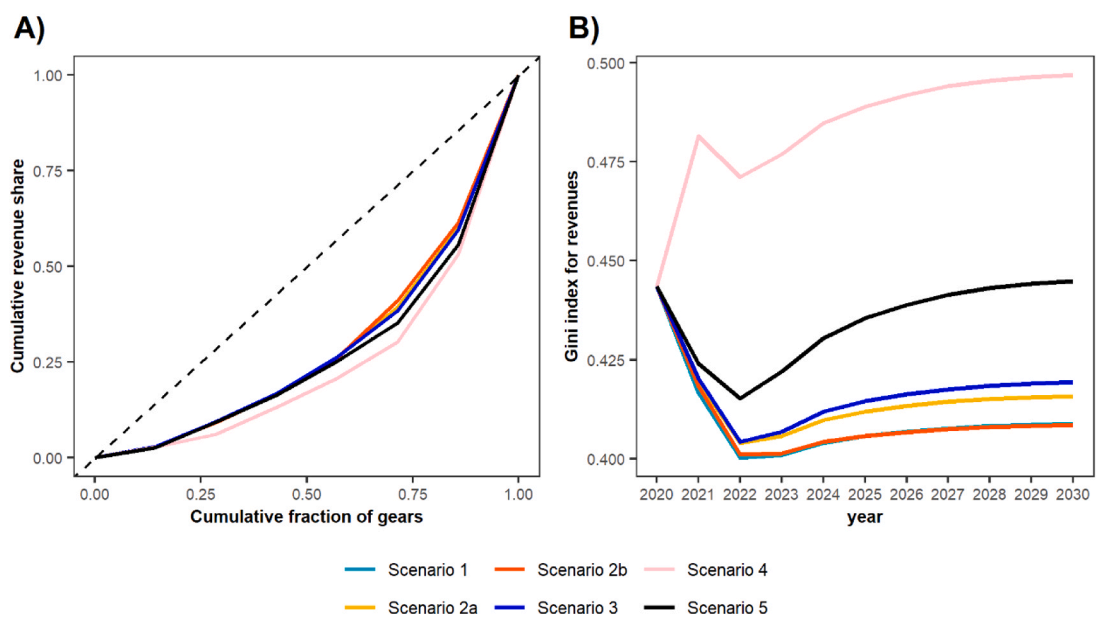

Fig. 5. Lorenz curve (**A**) of the revenue per gear projected in 2030 and yearly evolution of the Gini index (**B**) estimated considering the revenues per gear for Scenarios 1–5 between 2020 and 2030. Note that the DFAD and FSC fisheries were amalgamated as one unique PS fishery for the calculation.

least one (6) concerning each considered sustainability variable, we synthesised the information in Table 3. A simple arithmetic mean is given in the last column to suggest the preference order without any weighting procedure applied to the criteria, nor any consideration of the spread magnitude shown in Table 2. Scenario 3 of DFAD closure would appear as the most desirable management policy. In contrast, scenario 2b (50 % reduction of operational buoys) is the last one, creating little effect on SSB recovery, catch, growth, or recruitment restoration. Scenario 4 is not far behind Scenario 3 overall, even showing more effective results in achieving stock recovery objectives, but it also creates

Table 3
Ranking numbers from the most desirable management scenario (1) to the least one (6).

	Catch increase	SSB recovery	Recruitment improvement	F reduction	Catch equality	Revenue equality	Mean
Scenario 1	4	5	5	6	4	2	**4.3**
Scenario 2a	3	4	4	4	2	3	**3.3**
Scenario 2b	6	6	6	5	5	1	**4.8**
Scenario 3	2	3	3	3	1	4	**2.7**
Scenario 4	1	1	1	2	6	6	**2.8**
Scenario 5	5	2	2	1	3	5	**3.0**

undesirable effects in terms of equity.

4. Discussion

Our research introduces an innovative method for evaluating the effects of management decisions on the status of tropical tuna populations and the distribution of catch and revenue. Additionally, it underscores the importance of utilising strong indicators to monitor progress toward sustainability objectives. By embracing this methodology, we can cultivate responsible management strategies that harmonise environmental preservation, socieal welfare, and economic advancement within our fisheries. We focus on the case of yellowfin tuna in the Indian Ocean, explicitly examining measures to reduce DFAD usage by industrial purse seiners. This issue sparked considerable debate within the IOTC, leading to the adoption and subsequent objection of a resolution proposing quarterly DFAD fishery closures in 2023 (IOTC Res. 23/02) due to the lack of consensus and scientific advice. A crucial step in evaluating the effects of management measures is implementing an OM capable of accommodating various DFAD management scenarios [31]. While the OM developed in this study simplifies certain aspects, such as consolidating the multi-regional SS3 model into a single zone, it aligns consistently with the spatialised SS3 model's outcomes regarding population dynamics, recruitment, and catch levels. Moreover, an OM is supposed to be flexible enough to account for the outcomes of distinct management options and harvest control rules (HCRs). The flexibility of the OM allows for the efficient comparison of diverse DFAD management scenarios, aiding discussions within the IOTC. Furthermore, in conjunction with the efficiency change study by [34], the current OM facilitates a rapid assessment of various scenarios regularly debated by stakeholders. The OM can extend its scope to encompass ecosystemic, e.g., bycatch, habitat changes, etc., and socioeconomic effects of management procedures, providing valuable insights for stakeholders when defining management objectives [31]. This broader perspective positions OMs as a crucial link between policymakers and stakeholders, contributing to an ongoing and collaborative improvement process.

The OM simulations' projected scenarios provide an analysis of the consequences of various management options in terms of both sustainability and equity. Given the yellowfin tuna stock's overfished status in 2021, coupled with ongoing overfishing (IOTC-2021-WPTT23–12), any increase in fishing mortality is anticipated to lead to future declines in catches, spawning stock biomass (SSB), and recruitment. Conversely, implementing substantial effort reductions (-50 % of DFAD sets and/or the annual third-quarter periodic closure) results in favourable long-term effects on yields, SSB, and recruitment levels compared to the baseline forecast, as illustrated in Figs. 1, 2, and Table 2.

Our findings align with empirical studies indicating that periodic closures contribute to increased biomass and catches compared to areas continually open to fishing (non-spatial management) [39,40]. Specifically, when the purse seine faces a 50 % reduction in the number of DFAD sets (Scenario 2a), it falls short of achieving the positive outcomes observed with the periodic closure, which exhibits higher biomass, recruitment, and catch levels after the 10-year projection. The annual closure of the third quarter is particularly effective in safeguarding the juvenile segment of the stock, allowing it to mature and thereby increasing the spawning stock biomass (SSB). However, it is essential to acknowledge that potential consequences of "effort creep" or effort reallocation within the fleet were not considered in this study and should be factored in [41].

Furthermore, the scenarios in this study are obtained deterministically from the base model, and it is important to acknowledge the inherent uncertainties that could influence the analysis outcomes. In fisheries, several factors can contribute to uncertainty, including structural uncertainty due to insufficient knowledge of key biological variables (e.g., natural mortality, steepness), biological variability due to environmental changes (e.g., recruitment deviates), and economic factors such as market conditions affecting prices and costs (cost data at country, fleet, and gear-specific levels would require even more assumptions, which was not the purpose of this paper). Moreover, the operational decisions of the fleets, including compliance with the different management measures or reallocations of effort, could also affect the projections [42]. Complying with restricted access resulting from a new management policy would face resistance due to reduced resource rents and profits. It would also be more costly to enforce due to the size of the fishery and the manpower needed. Better compliance could be achieved by electronic monitoring and onboard cameras at the operational level, like in other fisheries, e.g., [43]. This could benefit this region by reducing discards and bycatch (see [44]) and monitoring the number of DFADs deployed on a trip. There could also be measures linked to market benefits that can encourage compliance as they open up higher-valued premium markets, e.g., through eco-labels or other quality standards [45].

An intriguing observation is the negative elasticity of yellowfin tuna catch to the number of operational buoys (Scenario 2b), indicating that catch increases as the number of buoys decreases [34]. While seemingly counterintuitive, this result suggests an excess in fishing capacity is associated with too many buoys. Nevertheless, the small elasticity value implies only minor changes with a 1 % change in the number of operational buoys (i.e., the response is weakly sensitive to change). Some authors [46] had also noted decreased tuna catch rates with higher DFAD density in specific areas. Another study [47] found a fragile and poorly significant relationship between the number of DFAD sets per fishing trip and the number of operational buoys at sea.

Further investigation is essential to more accurately assess the relationship between the number of operational buoys and the number of DFAD sets from the entire purse seine fleet per vessel per year in the Indian Ocean. Unfortunately, the data used in the present study was unavailable at the individual vessel level due to confidentiality constraints. Additionally, the Total Allowable Catch (TAC) limit for yellowfin tuna, introduced by IOTC in 2017, plays a significant role in the fishery's dynamics (IOTC Res. 2016/01). While designed to support the recovery of yellowfin tuna stocks towards Maximum Sustainable Yield (MSY), the TAC also constrains the transfer of effort between DFAD and Free School Catch fisheries for purse-seiners. Hence, any further development of the OM should duly incorporate the influence of the TAC.

In assessing conservation measures' social and economic impacts, the distributional consequences play a crucial role in gaining acceptance from contracting parties [7]. This study incorporates this dimension by employing the Gini index for catch and revenue distributions by fishing gear, as done in other contexts [17]. Alternative indicators, such as the Generalised Gini, the Atkinson, or the Theil index, could account for a decomposition into sub-groups or different weights across the distribution [25]. However, with a simple Lorenz curve and Gini index, we demonstrate the positive effects of specific management scenarios on equality in catch distribution, notably the Q3 DFAD closure scenario 3. Contrarily, results are more varied when examining revenue distribution between fisheries after a decade. The quarter three closure scenarios 3 and 5 do not enhance equality among gears, and a complete DFAD ban increases revenue inequality significantly. This outcome aligns with findings in studies examining the impacts of rights-based management policies [18,19]. The price effect accentuates the importance of small-scale fisheries, reducing the shares of industrial fleets (PS and LL), whose price per tonne is the lowest (Fig. 5 and Table 1). This transfer of fishing rent between fishing gears could be well advocated by some authors arguing against the growth-driven model of the IO tuna fishery to achieve sustainability [8]. Some authors also noted that IOTC was perhaps the least advanced tuna RFMO to define allocation principles and rules among its members [9,11]. However, negotiations regarding these principles started over a decade ago [48]. We, therefore, recommend that RFMOs consider catch value, fisheries' contribution to coastal economies, and distributional aspects in management policies, using simulation tools to evaluate outcomes in terms of equity. Beyond historical catch-based allocation legitimacy, more significant considerations should also include the aspirations of contracting parties for fisheries' development, fairness of catch allocation, and ecological impacts [11], including social objectives and assessing social outcomes via specific social harvesting strategies, as stated by [49].

5. Conclusion

This study provides new knowledge for decision-makers when they consider implementing new input-based management measures of DFAD use in the region to prevent further risks of overfishing to yellowfin tunas and ultimately to ensure their essential contribution as a sustainable global food source. To achieve sustainability of fisheries, we must continue to i) assess the current sustainability status of fisheries concerning multiple targets (e.g., ecological, social, and economic), ii) understand the trade-offs among these targets, and iii) use indicators that are robust for use in tracking our progress towards meeting these targets. Fisheries policy within the region must evolve towards a more holistic approach that includes multiple targets and develops more robust frameworks for addressing them. A simulation approach is one effective method for evaluating management plans' success, e.g., Management Strategy Evaluation (MSE). This approach helps fishery managers make informed decisions by working closely with stakeholders. This collaborative process, called participatory modelling, involves scientists and stakeholders developing flexible and transparent models like the one we used in this study. These models foster a shared understanding of biological and fishery management issues, reduce the risks and unexpected consequences of different management strategies, and encourage greater involvement of fishers in the management process. The analysis from this study was conducted at the gear level only and considered a simple inequality index (Gini). However, it already highlights how management measures can produce different levels of inequality of opportunities between fleets. It opens a new pathway in the decision-making process, where quantitative inputs on the implications of management measures can be provided, not only regarding the dynamics of tuna stocks but also other dimensions, such as the distributional aspects. The objection to the 2023 CMM highlighted tensions and difficulties in achieving consensus, especially when national economic interests were at stake. The opposition of views points to the fact that some member states perceive current approaches as unfair or inadequate, while others refuse to change their dominant position. Providing a more transparent process in the decision-making, i.e., the member states that gain economically from a management decision and the compensatory mechanisms for countries that suffer the losses, will undoubtedly benefit these tuna fisheries while preserving the tuna stocks for the future.

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CRediT authorship contribution statement

Iago Mosqueira: Writing – review & editing, Writing – original draft, Software. **Dan Fu:** Writing – review & editing, Writing – original draft, Data curation. **Manuela Capello:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Laurent Dagorn:** Writing – review & editing, Writing – original draft, Funding acquisition. **Patrice Guillotreau:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alex Tidd:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no competing financial or non-financial interests that could have influenced the work reported in this paper and that the research does not involve human participants and animals.

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Data availability

The authors do not have permission to share data.

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