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ORIGINAL RESEARCH

Individual and fleetwide bycatch thresholds in regional fisheries management frameworks

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Abstract Fisheries can adversely affect threatened bycatch species and vulnerable marine ecosystems (VMEs). Thresholds are unique amongst bycatch management methods in providing flexibility in individual participants' approaches to avoid exceeding limits, and particularly for individual vessel quotas, in incentivizing the innovation of effective and commercially viable solutions. This study assessed bycatch thresholds for sharks and relatives, air-breathing marine species and macroinvertebrate indicators for identifying benthic VMEs of 21 intergovernmental organizations and arrangements (IGOs). Seven IGOs lacking bycatch thresholds, who tended to have fewer members, might rely on bycatch management by national authorities. Sharks were the predominant focus. IGOs did not know if thresholds were reached for almost half of measures, likely due to compliance monitoring deficits. Individual vessel limits may be more equitable and prevent a race for fish. However, risk pools and fleetwide thresholds may be more effective when mitigation approaches for individual vessels are limited. No IGO uses individual transferable bycatch quotas or risk pools, which would be challenging to implement regionally. No thresholds were reference points of a harvest strategy. There were limited incidences of thresholds being reached. Thresholds might be set too high to meet objectives. When reached, there was high variability in management responses being systematically implemented. Addressing deficits of thresholds being set too low, inadequate compliance monitoring and inconsistent management response implementation could improve performance. Thresholds have the potential to be an effective component of regional bycatch management strategies, incentivizing fishers to minimize their individual and collective bycatch fishing mortality and adverse effects on VMEs.

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Introduction

Fisheries can have profound impacts on co-occurring, incidentally caught bycatch species, particularly those with low reproductive potential due to long generation lengths, low fecundity and other life history traits that make them especially vulnerable to anthropogenic mortality (Smith et al. 1998; Musick 1999; Chaloupka 2002; Forrest and Walters 2009; Pardo et al. 2016; Dulvy et al. 2021). There has been growing concern over the sustainability of bycatch mortality of marine megafauna given their vulnerability to exploitation, ecosystem-level cascading effects through food web links for some apex predators in some systems (Estes et al. 2011; McCauley et al. 2015; Young et al. 2016; Pacoureau et al. 2021), and reduced population fitness from fisheries-induced evolution (Stevens et al. 2000; Heino et al. 2015; Hollins et al. 2018). There has also been increasing attention to risks from bycatch to food, nutrition and livelihood security (Belton and Thilsted 2014; Bene et al. 2015; FAO 2020).

Marine megafauna belong to some of the most globally threatened taxonomic groups, and include marine apex and mesopredators with a broad range of ecological roles across coastal, demersal and pelagic marine ecosystems. This includes large-bodied apex sharks that have relatively large roles in regulating some marine ecosystem that are disproportionate to their abundance and biomass (Ferretti et al. 2010; Heithaus et al. 2014; Estes et al. 2016). Many species of chondrichthyans (cartilaginous fishes: sharks, rays, skates, sawfishes and chimaeras), marine reptiles, marine mammals, seabirds and teleosts are threatened due to fisheries bycatch (Wallace et al. 2013; Udyawer et al. 2018; Dias et al. 2019; Dulvy et al. 2021; Nelms et al. 2021). Invertebrates are also bycatch, including species used as indicators for identifying benthic vulnerable marine ecosystems (VMEs) such as seamounts, hydrothermal vents, cold water corals, sponge fields and seep and vent communities (FAO 2009; Thompson et al. 2016; Walmsley et al. 2021).

Fishers may require strong incentives to implement methods that mitigate the catch and fishing mortality of threatened species and the effects of fishing on VMEs when the mitigation approaches create substantial costs to economic viability, practicality and crew safety. Thresholds or limits are a type of fisheries output control measure that under certain circumstances can effectively manage problematic bycatch and can incentivize fishers to minimize their individual and collective bycatch fishing mortality and adverse effects on VMEs (Branch and Hilborn 2008; Pascoe et al. 2010; Somers et al. 2019). A bycatch threshold can be instituted through the following four designs (Pascoe et al. 2010; Kauer et al. 2018; Holland and Martin 2019; Squires et al. 2021a):

Individual vessel quotas

- Individual non-transferable bycatch quotas: Vessel-level bycatch quotas that cannot be exchanged between vessels.
- Individual transferable bycatch quotas (ITBQs): Also referred to as bycatch shares or bycatch cap-and-trade, it is similar to individual transferable quotas or catch shares for target species, where vessels can sell their unused bycatch quota to other vessels in the fishery.

Pools

- Bycatch risk pools: Bycatch quota is combined for a group of quota owners that make up a subset of the fishery. This is a form of ITBQ system where the sharing of unused bycatch between vessels is restricted to a subset of a fishery's quota holders;
- Common-pool, fleetwide bycatch caps: A total allowable catch (TAC) limit for a bycatch species that is allocated to an entire fishery.

Rights-based quota systems could be applied by fishing operation, trip, season or year, and fleetwide caps by season or year. Bycatch threshold programs may be government command and control requirements, voluntary industry initiatives, co-management arrangements, market-based measures or a combination of these mechanisms (Hall et al. 2017; Roheim et al. 2018; Agnew 2019; Squires et al. 2021b). There are various possible definitions for a bycatch threshold, such as limits on the:

- Catch magnitude as the weight or number of individuals of bycatch species during a specified time period (e.g., fishing season, calendar year);
- Catch rate, such as number or weight of bycatch per unit of effort, or a ratio of bycatch-to-target catch or bycatch-to-total catch during a specified time period or unit of effort;
- Retention magnitude, such as the number or weight of bycatch species that can be retained during a specified time period or unit of effort, and.
- Retention rate, such as a percentage of the weight of retained target or total catch that can be retained during a specified time period or unit of effort.

There are also examples of bycatch limits based on the estimated magnitude and rate of fishing mortalities and injuries. For example, there are fleetwide and individual vessel dolphin mortality limits in place for sets made on dolphin schools by the eastern Pacific Ocean regional tuna purse seine fishery (AIDCP 2017, 2022). And, under the U.S. Marine Mammal Protect Act, a threshold level of estimated mortalities and serious injuries of false killer whales triggered an area closure for a U.S. central Pacific pelagic longline fishery (NMFS 2012).

Bycatch thresholds based on total (retained plus discarded) catch are applicable to both commercial and non-commercial catch, while retention-based thresholds apply only to catch with commercial value. The limit might be applicable to a particular area or to all fishing grounds. The threshold can be for the total catch of non-marketable species that are typically not retained, or for retained or total catch, or certain sizes or sex of marketable species (Arnason 1994; Somers et al. 2019). Harvest strategies, which include target and limit threshold reference points and are typically employed for target species, can also be used to manage fishing mortality of bycatch species (Sainsbury et al. 2000; Butterworth 2007; Rayns 2007; Punt 2010; Kaplan et al. 2021). Rewards, penalties and combinations of the two can be used as the management response that are triggered when a bycatch threshold is reached.

This study established a baseline for intergovernmental bodies' employment of bycatch management thresholds for commercial marine fisheries. The study assessed the application of different bycatch threshold measure designs and definitions for chondrichthyans, air-breathing marine megafauna (marine turtles, sea snakes, seabirds and marine mammals) and invertebrates. For each bycatch threshold measure, the study determined whether members report to the intergovernmental body when thresholds were reached and management responses were implemented. We applied a conditional inference regression tree approach to explore potentially informative predictors for intergovernmental bodies' adoption of bycatch thresholds and use of different categories of measures. Findings benchmark the global use of bycatch thresholds by intergovernmental bodies, the prevalence of compliance monitoring of the measures, and evidence of whether management responses triggered by these bycatch thresholds are systematically employed. We discuss compliance monitoring requirements and the benefits and limitations of different approaches to bycatch thresholds, including designs that create incentives for employing methods that reduce the catch risk of threatened bycatch species and fishery impacts on VMEs.

Methods

In-force and binding conservation and management measures were compiled in February 2023 for 17 regional marine fisheries management organizations and arrangements (RFMO/As) and 3 intergovernmental bodies with remits broader than managing fishery marine resources, obtained from the Regional Fishery Bodies database of the Food and Agriculture Organization of the United Nations (FAO 2023) (Table 1). For convenience hereafter we refer collectively to these 3 types of bodies as intergovernmental organizations (IGOs). The compiled measures were then screened to identify all bycatch threshold output control measures for non-teleost species. Historical records of thresholds that had been reached and management responses that had been applied were obtained through a review of IGOs' compliance committee reports, individual member annual reports to the IGO, and personal communications with IGO Secretariats and commission members.

RFMO/As are a type of regional fishery body that has a mandate to adopt measures that are binding on

Table 1 Regional intergovernmental organizations and arrangements with the competence to establish binding measures for marine capture fisheries

Intergovernmental body	Acronym
Mandate broader than managing fisheries and fishery resources	
Commission for the Conservation of Antarctic Marine Living Resources	CCAMLR
North Atlantic Salmon Conservation Organization	NASCO
North Pacific Anadromous Fish Commission	NPAFC
Tuna RFMOs	
Commission for the Conservation of Southern Bluefin Tuna	CCSBT
Indian Ocean Tuna Commission	IOTC
Inter-American Tropical Tuna Commission[1]	IATTC
International Commission for the Conservation of Atlantic Tunas	ICCAT
Western and Central Pacific Fisheries Commission	WCPFC
Other RFMO/As	
General Fisheries Commission for the Mediterranean	GFCM
International Pacific Halibut Commission	IPHC
Joint Norwegian-Russian Fisheries Commission	JNRFC
Joint Technical Commission of the Maritime Front (Comision Tecnica Mixta del Frente Maritimo)	CTMFM
North East Atlantic Fisheries Commission	NEAFC
Northwest Atlantic Fisheries Organization	NAFO
North Pacific Fisheries Commission	NPFC
Pacific Salmon Commission	PSC
Regional Committee for Fisheries	RECOFI
South East Atlantic Fisheries Organisation	SEAFO
Southern Indian Ocean Fisheries Agreement	SIOFA
South Pacific Regional Fisheries Management Organisation	SPRFMO

[a] The assessment of IATTC measures included those of the Agreement on the International Dolphin Conservation Program (AIDCP), for which IATTC serves as the secretariat

their members. Unlike RFMOs, RFMAs have a form of arrangement through which States adopt binding conservation and management measures that do not provide for the establishment of a Secretariat under a governing body of member States (FAO 2023). One of the RFMOs, the Inter-American Tropical Tuna Commission (IATTC), serves as the secretariat for both the *Convention for the Strengthening of the Inter-American Tropical Tuna Commission Established by the 1949 Convention Between the United States of American and the Republic of Costa Rica* (the Antigua Convention) and the *Agreement on the International Dolphin Conservation Program* (AIDCP). Active binding conservation and management measures of both IATTC and AIDCP were assessed. The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), North Atlantic Salmon Conservation Organization (NASCO) and North Pacific Anadromous Fish Commission (NPAFC), which have a wider mandate than the management of fisheries, were also included as these management bodies adopt fisheries conservation and management measures that are binding on their members (Gilman et al. 2014). The study excluded the Convention on the Conservation and Management of Pollock Resources in the Central Bering Sea (CCBSP) and the International Baltic Sea Fishery Commission (IBFC). There are currently no active CCBSP-managed fisheries and IBSFC was dissolved in 2005 (Gilman et al. 2014; FAO 2023). We also excluded the International Whaling Commission (IWC), because currently aboriginal subsistence whaling is the only whaling operation occurring under IWC jurisdiction (personal communication, Rebecca Lent, IWC, 4 Jan. 2023) and gear types used such as harpoon, lance and rifles do not result in bycatch.

Measures were included that met a screening criterion of describing a threshold policy (quota, risk pool or cap) for a commercial marine fishery for the bycatch of an invertebrate, chondrichthyan or air-breathing marine species. Measures that ban discarding of non-teleost bycatch that are dead at haulback or that ban retention when alive at haulback were included. Measures were also included that fully ban discarding (i.e., require full retention) and that fully

Table 2 Information extracted on IGOs and on individual bycatch threshold measures, and definitions of terms included in an IGO-level conditional inference tree model with an ordinal response and in a bycatch threshold measure-level model with a binary response

Extracted information	Conditional inference tree model term definitions	IGO model	Measure model
IGO name	IGO name	x	x
IGO category (categories are defined in Table 1)	Tuna RFMO, other RFMO/A, IGO with broad remit	x	x
	Tuna RFMO, other	x	
Year IGO was established	Year established	x	x
IGO area of competence	Atlantic Ocean (including Mediterranean and Black Seas), Pacific Ocean, Indian Ocean, Southern Ocean	x	x
Number of IGO members	Number of members	x	x
Members' mean gross domestic product (GDP) per capita in 2020 (from UN 2022, except European Union and Taiwan from IMF 2022, and Faroe Islands, Greenland, and French overseas territories from World Bank 2022)	Mean GDP per capita	x	x
Date measure entered into force	Year measure entered into force		x
Bycatch threshold on: catch and mortality magnitude, catch and mortality rate, retention magnitude, retention rate	Catch or mortality magnitude, catch or mortality rate, retention magnitude, retention rate		x
	Only catch- or mortality-based limits	x	
	Only retention-based limits	x	
Species or group subject to the bycatch threshold	≥ 1 measure for chondrichthyans	x	
	≥ 1 measure for invertebrates	x	
	≥ 1 measure for seabirds	x	
	≥ 1 measure for marine mammals	x	
	≥ 1 measure for marine turtles	x	
Fishing depth zone and gear type of fisheries managed by the IGO	Surface and midwater; deepwater and demersal; multiple	x	
Fishing depth zone and gear type of fisheries subject to the bycatch threshold	Surface and midwater; deepwater and demersal; multiple		x
Target species of fisheries managed by the IGO	Pelagic fishes, diadromous fishes; demersal (benthic, benthopelagic) fishes; other or multiple	x	
Target species of fisheries subject to the threshold	Pelagic fishes, diadromous fishes; demersal (benthic, benthopelagic) fishes; other or multiple		x
Management response triggered when threshold is reached: (1) retention ban, (2) retention restriction, (3) move-on, (4) reward of reduced bycatch mitigation requirements, (5) penalty of increased bycatch mitigation requirements, (6) fishery area closure, (7) closure of purse seine sets on dolphins, (8) required retention if dead at haulback	Move-on with or without area closure, other		x
Number of times the threshold was exceeded, if known	Knows if threshold was reached		x
Number of times the management response to reaching the threshold was implemented, if known	Knows if response was implemented		x
Bycatch threshold approach: Individual vessel non-transferable bycatch quota or fleetwide bycatch TAC (no IGO has adopted an ITBQ or bycatch risk pool measure)	3-level ordinal response: (1) 0 bycatch threshold measures, (2) 1 type, (3) both types	x	
	Binary response: (1) individual vessel, (2) fleetwide		x

ban retention (i.e., require discarding) of chondrichthyan bycatch species - an individual vessel limit of 0 for discarding or retention. But the study scope excluded retention bans for air-breathing bycatch. We excluded measures that ban shark finning, where shark fins can be retained only with the retention of the corresponding carcass, as these measures do not include a limit. Here we use the term bycatch to generally refer to species, and in some cases, sizes and sex within species, that are not the target of a fishery, or that stakeholders aim to avoid and minimize capture and fishing mortality in order to achieve ecological and socioeconomic objectives. Because of the broad diversity in global fisheries, including in their markets, management frameworks and fisher practices, the definition of bycatch will vary broadly by individual fishery and over time. As a result, a wide range of definitions of bycatch have been used by different governments, fishery-specific management plans, regulations and publications, and the Food and Agriculture Organization of the United Nations deemed it impossible to adopt a standard international definition of bycatch (FAO 2011).

Information was extracted from the compiled publications to support summarizing IGO bycatch threshold measures and to assemble two datasets, one comprised of records for each unique bycatch threshold measure, and one containing one record for each IGO. Table 2 summarizes the extracted information used to define variables that were included in these two datasets. Information was also extracted for each measure on the time period during which the IGO knew the number of times a threshold was reached and number of times a management response was implemented.

Each bycatch threshold-fishery record was categorized as individual vessel, risk pool or fleetwide based on the definition of the threshold and not the management response. For example, a VME encounter measure may specify a threshold magnitude of bycatch of VME indicator species in a haul by an individual vessel, and hence the record is classified as an individual vessel non-transferable bycatch quota even though the management response may include an area closure applicable to the entire fishery. Measures where the threshold definition applies both fleetwide and to individual vessels, such as retention bans and restrictions, were categorized as fleetwide. The basis for determining whether an IGO commission knows whether a measure's threshold was reached and response was implemented, which is information that can contribute to implementing performance assessments, was if information on the number of times a measure's threshold was reached and management response implemented was contained in a commission report. For example, for a retention ban measure, a commission report would need to contain summary information on individual member's number or weight of total catch and proportion that was retained and discarded for that species/group. Or, for example, for a VME move-on rule, a commission document summarizing the number of times VME encounters occurred and whether vessels implemented the required move-on response for each incident would be needed. Documents with member reporting on compliance with the measure that do not include these details would not provide needed evidence that the IGO commission is knowledgeable of the measure's implementation.

We assessed the database of bycatch threshold records to identify the frequency of application of each of the bycatch threshold approach categories and bycatch threshold definition categories, frequency of taxonomic groups subject to bycatch thresholds, and frequency of categories of management responses. We summarized the proportion of thresholds with available information on the number of times it has been reached and proportion of times that the threshold was reached that the management response was implemented. This provided a measure of feedback control strength in the management system.

We used a supervised machine learning-based decision tree approach (Strobl et al. 2009) with either binary or ordinal response (Buri and Hothorn 2020; Tutz 2022) to explore potential predictors of the adoption of various categories of bycatch mitigation measures. Details on the approach are in Supplemental Material Section S2. The ordinal response for bycatch mitigation measure in the IGO-level dataset (N = 21) comprised 3 ordered categories of increasing complexity: (1) no bycatch threshold measures, (2) either individual non-transferable vessel quota measures or fleetwide bycatch TAC measures (vessel or fleet), and (3) both types of measures (vessel and fleet). The binary response for mitigation measure in the bycatch threshold measure-level dataset (N = 67) comprised the following categories: (1) individual non-transferable vessel quota measures and (2) fleetwide bycatch TAC measures. No IGO has adopted an ITBQ or bycatch risk pool measure and hence these were not included as responses variables in the decision tree models. The model-specific predictors and response variable are shown in Table 2.

Results

Table 3 summarizes bycatch threshold measures by IGO. Supplemental Material Table S1 summarizes the in-force bycatch threshold measures of global IGOs. Of the 21 assessed IGOs, 7 (CCSBT, IPHC, JNRFC, NASCO, NPAFC, PSC, RECOFI) did not have any in-force, binding bycatch threshold measures for non-teleost species (Table 3). These 7 IGOs tend to have fewer members, and include 3 of the 4 bilateral IGOs. SPRFMO and ICCAT have adopted over a third of the IGO bycatch threshold measures (Table 3). Measures include individual vessel non-transferable and fleetwide limits. No IGO employs ITBQs or risk pools.

The only significant predictor of ordinal category of bycatch measure approach in the IGO-level conditional inference tree model was whether an IGO had a bycatch threshold measure for chondrichthyans (Fig. S1, see Section S2 for detailed results). IGOs with a chondrichthyan bycatch threshold measure have a 0.8 probability of having both fleetwide and individual vessel bycatch output controls, and a 0.2 probability of having only one of these types of bycatch threshold measures. IGOs without a chondrichthyan measure were predicted to be more likely to have no bycatch threshold measures at all (0.64 probability of no

Table 3 Summary of IGOs' binding and in-force bycatch threshold measures

IGO	Bycatch measure types[a]	No. bycatch threshold measures	Threshold species group	Fishing depth of fisheries subject to bycatch threshold measure	Target species of fisheries subject to bycatch threshold measure	Region[b]	No. members	Mean gross domestic product per capita	Year established
AIDCP	Both	2	Dolphin	Surface, midwater	Pelagic fishes	EPO	14	12,520	1999
CCAMLR	Both	5	Chondrichthyan, invertebrate	Multiple	Other, multiple	SO	27	28,912	1982
CCSBT	None	0	None	None	None	SO	8	32,371	1994
CTMFM	Both	4	Chondrichthyan	Demersal	Pelagic fishes	SWAO	2	11,957	1973
GFCM	Fleetwide	3	Chondrichthyan	Multiple	Demersal fishes	MBS	23	24,020	1949
IATTC	Both	7	Chondrichthyan	Surface, midwater	Pelagic fishes	EPO	21	17,996	1949
ICCAT	Both	11	Chondrichthyan	Surface, midwater	Pelagic fishes	AO	52	12,553	1966
IOTC	Fleetwide	3	Chondrichthyan	Surface, midwater	Pelagic fishes	IO	30	11,600	1996
IPHC	None	0	None	None	None	NEPO	2	53,341	1923
JNRFC	None	0	None	None	None	BNS	2	38,518	1976
NAFO	Both	5	Chondrichthyan, invertebrate	Multiple	Other, multiple	NWAO	13	39,279	1979
NASCO	None	0	None	None	None	NAO	7	46,729	1983
NEAFC	Both	3	Chondrichthyan, invertebrate	Multiple	Other, multiple	NEAO	6	47,345	1959
NPAFC	None	0	None	None	None	NPO	5	37,757	1992
NPFC	Individual	2	Invertebrate	demersal	Demersal fishes	NEPO	9	31,119	2015
PSC	None	0	None	None	None	NEPO	2	53,341	1985
RECOFI	None	0	None	None	None	PGGO	8	22,460	2001
SEAFO	Individual	1	Invertebrate	Demersal	Other, multiple	SEAO	7	27,462	2003
SIOFA	Individual	2	Invertebrate, seabird	Demersal	Demersal fishes	SIO	10	25,296	2012
SPRFMO	Both	14	Chondrichthyan, invertebrate, seabird	Multiple	Other, multiple	SPO	17	26,670	2012
WCPFC	Fleetwide	5	Chondrichthyan, turtle	Surface, midwater	Pelagic fishes	WCPO	26	19,118	2004

[a]Both, the IGO has individual vessel non-transferable quota and fleetwide TAC bycatch threshold measures; Fleetwide, the IGO only has fleetwide TAC bycatch threshold measures; Individual, the IGO only has individual vessel non-transferable quota bycatch threshold measures; None, the IGO has no bycatch threshold measures

[b]Region: AO, Atlantic Ocean; BNS, Barents and Norwegian Seas; EPO, eastern Pacific Ocean; IO, Indian Ocean; MBS, Mediterranean and Black Seas; NAO, north Atlantic Ocean; NEAO, northeast Atlantic Ocean; NEPO, northeast Pacific Ocean; NPO, north Pacific Ocean; NWAO, northwest Atlantic Ocean; PGGO, Persian Gulf and Gulf of Oman; SEAO, southeast Atlantic Ocean; SIO, southern Indian Ocean; SO, Southern Ocean; SPO, south Pacific Ocean; SWAO, southwest Atlantic Ocean; WCPO, western and central Pacific Ocean

Table 4 Summary of 14 IGOs' binding and in effect bycatch threshold measures by type of threshold, bycatch taxa, threshold definition, management response, whether the threshold was reached, and whether the management response triggered by reaching the threshold was implemented

Variable	Category	% of IGOs	% of measures
Threshold approach	Individual vessel non-transferable limit	79	37
	Fleetwide TAC	79	63
Bycatch taxa	Shark	64	48
	Shark and other chondrichthyan	29	12
	Other chondrichthyan	43	12
	Invertebrate	50	13
	Dolphin	7	3
	Seabird	14	10
	Marine turtle	7	1
Threshold definition	Catch or mortality magnitude	50	21
	Catch or mortality rate	79	36
	Retention magnitude	64	40
	Retention rate	14	7
Management response	Retention ban	50	30
	Retention restriction	43	22
	Move-on with or without area closure	50	24
	Reward - reduced bycatch mitigation requirements	14	4.5
	Penalty - increased bycatch mitigation requirements	21	7.5
	Fishery closure	14	6
	Closure of purse seine sets on dolphins	7	3
	Required retention if dead at haulback	14	3
Threshold reached	Know if threshold reached	57[a]	51[b]
	Threshold reached	10[c]	29[d]
Management response implemented	Know if management response was implemented	90[e]	97[f]
	Response implemented	50[g]	56[h]

[a]8 of 14 IGOs know if the threshold was reached for > 50% of their bycatch threshold measures

[b]IGOs know whether the threshold was reached for 34 of 67 measures (not including one measure that has not yet come into effect)

[c]One of the 10 IGOs with at least 1 measure for which they knew if the threshold has been reached had > 50% of its measures reach the threshold at least once

[d]Of 34 measures for which IGOs know if the threshold was reached (excluding one measure that has not yet come into effect), 10 reached the threshold at least once

[e]Nine of the 10 IGOs with 1 or more measure for which they know if the threshold was reached knew if the management response was implemented for > 50% of those measures

[f]IGOs know if a management response was implemented for 33 of 34 measures for which the IGO knows whether the threshold was reached

[g]Two of the 4 IGOs with at least 1 measure for which they knew if the management response was implemented and that have at least 1 measure that reached the threshold at least once had > 50% of their measures where the response was implemented > 50% of the times that the threshold was reached

[h]Of 9 measures for which the IGO knows whether the management response was implemented and that reached their threshold, 5 had the response implemented > 50% of the times that the threshold was reached

measure, 0.27 for only one measure, and a 0.09 probability for both types of measures). For the bycatch threshold measure-level conditional inference tree model, the only significant predictor of binary category of bycatch threshold measure approach was management response category (Fig. S2, see Section S2 for detailed results). All 16 move-on measures are categorized as applicable to individual vessels, while 42 of the 51 other types of bycatch threshold measures are applicable fleetwide.

Table 4 provides a summary of the percentage of the 14 IGOs with one or more bycatch threshold measure and of the 67 bycatch threshold measures that met various categories within six variables. Of the 14 IGOs with bycatch threshold measures, 11 have at least 1 individual vessel measure, 11 have at least 1 fleetwide TAC, and 8 have both types of measures (Tables 3 and 4). Of 25 individual vessel bycatch threshold measures, the largest proportion are move-on rules (N = 16) for either benthic VME encounters or elasmobranch catch rate thresholds. Of

42 fleetwide TACs, the largest proportion are elasmobranch retention bans (N = 20) followed by retention restrictions (N = 11).

Most of the measures are limits on sharks and other chondrichthyans (N = 48), and 10 of the 14 IGOs with bycatch threshold measures have at least 1 measure for chondrichthyans (Tables S1, 4). About half of the measures have thresholds that limit bycatch catch or mortality magnitude or rates (N = 37), and half that limit bycatch retention magnitude or rates (N = 31) (one SPRFMO measure includes both catch and retention limits) (Tables S1, 4).

IGOs know whether thresholds were reached for about half (34 of 67) of the measures (Table 4). The 6 IGOs with low probability of knowing whether a threshold was reached (CTMFM, GFCM, IATTC, ICCAT, IOTC, NAFO) know whether 5 of their 33 measures reached thresholds. These 6 IGOs tend to have more parties, tend to have been established relatively early, and tend to have fleetwide threshold measures that ban or restrict shark retention. Of 9 measures for which the IGO knew whether the management response was implemented and that reached their threshold, 5 had the response implemented > 50% of the times that the threshold was reached (Table 4).

Discussion and conclusions

IGOs lacking bycatch threshold measures

Six of the seven IGOs lacking bycatch threshold measures do not have any binding measures on the conservation and management of threatened bycatch species (NPAFC 2021; RECOFI 2021; NASCO 2021, 2022; PSC 2022; IPHC 2023; JNRFC 2021). CCSBT has adopted a binding measure that requires members to comply with measures on ecologically-related species adopted by the other four tuna RFMOs (CCSBT 2021a). Three of the six IGOs lacking bycatch measures are bilateral organizations (Table 3). Some IGOs, and particularly bilaterals, might not adopt bycatch-related measures because they rely on bycatch management through national management frameworks (Pudden and VanderZwaag 2007; personal communication, Daniel Howell, Norway Institute of Marine Research, 13 Feb. 2023; personal communication, Barbara Hutniczak, International Pacific Halibut Commission, 16 Feb. 2023).

Of the seven IGOs lacking bycatch threshold measures, three (IPHC 1979; NASCO 1983; PSC 2022) lack a remit that includes impacts on associated and dependent species. Modernizing these IGOs' mandates might contribute to improved management of threatened species bycatch (Lodge et al. 2007; Gilman et al. 2014). CCSBT members historically disagreed over whether or not the mandate supports the adoption of binding measures for ecologically related species, and a performance assessment referred to this discrepancy as an example to highlight the need to amend or replace the Convention to bring it in line with modern instruments (CCSBT 2008a, b). However, CCSBT has since adopted binding measures on ecologically related species and the most recent CCSBT performance review did not identify the scope of the CCSBT mandate as continuing to be in question (CCSBT 2021a, b).

Species focus

Sharks and relatives were the predominant focus of IGOs' bycatch threshold measures (48 of 67 bycatch threshold measures, Table 4). This likely explains the finding of the inference tree model that IGOs with a chondrichthyan bycatch threshold measure have a high probability of having both individual vessel and fleetwide thresholds while IGOs without a chondrichthyan threshold are more likely to not have any bycatch threshold measures. This may be because chondrichthyans, an economically important incidental catch in many multispecies fisheries, occur globally (except perhaps in the oceanic abyss, Priede et al. 2006), and might have relatively high political attention across regionally-managed fisheries and gear types (Croll et al. 2015; Oliver et al. 2015; Dulvy et al. 2016; Finucci et al. 2021). Conversely, bycatch of other threatened groups (macroinvertebrates N = 9 IGO bycatch threshold measures, seabirds N = 7, marine mammals N = 2, marine turtles N = 1, sea snakes N = 0) are region- and gear-specific, in most fisheries have no market value, and might receive lower international political attention compared to sharks and relatives (Zydelis et al. 2009; FAO 2010; Anderson et al. 2011; Wallace et al. 2013; Lewison et al. 2014; Thompson et al. 2016; Udyawer et al.

2018; Dias et al. 2019; Nelms et al. 2021; Walmsley et al. 2021).

Bycatch threshold design

The only predictor for bycatch threshold measure design (individual vessel vs. fleetwide) was the type of management response. All move-on rules apply to individual vessels, while > 80% of other combined types of measures are applicable fleetwide. The vessel-specific threshold measures with management responses other than move-on rules were four trip limit measures, three measures requiring the employment of seabird gear technology bycatch mitigation methods, one measure requiring the employment of a shark gear technology bycatch mitigation method, and one measure requiring tuna purse seine vessels that reach their allocated individual vessel dolphin mortality limit to cease making sets associated with dolphins for the remainder of the time period (Table S1).

Almost two thirds of the bycatch thresholds were fleetwide measures (Table 4). This may reflect monitoring framework limitations. While fleetwide limits can be implemented with partial monitoring of vessels in a fleet, compliance monitoring requirements for individual vessel measures are substantially more arduous, discussed below.

Limited IGO knowledge of compliance

IGO knowledge of whether thresholds were reached was limited. IGOs did not know if limits have been reached for almost half of bycatch threshold measures. Improvements in IGO's compliance monitoring schemes such as in requirements for party reporting, party implementation of reporting requirements, and in monitoring and surveillance frameworks (Gilman et al. 2014; van Helmond et al. 2020) could address these deficits. For example, a tuna RFMO identified inadequate party reporting and limited observer coverage as preventing the Secretariat from determining compliance with limits on silky shark bycatch for pelagic longline fisheries and small tuna purse seine vessels (IATTC 2023).

Limited incidences of thresholds being reached

There were limited incidences of thresholds being reached. Over 70% of 34 measures for which IGOs knew whether the threshold was reached have never been exceeded. Over half of the measures that IGOs documented as having not been breached were adopted in 2020 or more recently. However, over half (11 of 19) of measures adopted prior to 2020 for which IGOs knew if the measure was breached have never been breached (Table S1), so the low frequency of limits being reached is only partially explained by some of the measures being relatively young.

Thresholds might be set too high to meet explicit or otherwise implicit objectives. This has been one hypothesized explanation for the rare exceedance of thresholds triggering benthic VME move on requirements (Geange et al. 2020; Walmsley et al. 2021). Benthic VME move-on rule thresholds might be set too high because of underestimates of what constitutes a significant adverse environmental impact or of what densities of VME indicator taxa represent a benthic VME, including in heavily fished areas where VMEs are disturbed versus in relatively undisturbed habitats in new fishing areas. Thresholds might not account for different rates of retaining specific indicator species by VME habitat type and might not use appropriate species and taxa as indicators for different types of benthic VME. Thresholds do not standardize fishing effort to account for significant predictors of indicator taxa catch rates such as gear type, tow duration and whether bycatch mitigation methods that reduce the catch rates of VME indicators were used (Auster et al. 2011; FAO 2016; Geange et al. 2020; Walmsley et al. 2021).

Conversely, thresholds may also be set too low resulting in a high probability of exceedance. For example, WCPFC requires shallow-set longline fisheries to employ specified turtle bycatch mitigation methods (large circle hooks or only finfish for bait, or otherwise another mitigation strategy approved by the commission) unless the fishery has a catch rate of combined species of turtles of ≤ 0.019 turtles per 1000 hooks over a three-year period, with observer coverage of at least 10% (Table S1) (WCPFC 2009, 2018). WCPFC's marine turtle threshold bycatch rate was based on the turtle catch rate of Hawaii's swordfish shallow-set longline fishery after regulations on hook and bait type to reduce loggerhead and leatherback turtle catch rates came into effect (WCPFC 2009). This did not consider the effect of the spatial distribution of effort on marine turtle catch rates nor what threshold meets objectives across the turtle populations exposed to western and central Pacific Ocean longline fisheries. The Hawaii fishery overlaps turtle populations with relatively low local and absolute abundances (Chaloupka et al. 2004; Wallace et al. 2011). Applying this rate to regional shallow-set fisheries that overlap with substantially more abundant turtle populations (e.g., olive Ridley west Pacific regional management unit, Wallace et al. 2011), and employing a bycatch rate for combined turtle species, is problematic (Gilman et al. 2022a).

This WCPFC turtle threshold case study illustrates the potential need for improvements in the strength of evidence employed to establish IGO biological bycatch threshold levels, where meta-analytic syntheses such as meta-analyses produce the most robust and generalizable findings that are optimal for guiding regional bycatch management strategy development (Gilman and Chaloupka 2023). Independent synthesis of all accumulated scientific information is a fundamental principle for developing transparent, evidence-informed conservation management decisions (Dicks et al. 2014; Nichols et al. 2019). This measure also illustrates the need for improved IGO knowledge of compliance and implementation of management responses, as WCPFC lacked information both on whether the measure's limit had been reached or response had been implemented by any WCPFC member (Table S1).

Management responses

When reached, there was large variability in whether management responses were systematically implemented (Table 4). However, this assessment is limited from a very small sample size of only 9 measures for which IGOs: (1) knew whether thresholds were reached or exceeded, (2) the threshold was reached/breached at least once, and (3) the IGO knew whether the management response was implemented. Two of these measures with low frequency of management response implementation when triggered have reward responses of reduced bycatch mitigation requirements had infrequent implementation, meaning that the parties opted to voluntarily employ more stringent requirements (Table S1). For some measures there was incomplete party reporting of compliance monitoring data. For some fleetwide bycatch TACs, lags in member catch data reporting can delay secretariat determination of whether the cap was exceeded.

None of the IGO bycatch thresholds are defined as part of a harvest strategy. Harvest strategies include target and limit thresholds that when exceeded trigger pre-agreed management responses by applying a harvest control rule. Harvest strategies are designed to maintain stocks near target thresholds and to reduce the exploitation rate when a stock is at risk of exceeding a biological limit threshold (Sainsbury et al. 2000; Butterworth 2007; Rayns 2007; Punt 2010). There may not be conclusive findings from population and stock assessments for threatened bycatch species. For example, a very small proportion of chondrichthyan stocks have undergone robust stock assessments that produced conclusive findings (Simpfendorfer and Dulvy 2017). However, there are approaches to harvest strategies that do not require assessment models (Carruthers and Hordyk 2018).

Only eight measures have rewards or penalties that either require increased or allow reduced use of gear technology bycatch mitigation methods. Increased IGO use of this bycatch threshold response may hold promise for achieving fleetwide bycatch management objectives, especially when applied as an individual vessel measure to incentivize effective employment of mitigation methods to avoid more burdensome requirements.

While there are deficits with IGO bycatch thresholds, including limits being set too low, inadequate compliance monitoring, and inconsistent implementation of management responses, in some cases these measures provided major improvements in bycatch management. For example, the adoption of shark thresholds by ICCAT was preceded by concerted efforts to establish data collection systems and analytical capacity necessary to implement the threshold measures (Kebe et al. 2002). This has resulted in time series of relative abundance and catch that have been used not only for shark threshold measures but also more sophisticated assessments (ICCAT 2019, 2020) and harvest strategy evaluations (Taylor et al. 2022a, b).

Compliance monitoring requirements

Because both individual vessel and fleetwide catch-based limits on threatened species bycatch can create large incentives for misreporting by fishers in logbooks, onboard human observer or electronic monitoring (EM) systems, or an EM audit model, is required for effective compliance monitoring. With an EM audit model, all vessels are equipped with EM systems, and random samples of imagery and sensor data are reviewed to assess the accuracy of logbook data (Emery et al. 2019). To incentivize accurate logbook reporting, responses - such as full review of EM imagery, assigning an observer, or issuing a fine - can be applied when a vessel is found to have systematically underreported bycatch (i.e., when logbook bycatch data has low precision with EM data) (Stanley et al. 2011; Emery et al. 2019).

Compared to observer programs, EM system can provide more certain data because EM can overcome sources of statistical sampling bias faced by observer programs (Babcock et al. 2003; Benoit and Allard 2009). As bycatch limits increase the sensitivity of reporting bycatch data, observers are increasingly vulnerable to coercion, corruption and safety risks (Gilman et al. 2019). This risk increases the more significant the consequences of the reporting. EM systems are not susceptible to these and other sources of statistical sampling bias faced by observer programs (observer effect, observer displacement effect). However, some contemporary EM systems are not yet capable of collecting accurate bycatch data for some gear types (Emery et al. 2019; Gilman et al. 2019). Furthermore, cooperation from fishers is necessary for maintaining EM equipment and for EM collection of some data fields, such as discarding catch from designated areas so that they are within a camera field of view, and periodically cleaning camera lenses (van Helmond et al. 2020).

IGOs surprisingly had more knowledge of whether thresholds were reached for catch/mortality- and individual vessel-based measures than retention-based and fleetwide measures (Table S1). Compliance monitoring requirements for individual vessel measures and catch or mortality-based limits are much steeper than for fleetwide and retention-based measures. Individual vessel bycatch thresholds require accurate monitoring at the vessel level. For example, monitoring compliance with move-on rules requires extensive (or complete) observer coverage (Hansen et al. 2013) or an EM audit model. Monitoring for fleetwide thresholds can employ extrapolated (raised) estimates of bycatch levels given adequate coverage levels and robust sampling designs (Babcock et al. 2003; Amande et al. 2012; Gilman et al. 2017). However, even with adequate monitoring for fleetwide bycatch TACs, extrapolated bycatch estimates might become available to an IGO after a season has ended and thus might not effectively constrain bycatch unless overcatch provisions are in place, where the exceedance is deducted from the following season's allocation.

Over half of the IGO measures defined a bycatch threshold based on total catch or mortality magnitude or catch or mortality rate (Table 4). Thresholds based on catch or mortality require quasi-real time and accurate at-sea monitoring. Conversely, surveillance and monitoring of retention-based bycatch limits are feasible through a broader range of approaches, including at-sea monitoring but also through port sampling of landed catch, and monitoring at-sea transshipment if permitted. The preferential use of limits for catch or mortality levels and rates of bycatch species is surprising given the overall low observer and EM coverage of regional fisheries (Gilman et al. 2014; van Helmond et al. 2020). Observer coverage rates remain at very low levels in most marine capture fisheries. For instance, 47 of 68 fisheries that catch marine resources managed by regional fisheries management organizations have no observer coverage (Gilman et al. 2014).

Benefits and costs of alternative bycatch threshold measure designs

Fleetwide bycatch TACs and risk pools might not provide sufficient incentives for individual fishery participants to voluntarily attempt to mitigate their bycatch if doing so entails some cost to commercial viability (Holland 2010; Pascoe et al. 2010). Fleetwide bycatch limits and risk pools can be inequitable as some vessels may be responsible for a disproportionate share of the quota-limited bycatch (Gilman et al. 2007; Holland and Martin 2019; Roberson and Wilcox 2022). Fleetwide quotas can also cause a race for fish, increasing bycatch rates and reducing fleetwide economic performance, such as by reducing the fishing season and target species catch levels (Abbott and Wilen 2009, 2010). Despite these limitations, for problematic bycatch where there are limited avoidance and minimization options for individual vessels, and when the bycatch limit is small on a per-vessel basis, such as less than 1 capture per vessel, risk pools and fleetwide limits may incentivize the employment of effective approaches to mitigate bycatch, such as industry fleet communication programs and other real-time dynamic area-based management tools (Holland 2010; Gilman et al. 2006; Little et al. 2015; Holland and Martin 2019).

Bycatch thresholds leave it up to the catch sector to determine how they avoid exceeding the limit. This allows for flexibility for individual participants to select approaches that they prefer, and particularly for individual vessel thresholds, might incentivize fishers' innovation of more effective and commercially viable bycatch mitigation methods. While fleetwide TACs can create a race to fish where individual vessels attempt to maximize their volume of catch of target species, individual vessel bycatch quotas and quota risk pools allow fishers to make adjustments that maximize the value of their catch of marketable species over a fishing season while addressing the constraints of the bycatch threshold. They do this by adjusting their seasonal and spatial distribution of fishing effort, as well as their fishing methods and gear designs that affect species selectivity (Adams 1996; Pascoe et al. 2010; Holland and Martin 2019; Somers et al. 2019; Abe et al. 2022).

Despite potential benefits, no IGO uses ITBQs nor risk pools. These approaches might be particularly challenging to operate and manage in multinational regional fisheries, especially for IGOs with numerous parties and large fleets (Pascoe et al. 2010). ITBQs create a market for bycatch quota, incentivizing fishers to minimize their bycatch so that they can sell their unused quota to less capable vessels (Ning et al. 2009; Pascoe et al. 2010). In fisheries with large variability in vessel-specific bycatch rates and ratios of bycatch-to-target catch (Gilman et al. 2007; Roberson and Wilcox 2022), ITBQs may incentivize vessels with relatively high bycatch rates, and high bycatch-to-target catch, to adjust fishing practices or gear designs to that of more capable vessels. Risk pool programs are useful when bycatch is rare and unpredictable, where there are limited bycatch avoidance and minimization options for individual vessels, and when individual vessel quotas are low (Holland 2010; Kauer et al. 2018). Risk pool programs can include fleet communication programs where participating fishers share quasi real time information on bycatch hotspots, and risk pools can also require participants to employ specific bycatch mitigation methods (Little et al. 2015; Holland and Martin 2019; Merrifield et al. 2019). These measures address the problem of risk pool members having low incentives to avoid bycatch if they can draw from the pooled bycatch quota, and of the inclusion of vessels in the risk pool with relatively high bycatch or lower bycatch quota relative to their bycatch (Holland and Martin 2019), which are problems also encountered with fleetwide bycatch TACs.

Bycatch thresholds can increase incentives for discarding, which will benefit bycatch species only if at-release and post-release mortality rates are sufficiently low or if the threshold measure incentivizes changes in fishing operations and gear that reduce bycatch rates (Gilman et al. 2022b). Thresholds for marketable species of elasmobranchs and teleosts can increase discarding through quota-induced high grading – when a species-based quota is reached, a vessel discards lower value catch, replacing them with higher value grades, and through over-quota discarding in multispecies fisheries – when a quota for one species is reached, but there either are no quotas for other marketable species or quotas for those other species have not been reached, the vessel discards additional catch of the "choke" species that has reached its quota (Batsleer et al. 2015; Somers et al. 2019). Total catch accounting (instead of limits only on retained and landed catch), overcatch provisions, quota risk pools, quota substitution, species-based quotas by grades, and deemed value measures have effectively reduced incentives for discarding in some fisheries. These measures also created incentives for increased selectivity to reduce catch rates of species subject to full retention requirements (Arnason 1994; Peacey 2003; Hall and Mainprize 2005; Iceland Ministry of Fisheries 2011; Holland and Jannot 2012; Kauer et al. 2018; Somers et al. 2019).

Specific, measurable and timebound objectives of bycatch threshold measures

RFMO's bycatch management measures have been criticized for not including explicit, measurable and timebound objectives that support performance assessments (Gilman et al. 2014). This study did not assess the objectives of bycatch threshold measures. An assessment could be made to determine whether measures explicitly define objectives, whether objectives are measurable, and whether they are impact, process or outcome objectives.

Ideally measures include specific and measurable outcome objectives, which define a response on the conservation status of populations or stocks of bycatch species (Grant 2012; Gregory et al. 2012; Gilman et al. 2022a). For example, a bycatch threshold could be designed to implement an outcome management objective of a harvest strategy that aims to maintain a stock's biomass above a biological limit reference point and near a target threshold, where the latter might be defined based on achieving an agreed balance of biological and socioeconomic objectives (Rayns 2007; Skirtun et al. 2019).

Alternatively, a bycatch threshold measure could support an indirect impact objective such as reducing the magnitude of catch from some benchmark, or a process objective such as adopting gear designs that increase selectivity if a threshold catch rate is exceeded. While potentially less effective at meeting ecological objectives, impact and process objectives may be the best available options for data-limited stocks and for IGOs with weaknesses in some components of their fisheries management frameworks (Gilman et al. 2022a).

Conclusions

Bycatch thresholds are but one available approach for bycatch management, where a suite of measures is often needed for bycatch management strategies to achieve objectives (Selig et al. 2017). Other bycatch management approaches include input controls, static and dynamic area-based management tools, reduced vertical overlap, methods that increase selectivity, mitigation of ghost fishing, handling and release practices, offsets, trade restrictions and bans, and market-based mechanisms such as ecolabeling (Hobday et al. 2011; Selig et al. 2017; Gilman et al. 2022a, 2023).

To be successful, optimal bycatch threshold management frameworks have (Branch and Hilborn 2008; Pascoe et al. 2010; Somers et al. 2019; Gilman et al. 2022a):

- Limits designed to address explicit and measurable outcome objectives, such as target and limit reference points of harvest strategies;
- Biological thresholds selected based on the highest strength of evidence;
- Robust compliance monitoring schemes, including: observer or EM coverage rates and designs, or EM audit models, that adequately minimize statistical sampling bias; and robust surveillance and enforcement frameworks;
- Management responses triggered when limits are reached; and.
- Management responses (penalties, rewards) that provide sufficient incentives for fishers to individually and collectively attempt to mitigate bycatch risk.

Individual vessel limits may be more equitable and prevent an incentive to race for fish. However, for bycatch with limited avoidance and minimization options for individual vessels, including when the bycatch limit is very small on a per-vessel basis, risk pools and fleetwide limits may be effective approaches to bycatch mitigation.

The performance of IGO bycatch threshold measures could be improved by addressing identified deficits of: thresholds being set too low; inadequate compliance monitoring schemes such as deficits in monitoring, surveillance, and member reporting; and inconsistent implementation of management responses. Bycatch thresholds have the potential to be an effective component of IGOs bycatch management strategies, incentivizing fishers to minimize their individual and collective bycatch fishing mortality and adverse effects on VMEs.

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Data availability The data supporting the study are available within the article and the supplementary material file.

Declarations

Conflict of interest The authors declare that they do not have any competing interests.

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Supplemental Material

Individual and fleetwide bycatch thresholds in regional fisheries management frameworks

Eric Gilman, Milani Chaloupka, Lyall Bellquist, Heather Bowlby, Nathan Taylor

Contents

S1. BYCATCH THRESHOLD MEASURES OF INTERGOVERNMENTAL BODIES

Table S1 summarizes the in-force, binding bycatch threshold measures of 17 regional fisheries management organizations and arrangements and 3 intergovernmental bodies with remits broader than managing fishery resources, which for convenience are collectively referred to as global intergovernmental organizations (IGOs). References to the measures and references for the sources of information on measure implementation summarized in Table S1 are in Section S3, organized by IGO.

Table S1. Binding and in-force bycatch threshold measures of global IGOs. NA=not applicable; unk=unknown. Measure ID is the IGO's identification number for the measure.

IGO	Measure ID	Fishery depth zone approach[1]	Bycatch threshold[2]	Taxonomic group subject to threshold	Management response[3]	No. times threshold reached	No. times management response implemented	No. years assessed	Bycatch threshold definition[4]
CCAMLR	22-07	2	1	invertebrate	3	82	82	10	1b
CCAMLR	33-03	3	2	ray, skate	6	0	NA	1	1a
CCAMLR	33-02	3	2	ray, skate	6	0	NA	1	1a
CCAMLR	33-03	3	1	ray, shark	3	unk	unk	NA	1b
CCAMLR	33-02	3	1	ray, shark	3	unk	unk	NA	1b
CTMFM	06/22	2	2	shark	2	unk	unk	NA	1a
CTMFM	15/22	2	1	shark	2	unk	unk	NA	1b
CTMFM	11/22	2	2	shark	2	unk	unk	NA	1a
CTMFM	5/09	2	2	shark	1	unk	unk	NA	2a

IGO	Measure ID	Fishery depth zone approach[1]	Bycatch threshold[2]	Taxonomic group subject to threshold	Management response[3]	No. times threshold reached	No. times management response implemented	No. years assessed	Bycatch threshold definition[4]
GFCM	39/2015/4	2	2	shark	1	unk	unk	NA	2a
GFCM	42/2018/2	3	2	ray, shark	1	unk	unk	NA	2a
GFCM	42/2018/2	3	2	shark	1	unk	unk	NA	2a
IATTC	C-04-05	1	2	ray, shark	1	unk	unk	NA	2a
IATTC	C-11-10	1	2	shark	1	unk	unk	NA	2a
IATTC	C-15-04	1	2	ray	1	unk	unk	NA	2a
IATTC	C-21-06	1	1	shark	2	unk	unk	NA	2b
IATTC	C-21-06	1	1	shark	2	unk	unk	NA	2b
IATTC	C-21-06	1	1	shark	5	unk	unk	NA	2b
IATTC	C-21-06	1	2	shark	1	unk	unk	NA	2a
AIDCP	AIDCP Agreement	1	2	dolphin	7	0	NA	30	1a
AIDCP	AIDCP Agreement	1	1	dolphin	7	22	unk	NA	1a, 1b
ICCAT	09-07	1	2	shark	1	unk	unk	NA	2a
ICCAT	10-07	1	2	shark	1	unk	unk	NA	2a
ICCAT	10-08	1	2	shark	1	unk	unk	NA	2a
ICCAT	11-08	1	2	shark	1	unk	unk	NA	2a
ICCAT	15-06	1	2	shark	2	unk	unk	NA	2a
ICCAT	19-07	1	2	shark	2	0	NA	1.5	1a
ICCAT	19-08	1	2	shark	2	2	0	1.5	1a
ICCAT	21-09	1	2	shark	2	unk	unk	NA	2a
ICCAT	21-09	1	2	shark	8	0	NA	NA	2a
ICCAT	21-09	1	2	shark	2	1	1	1	1a
ICCAT	21-09	1	1	shark	2	0 [5]	NA	0	1b
IOTC	12-09	1	2	shark	1	unk	unk	NA	2a
IOTC	13-06	1	2	shark	1	unk	unk	NA	2a
IOTC	19-03	1	2	ray	1	unk	unk	NA	2a
NAFO	Article 12	2	1	invertebrate	3	0	NA	14.2	1b

IGO	Measure ID	Fishery depth zone approach[1]	Bycatch threshold[2]	Taxonomic group subject to threshold	Management response[3]	No. times threshold reached	No. times management response implemented	No. years assessed	Bycatch threshold definition[4]
NAFO	Article 12	3	2	shark	1	unk	unk	NA	2a
NAFO	Article 12	3	2	shark	8	unk	unk	NA	2a
NAFO	Article 6	3	1	skate	3	unk	unk	NA	1b
NAFO	Article 6	3	2	skate	2	unk	unk	NA	1a
NEAFC	8-2020	3	2	shark	2	0	NA	1	2a
NEAFC	7-2020	3	2	shark	2	0	NA	1	2a
NEAFC	19-2014	2	1	invertebrate	3	0	NA	14.2	1b
NPFC	2019-06	2	1	invertebrate	3	0	NA	7.5	1b
NPFC	2021-05	2	1	invertebrate	3	0	NA	7.5	1b
SEAFO	30/15	2	1	invertebrate	3	0	NA	13.2	1b
SIOFA	2020/1	2	1	invertebrate	3	0	NA	4	1b
SIOFA	2022/13	2	1	seabird	5	0	NA	4.2	1a
SPRFMO	09-2017	2	2	seabird	4	13	3	5.9	1b
SPRFMO	09-2017	2	1	seabird	5	1	1	5.9	1b
SPRFMO	09-2017	3	2	seabird	4	16	0	5.9	1b
SPRFMO	09-2017	3	1	seabird	5	0	NA	5.9	1a
SPRFMO	14d-2020	2	1	chondrichthyan	3	unk	unk	NA	1b
SPRFMO	03a-2021	2	2	chondrichthyan	6	0	NA	3.4	1a
SPRFMO	14e-2021	2	2	seabird	5	0	NA	1.4	1b
SPRFMO	14e-2021	2	1	shark	3	0	NA	1.4	1b
SPRFMO	14e-2021	2	1	skate	3	0	NA	1.4	1b, 2b
SPRFMO	14e-2021	2	2	shark, skate	2	0	NA	1.4	2a
SPRFMO	11-2021	2	2	seabird	6	0	NA	0.04	1a
SPRFMO	14a-2022	2	1	chondrichthyan	3	0	NA	3.1	1b
SPRFMO	03-2022	2	1	invertebrate	3	2	1	8.4	1b
SPRFMO	14b-2022	2	1	invertebrate	3	0	NA	1	1b
WCPFC	2008-03	2	2	turtle	4	unk	unk	NA	1b
WCPFC	2019-05	2	1	ray	1	unk	unk	NA	2a

IGO	Measure ID	Fishery depth zone approach[1]	Bycatch threshold[2]	Taxonomic group subject to threshold	Management response[3]	No. times threshold reached	No. times management response implemented	No. years assessed	Bycatch threshold definition[4]
WCPFC	2019-04	2	1	shark	1	0	NA	0.2	2a
WCPFC	2011-04	2	1	shark	1	28[6]	27[6]	1	2a
WCPFC	2013-08	2	1	shark	1	29[6]	28[6]	1	2a

[1] 1=pelagic and midwater; 2=demersal; 3=multiple

[2] 1=individual vessel quota, 2=fleetwide limit

[3] Management response categories: 1=retention ban, 2=retention restriction, 3=move-on or move-on plus area closure, 4=reward of reduced bycatch mitigation method requirements, 5=penalty of increased required bycatch mitigation method requirements, 6=fishery closure, 7=closure of purse seine sets on dolphins, 8=required retention if dead at haulback.

[4] 1a=catch or mortality magnitude, 1b=catch or mortality rate, 2a=retention magnitude, 2b=retention rate.

[5] The measure is not currently in effect. Starting in 2024 the measure allows ICCAT to begin to allow retention of north Atlantic shortfin mako, only when dead at haulback, and with a limit of 1 per trip for vessels ≤ 12 m and with an observer or electronic monitoring system.

[6] The values for response implemented are the number of Members reporting they were not in compliance with the measure.

S2. CONDITIONAL INFERENCE TREE MODELS

We used a supervised machine learning-based decision tree approach (Strobl et al 2009) with either binary or ordinal response (Buri and Hothorn 2020; Tutz 2022) to explore potential predictors of the adoption of various categories of bycatch mitigation measures. This conditional inference tree modelling approach is a nonparametric technique that produces a classification or regression tree where all cases are assigned to mutually exclusive subsets (or nodes) according to a set of informative predictors. Importantly, linear, nonlinear and interactions were all explicitly accounted for, if applicable. The modelled result is a decision tree where binary nodal splits (if any) are statistically significant based on permutation tests to support a rigorous conditional inference framework given the predictors (Zeileis et al. 2008).

The model-specific predictors and response variable are shown in Table 2. Model terms that describe an IGO and describe an individual bycatch threshold measure were included in both the IGO-level and measure-level models – this applied to 6 terms such as the IGO category, year the IGO was established, and number of members. There were 9 terms that are attributes of an IGO such as having only retention-based bycatch threshold measures and having one or more bycatch threshold measure on marine turtles – these attributes are not applicable at the individual measure level and hence were only included in the IGO-level model. Similarly, there were 7 terms that are attributes of individual bycatch threshold measures, such as the year that a measure entered into force, and whether the IGO knew if the measure's threshold had been reached – these attributes are not applicable at the IGO-level and thus were not included in the IGO-level model.

These 2 conditional inference tree models were fitted using the `partykit` package for R (Hothorn and Zeileis 2015) with a minimum binary split criterion of 0.95, where predictors were included in the best-fit model only if they met this minimum split criterion. We also derived the ordinal or binary response classification rate or accuracy metric for the best-fit model using the confusionMatrix function in the `caret` package for R (Kuhn 2008) as an appropriate measure of model adequacy. We then visually summarised the best-fit conditional inference tree using the `ggparty` (Borkovec and Madin 2019) and `ggplot2` (Wickham 2016) packages for R, with only statistically significant predictors shown in the decision tree plots.

As part of the modelling workflow, we also used an ensemble of the conditional inference tree (a forest of conditional trees) to assess relative predictor importance in the final accepted or best-fit decision tree (Strobl et al 2009, Tutz 2022). The ensemble or conditional random forest was also fitted using the `partykit` package for R (Hothorn and Zeileis 2015).

The only significant predictor of ordinal category of bycatch measure approach in the IGO-level conditional inference tree model (Fig. S1) was whether an IGO had a bycatch threshold measure for chondrichthyans ($p=0.002$, $N=21$, 10 IGOs with and 11 IGOs without a chondrichthyan bycatch threshold measure). The predictive accuracy rate was 0.71 (95% CI: 0.48-0.89), indicating that the best-fit ordinal inference tree model was an adequate fit for a small data set (Kuhn 2008, Levshina 2022). A conditional forest ensemble comprising the same set of 16 predictors confirmed that the most important predictor of category of bycatch measure ordinal status was whether an IGO has a bycatch threshold measure for chondrichthyans. IGOs with a chondrichthyan bycatch threshold measure have a 0.8 probability of having both fleetwide and individual vessel bycatch output controls, and a 0.2 probability of having only one of these types of bycatch threshold measures. IGOs without a chondrichthyan measure were predicted to be more likely to have no bycatch threshold measures at all (0.64 probability of no measure, 0.27 for only one measure, and a 0.09 probability for both types of measures).

For the bycatch threshold measure-level conditional inference tree model, the only significant predictor of binary category of bycatch threshold measure approach was management response category ($p<0.001$, $N=67$, 16 move-on rule measures, 51 other types of measures) (Fig. S2). The predictive accuracy rate was 0.87 (95% CI:0.76-0.94), indicating that the best-fit inference tree model was an adequate fit (Kuhn 2008, Levshina 2022). A conditional forest ensemble confirmed that this was the most important predictor of the 13-predictor set. Move-on measures had a 1.0 probability of being individual vessel thresholds (all 16 move-on measures are categorized as applicable to individual vessels), while all other types of bycatch threshold measures had around a 0.82 probability of comprising fleetwide limits (42 of the 51 "other" measures are applicable fleetwide).

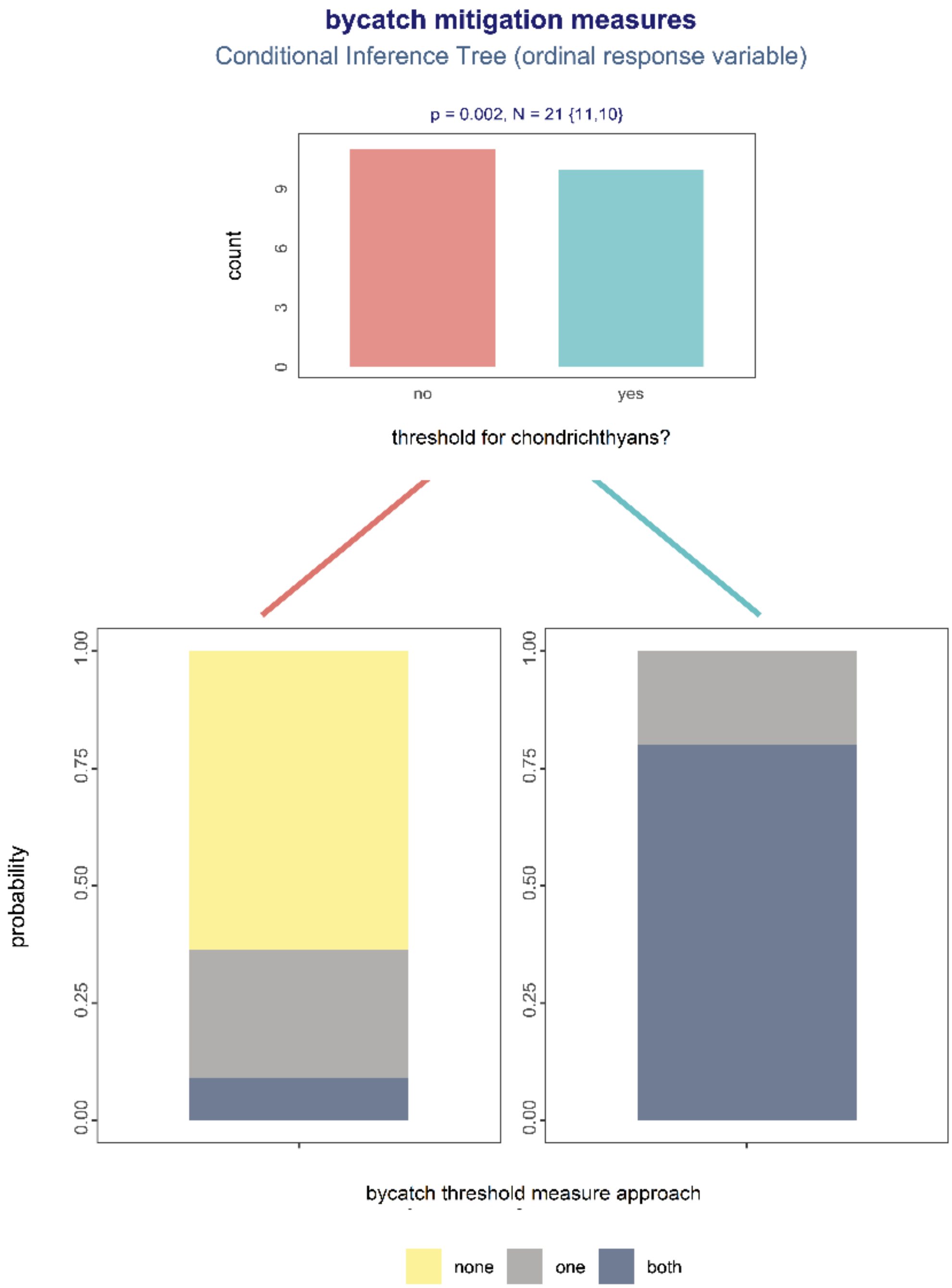

Figure S1. Conditional inference tree showing the probability of IGOs having 0 bycatch threshold measures, either individual vessel quota measures or fleetwide TAC bycatch thresholds, or both types of bycatch thresholds, defined by model-based recursive partitioning given the informative predictor of IGOs with or without a bycatch threshold measure for a chondrichthyan species. The stacked bars in the two terminal nodes summarize the predicted conditional probability for each of the 3 ordinal responses for that subgroup of IGOs given the bycatch threshold.

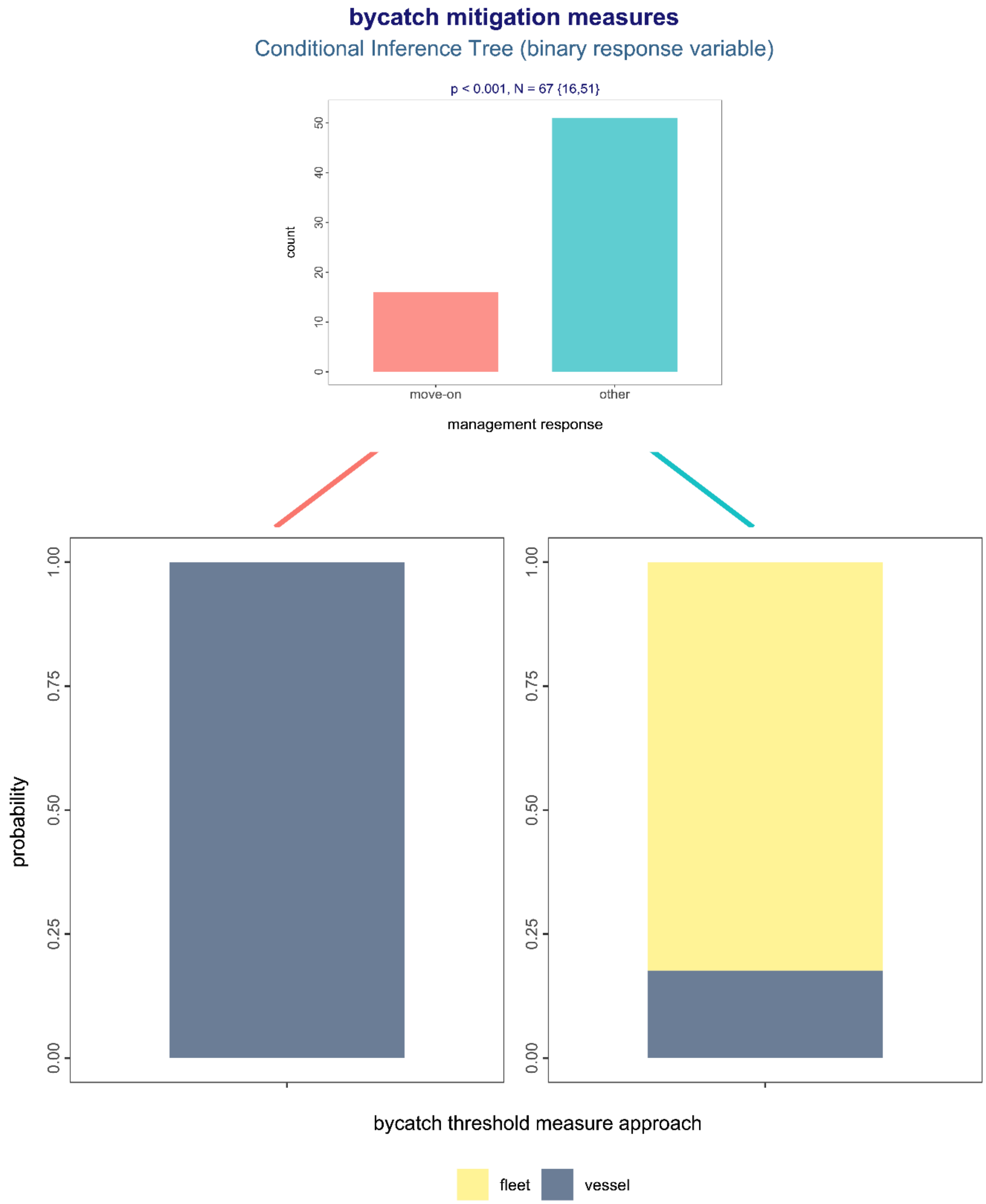

Figure S2. Conditional inference tree showing the probability of bycatch threshold measures being either individual vessel quotas or fleetwide TACs, defined by model-based recursive partitioning given the informative predictor of the management response that is triggered when a bycatch threshold is reached for either: (1) move-on rules with or without a fleetwide area closure, or (2) other types of management response. The stacked bars in the two terminal nodes summarize the predicted conditional probability for each of the binary responses for that subgroup of bycatch threshold measures given the management response.

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