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Using harmonized historical catch data to infer the expansion of global tuna fisheries

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ABSTRACT

Despite worldwide demand for tuna products and considerable conservation interest by civil society, no single global dataset exists capturing the spatial extent of all catches from fisheries for large pelagic species across all ocean basins. Efforts to spatially quantify the historical catch of global tuna fisheries have been restricted to the few taxa of major economic interest, creating a truncated view of the true extent of the fisheries for tuna and other large pelagic fishes. Individual Regional Fisheries Management Organizations (RFMOs) have given varying degrees of attention to minor taxa and non-target species only in more recent years. Here, we compiled and harmonized public datasets of nominal landed catches, as well as spatial data on reported catches of large pelagic taxa reported for the industrial tuna and large pelagic fisheries by tuna RFMOs for the last 60+ years. Furthermore, we provide a preliminary estimate of marine finfishes discarded by these fisheries. We spatialized these data to create a publicly available, comprehensive dataset presenting the historical reported landed catches plus preliminary discards of these species in space for 1950–2016. Our findings suggest that current public reporting efforts are insufficient to fully and transparently document the global historical extent of fisheries for tuna and other large pelagic fishes. Further harmonization of our findings with data from small-scale tuna fisheries could contribute to a fuller picture of global tuna and large pelagic fisheries.

1. Introduction

What are generally called “tuna fisheries”, i.e., fisheries for large pelagic tuna, billfishes and pelagic sharks are some of the oldest fisheries in the world, with evidence that humans had pelagic fishing capabilities over 40,000 years ago (O’Connor et al., 2011). Coastal artisanal fisheries for large pelagic species have existed for millennia in tropical and sub-tropical areas, while industrial efforts developed over the last century. Japan was the first country to foray into industrial fisheries for tuna in the 1920s, investing in bait boat operations in the Pacific Islands (Gillett, 2007). With an increasing demand for canned seafood, the industrial fishing effort intensified after World War II (Miyake et al., 2004). Improvements in vessel technology and freezer capabilities allowed these industrial tuna fisheries to rapidly expand, with fleets operating across virtually all of the Atlantic, Indian and Pacific Oceans since the 1980s (Majkowski, 2007).

Demand for tuna and tuna-like species is at an all-time high, with record reported landings of 7.7 million t in 2014 (FAO, 2016), after which it levelled off to around 7.5 million t·year^{-1} since (FAO, 2018). Tuna fisheries can be highly profitable, partly due to subsidies that offset their often high operational costs (Lam et al., 2011; Sumaila et al., 2016), although economic and cost challenges remain (Sala et al., 2018), as do concerns about resource-use equity (Sumaila et al., 2015) and relevance to food security (Schiller et al., 2018). There are currently five Regional Fisheries Management Organizations (RFMOs) responsible for ensuring long-term sustainability of the stocks under their jurisdiction: the Commission for the Conservation of Southern Bluefin Tuna (CCSBT), the Indian Ocean Tuna Commission (IOTC), the Inter-

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Fig. 1. Areas of responsibility for each of the tuna Regional Fisheries Management Organizations (RFMO). ICCAT: International Commission for the Conservation of Atlantic Tunas; IOTC: Indian Ocean Tuna Commission; CCSBT: Commission for the Conservation of Southern Bluefin Tuna; WCPFC: Western and Central Pacific Fisheries Commission; IATTC: Inter-American Tropical Tuna Commission.

American Tropical Tuna Commission (IATTC), the International Commission for the Conservation of Atlantic Tunas (ICCAT), and the Western and Central Pacific Fisheries Commission (WCPFC).

While the scope and research capacity of each RFMO differs, all facilitate data collection and stock assessment in their management area (Fig. 1) and set regulations on fishing activity for member countries. However, there continue to be instances of considerable overfishing of high-seas fish stocks, and all RFMOs have been challenged on their ability to successfully manage stocks and fisheries (Cullis-Suzuki and Pauly, 2010, 2016) as well as protect non-target species impacted by fishing fleets (Juan-Jordá et al., 2018).

Despite the high economic value of tuna landings (FAO, 2016) and the considerable interest by the general public in the conservation and sustainable management of large pelagic species, there is, to date, no single, combined global dataset presenting all catches of species caught by these fisheries over time and space. The Food and Agriculture Organization of the United Nations (FAO) produces the ‘Atlas of Tuna and Billfish Catches’ (referred to here as the ‘FAO Tuna Atlas‘), which covers only the catch of 12 species of tuna and billfishes. The FAO Tuna Atlas (FAO, 2017) presents data only for albacore tuna (*Thunnus alalunga*), Atlantic bluefin tuna (*T. thynnus*), Atlantic white marlin (*Kajikia albida*), bigeye tuna (*T. obesus*), black marlin (*Istiompax indica*), blue marlin (*Makaira nigricans*), Pacific bluefin tuna (*T. orientalis*), skipjack tuna (*Katsuwonus pelamis*), southern bluefin tuna (*T. maccoyii*), striped marlin (*K. audax*), swordfish (*Xiphias gladius*), and yellowfin tuna (*T. albacares*). While this dataset encompasses the major target species, it does not account for the landings of other species of commercial and conservation interest (e.g., sharks), which are reported by RFMOs, nor does it address discarded catch (Zeller et al., 2018).

Additional species-specific information on landed catches is available from national fisheries statistics presented by FAO on behalf of member countries (Garibaldi, 2012), but these data explicitly do not account for discarded bycatch, nor provide details on gear types used or fisheries sectors, nor include detailed spatial information (FAO, 2019). Addressing this data gap requires a synthesis and harmonization of all spatial data with all nominal catch data reported by each of the tuna RFMOs, as well as the addition of data on discards, which will allow for a better understanding of the full scope of global fisheries for large pelagics over the last six decades. A recent initiative by the *Institut de Recherche pour le Développement* (IRD) and the FAO has aimed to harmonize global tuna catches across space and time for all RFMOs (Taconet et al., 2017). However, while a great improvement from isolated RFMO data repositories, the dataset of Taconet et al. (2017) does not spatialize all nominal catches or estimate discards for all regions, but only for subsets of data as provided by the RFMOs. Therefore, we build on these excellent, initial initiatives, and the preliminary work described in Le Manach et al. (2016), to develop and present a harmonized, comprehensive and spatialized global dataset of historical large pelagics catch data from 1950 to 2016. It differs from other studies by spatializing all nominal reported landings, as well as preliminary estimates of discards. Results provide a global overview of tuna catches over the last sixty years, and allow for analysis of large-scale patterns in space and time that can combine with ongoing regional data collection to inform better long-term policies.

2. Methods

2.1. Source data

We assembled public domain datasets from all five tuna RFMOs (Table 1), which include catch data reported by member countries fishing in the corresponding management areas. For each RFMO, this information is provided in two separate datasets. Firstly, the ‘nominal’ catch dataset represents all reported catches of species within each RFMO’s purview in a given year, and includes information on the fishing country, gear (or gear type), taxon, time (year), ocean area (for RFMOs spanning more than one, e.g., North and South Pacific), and weight of catch (here deemed to represent whole, wet weight). Secondly, the ‘spatial’ catch dataset is a subset of nominal data (i.e., not all yearly catches are included for most countries) that includes georeferenced information on the spatial location of catch. The ‘spatial’ dataset from the WCPFC is an exception, as it does not report fishing country for confidentiality reasons.

The aim of our methodology was to harmonize and spatialize these separate datasets using a rule-based, step-wise approach to match all nominal catch data to corresponding spatial data, geographically refined in what we call ‘tuna blocks’, i.e., the spatial data reporting blocks ranging from 1° x 1° to 20° x 20° as used by RFMOs for spatial reporting.

Table 1

Overview of the data sources and tuna block resolution for reporting by each RFMO used here for the development of the harmonized global catch dataset and catch maps of industrially caught tuna and other large pelagic fishes.

Ocean	RFMO	Tuna block spatial resolution	Countries*/gears/taxa	Year of first spatial data
Atlantic	ICCAT	1°x1°, 5°x5°, 5°x10°, 10°x10°, 10°x20°, 20°x20°	104/50/164	1950
Indian	IOTC	1°x1°, 5°x5°, 10°x10°, 10°x20°, 20°x20°	51/35/28	1952
Eastern Pacific	IATTC	1°x1°, 5°x5°	27/11/21	1954
Western Pacific	WCPFC	5°x5°	39/10/16	1950
Southern	CCSBT	5°x5°	9/8/1	1965

* "Countries" includes former countries (i.e. USSR and Yugoslavia) and joint ventures.

As a second goal, we added preliminary estimates of discards to all reported catches.

2.2. Spatialization method

For each ocean basin, the nominal catch data were spatialized to tuna blocks according to the reported proportions in the spatial data. The ideal, best case spatialization scenario assigned a given nominal catch entry to tuna blocks using only spatial catch data with an exact match for all data categories (i.e., where both datasets contain catch records for the same country, year, taxon, and gear). For example, if the nominal dataset for a given RFMO included a record of France catching 10 t of bigeye tuna using longline in 1983, and the spatial dataset included records of France catching 8 t of bigeye tuna using longline in 1983, with 4 t caught in spatial tuna block A and 4 t in block B, the 10 t reported in the nominal catch would be assigned as 5 t in each of the two tuna blocks. Thus, the total catch reported in the nominal data (which in theory represents the total reported catch in a given year) would be unchanged, but allocated to its most likely catch locations based on available spatial records. We thus assumed that the reported, spatial subset of data as nearly as possible represented the most likely true spatial extent of all catches with the given data categories.

This matching of the nominal and spatial catch data records was repeated over a series of successive refinements. After all full data category matches were spatially allocated, we focused on matching all nominal catch records with less than perfect data category match with spatial data for one fishing country (flag state) at a time. With each successive matching iteration, the year span of spatial data being used to match nominal data records were relaxed to intervals of +/-2 and then +/- 5 years. After attempting to match all nominal and spatial record categories over all year ranges, the procedure was re-run using successively less-precise data category matches and including categories for groups of gears and groups of species. Each successive matching step was used before expanding the year ranges further to 10, 20, and 35 years. While these year ranges were much larger than would be ideal, they were necessary to capture the limited spatial data for some RFMOs. This applied especially to the IOTC, which has nominal data only from 1952 and limited spatial data from 1952 to 1966, but with better spatial coverage from 1967 to present. These wider year ranges were only utilized to spatialize data if no other records for closer years were available. Thus, our final spatialized dataset is likely more broadly assigned for earlier years.

After each successive refinement, the matched and unmatched records were stored separately, so that at each new refinement, only the previous step's unmatched records were used. The end-result was a catch database where all nominal catch records were spatialized to the existing global spatial catch records by tuna blocks of various sizes (Table 1) and containing all original nominal records. Thus, the final spatial catch database generated here matches the nominal catch amounts for each RFMO.

This approach represented the core of the matching methodology, and below we highlight specific refinements that were applied throughout the routine to obtain spatialized catch data given available information on country-specific tuna fisheries; all such refinements are documented in full in the Supplementary Materials. The procedures for the spatialization of each RFMO's nominal dataset were developed in R statistical programming software (R Core Team, 2016), and are archived in the *Sea Around Us* GitHub repository (https://github.com/SeaAroundUs/Tuna). We welcome collaborations for further improvements.

2.3. Refinements and limitations

As the spatial data reported by RFMOs were limited by the levels of detail of reporting by fishing countries and were missing exact matches for many records of nominal data as reported by the RFMOs, a series of rules incorporating additional available information were developed to improve the quality of the spatialization method. Prior to spatialization, spatial catch records that were erroneously reported as having occurred on land were eliminated from the spatial database to prevent the algorithm assigning nominal catch to terrestrial locations. Furthermore, we adjusted suspected but likely accidental spatial misreporting of Spain fishing in the Atlantic Ocean, as some of the spatial data reported by Spain were reported only at exact 1° x 1° spatial resolution, but at distinct 5° intervals. These 1° x 1° reporting records were thus assumed to actually refer to the corresponding 5° x 5° resolution tuna reporting blocks and hence were reassigned to this 5° x 5° resolution. In other words, the existing 1° records, which are equally spaced at 5° intervals, were spread over their affiliated 5° x 5° blocks.

Many countries with smaller-scale tuna fishing fleets, defined here as countries that fish for tuna only within their home FAO area, in contrast to distant-water fleets, do not report gear types to their respective RFMO. For instance, Jordan's tuna fisheries do not report their gear use to the IOTC, but an independent literature review suggested they only use hand lines (Morgan, 2006). Therefore, all of Jordan's tuna catches were assigned as hand line catches for more accurate spatial assignment. To increase the precision of gear assignment in the spatialization, we limited the spatial data used for the matching of nominal data to spatial data from gears used by a country and excluded spatial data from gears not used by a country, if so known. This was done through a literature review, detailed in the 'Supplementary Methods: Gear restrictions' document, where evidence of absence was used as the criterion to restrict a country to using only specific gear types. For instance, French Polynesia has only two tuna fleets: a coastal fleet and an offshore longline fleet (Misselis, 2003). Therefore, when spatializing the nominal catch of French Polynesia across possible spatial matches when no gear type is specified in the nominal data being spatialized, the possible matches are still restricted to the two gear types known to be used in French Polynesia, namely longlines and small-scale gears, rather than all possible gears. In this manner, the spatial extent of a fishing country's nominal tuna catches were restricted to the most likely actual spatial extent of the relevant gears used.

In addition, the overall spatial extent of some countries' tuna fisheries was restricted to a defined area. For example, many countries in the Red Sea and Persian Gulf area have fisheries that operate more locally, and thus only within these seas. The lack of matching data in the spatial database would otherwise spread these catches over a larger geographic zone in the RFMO reporting area (e.g., all of the Western

Indian Ocean). Restricting these countries' catches to a smaller area based on known fishing effort data and tuna fleet characteristics (e.g., only using *dhows*) provided a likely more accurate distribution of tuna catches for these countries. See 'Supplementary Methods: Area restrictions' for specific details on this restriction. At the very least, this spatial restriction reduced the highly unlikely spread of relatively small catch tonnages for a given fishing country over unrealistically large spatial areas. As such area restrictions were only applied to a few fishing countries in the Indian Ocean (see 'Supplementary Methods: Area restrictions'), this restriction had very limited impact on the spatialization of tuna catches.

2.4. Discards

In addition to spatializing all the RFMO-reported nominal landings data, we derived preliminary estimates of discards by tuna fisheries by ocean basins. Discard rates by fishing country and gear for the Pacific Ocean were calculated using reconstructed landed and discarded catch of large pelagic species for 1950 to 2010 based on Schiller (2014). The reconstructed discard rates were projected forward to 2016 by applying the average rate from 2005 to 2010. Discard rates were then applied to the spatialized nominal landings data to calculate discard tonnages for Pacific Ocean catches. For industrial fishing fleets, it was assumed that discarding practices would be similar, because the volume and rate of discarded catch is often linked to the value of the species incidentally caught, and the amount of space onboard at a given point in a trip (Schiller, 2014). In many cases, more coastal smaller-scale fisheries will generally target large pelagics and although they have high bycatch rates, much of the non-target catch is retained for local sale or consumption rather than discarded at sea. Thus, we assumed no discarding for the smaller-scale fleets.

A literature review was conducted for the Atlantic and Indian Oceans (Le Manach et al., 2016) to collect estimates of discards. Because of the limited amount of country- and fleet-specific data that this search revealed, we averaged discard percentages across the entire time period and applied these percentages to the region of origin of a fleet (e.g., Western Europe) rather than the specific country of origin. For the Indian Ocean, our lowest discard percentage was 1.5% (gillnets in Iran, Shahifar, 2012), the median was 7.2% (longline in Asian fleets, IOTC, 2000) and the highest percentage was 113% (longline, Alverson et al., 1994). For the Atlantic Ocean, the lowest discard percentage was 1.1% (longlines in North America, ICCAT, 2009), the median was 10.7% (purse-seine in western and northern Europe, Amandè et al., 2011) and the highest percentage was 100% (swordfish longlines, European Commission, 2011).

3. Results

3.1. Global

Industrial, or large-scale fisheries for tuna and other large pelagic species have expanded globally over the last six decades, as illustrated clearly by the spatial extent of their reported landings data over time (Fig. 2). During the 1950s, catches were largely concentrated off the coasts of North and Central America in the Eastern Pacific Ocean, and around the Western Pacific Islands (Fig. 2A). Relatively little fishing effort, and hence catches, were derived from the Atlantic and Indian Oceans. However, by the 1980s, tuna fisheries were active along the equatorial areas across the globe and into temperate regions in most ocean areas (Fig. 2B). In recent years, fisheries catches of tuna and other large pelagic species have been ubiquitous across all tropical and subtropical regions of the world, with the most catch caught in tropical areas (Fig. 2C).

Global landed catches as reported by the RFMOs, plus preliminary estimates of unreported discards of the world-wide tuna fisheries increased from around 450,000 t in 1950 to approximately 5.6 million t in 2016 (Fig. 3). Across the whole time period, catches were dominated by the Pacific Ocean tuna fisheries, which accounted for around 67% of total global catches over the full time period, and around 74% in 2016 (Fig. 3A). Pacific Ocean tuna catches increased from around 310,000 t in 1950 to over 4.1 million t by 2016 (Fig. 3A). The Atlantic Ocean tuna catches steadily increased from 38,000 t in 1950 to around 840,000 t·year^{-1} (i.e., 20% of global catch) by the mid-1990s, before gradually declining thereafter to just over 600,000 t by 2016 (i.e., 12% of global, Fig. 3A). Tuna catches in the Indian Ocean began to grow in importance only in more recent decades, from around 330,000 t·year^{-1} in the mid-1980s (12% of global) to a peak of slightly over 990,000 t·year^{-1} in the mid-2000s, and around 700,000 t in 2016 (12% of global, Fig. 3A). The Mediterranean Sea has accounted for approximately 2% of the global catch across the study period, growing from 21,000 t·year^{-1} in the early 1950s to around 100,000 t in 2016 (Fig. 3A).

Globally, catches of skipjack tuna have dominated over time, accounting on average for 34% of total global catches over the 1950–2016 time period (Fig. 3B). Skipjack catches increased from around 103,000 t in 1950 (23% of global catch) to 2.7 million t by 2016 (49% of global). Yellowfin tuna has the second highest catch globally, with catches peaking in 2003 at 1.5 million t (29% of global), before gradually declining thereafter to around 1.4 million t, or 22% of global catches in 2016 (Fig. 3B). Other major taxa in the global catch include bigeye tuna with a global average catch of 10% and a generally declining trend to around 430,000 t in 2016, and albacore tuna, with around 9% of global total catches at around 250,000 t in 2016 (Fig. 3B). In addition to the 12 major tuna and billfish taxa detailed in the FAO Tuna Atlas, the global tuna fisheries currently catch over 700,000 t·year^{-1} of so-called 'minor taxa', or what we here call 'non-Atlas' taxa (Fig. 3C). Blue shark (*Prionace glauca*) has the highest catch of these non-Atlas taxa, with massive increases in catches over the last two decades to nearly 160,000 t in 2016 (Fig. 3C). Other important non-Atlas taxa include Atlantic bonito (*Sarda sarda*), little tunny (*Euthynnus alletteratus*), common dolphinfish (*Coryphaena hippurus*) and frigate tuna (*Auxis thazard*).

Overall, reported landings accounted for 89% of total catches, while our unreported preliminary discard estimates accounted for the remaining 11% (Fig. 3A, B). However, among the non-Atlas taxa, reported landings data accounted for only 40% of total estimated catches, indicating that discards accounted for 60% of total catches of non-Atlas taxa (Fig. 3C).

3.2. Ocean basins

Catches of large pelagic taxa in the Atlantic Ocean have been dominated by Spain across the whole time period (Fig. 4A). Spain's large pelagic catches in the Atlantic Ocean peaked at over 210,000 t in 1991 and have since been gradually declining to around 106,000 t·year^{-1} by the mid-2010s, which accounted for around 17% of total Atlantic catches of large pelagics (Fig. 4A). France, the country with the second highest total catch, also peaked in the early 1990s, at 130,000 t·year^{-1} but has since declined more strongly (Fig. 4A). Japan was the dominant fishing country in the Atlantic Ocean during the 1960s, with a peak catch of over 160,000 t in 1965 accounting for well over 40% of total catches (Fig. 4A). By 2016, however, Japan's catches accounted for a far more modest catch share of around 8% with 38,000 t (Fig. 4A). Of note is the considerable increase in large pelagic catches assigned to the flag of Ghana over the last two decades, which has seen its share increase dramatically since the mid-1990s, to account for 13% (79,000 t·year^{-1}) of total Atlantic catches by the mid-2010s (Fig. 4A). Given the absence of truly domestic industrial tuna fleets in Ghana, these are foreign majority-owned vessels operating under joint venture arrangements, and are dominated by Japanese and Korean vessels (Nunoo et al., 2014).

During the 1950s, catches in the Atlantic Ocean were mainly

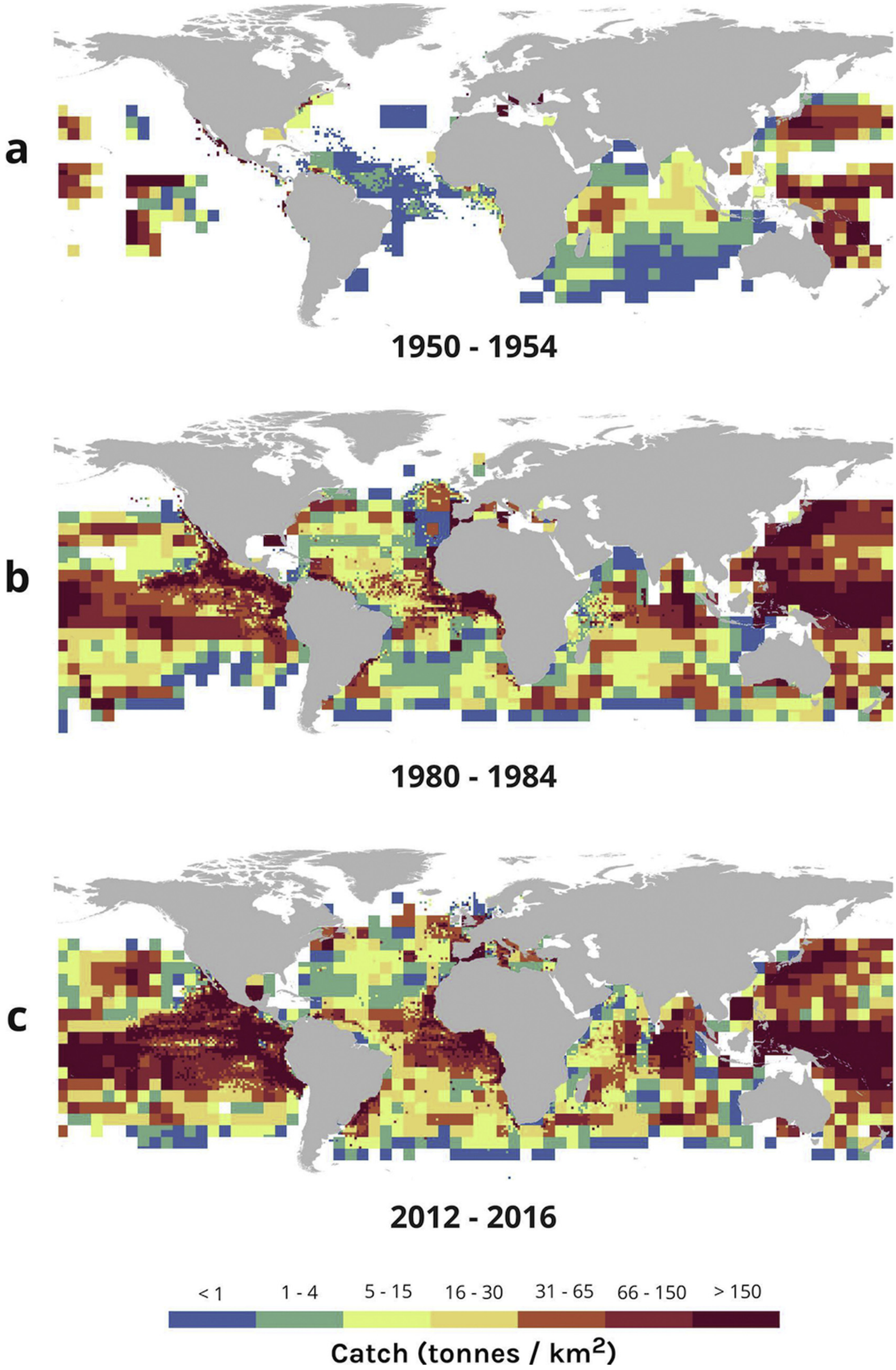

Fig. 2. Global catches of tuna and large pelagic fisheries as spatially assigned by the present study to the variously sized tuna reporting blocks used by each RFMO, averaged for a) 1950–1954; b) 1980–1984; and c) 2012-2016. The appearance of larger and smaller tuna blocks in this figure is an artefact of differences in spatial reporting resolutions from RFMOs, with RFMO spatial reporting blocks ranging from 1°x1° degrees (small dots) to 20°x20° degrees. Most common, and dominating the global map are 5°x5° degree tuna reporting blocks (see Table 1).

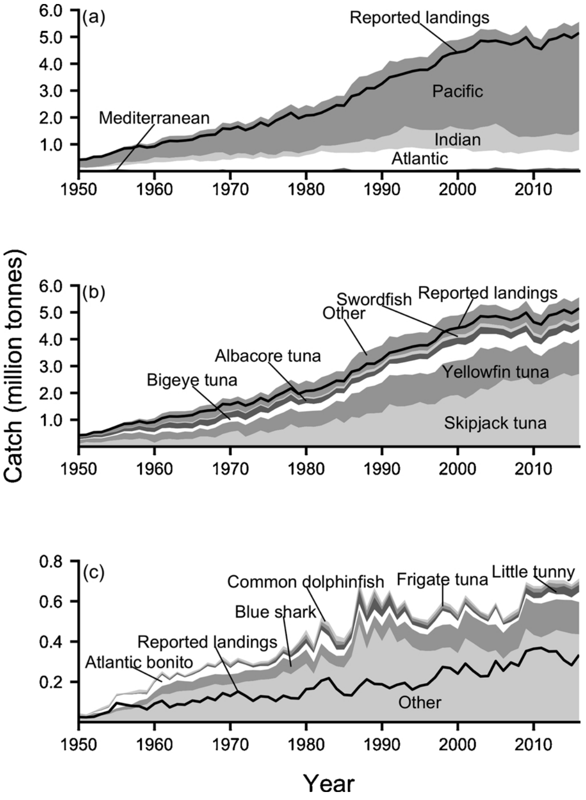

Fig. 3. Global catches of tuna and other large pelagic fishes from 1950 to 2016 as assembled and harmonized from the five separate tuna RFMO datasets, by a) ocean basins; b) major taxa (156 additional taxa are pooled in 'Other'); and c) important taxa beyond the 12 major target species covered in the FAO Atlas of Tuna and Billfish Catches (144 additional taxa are pooled in 'Other').

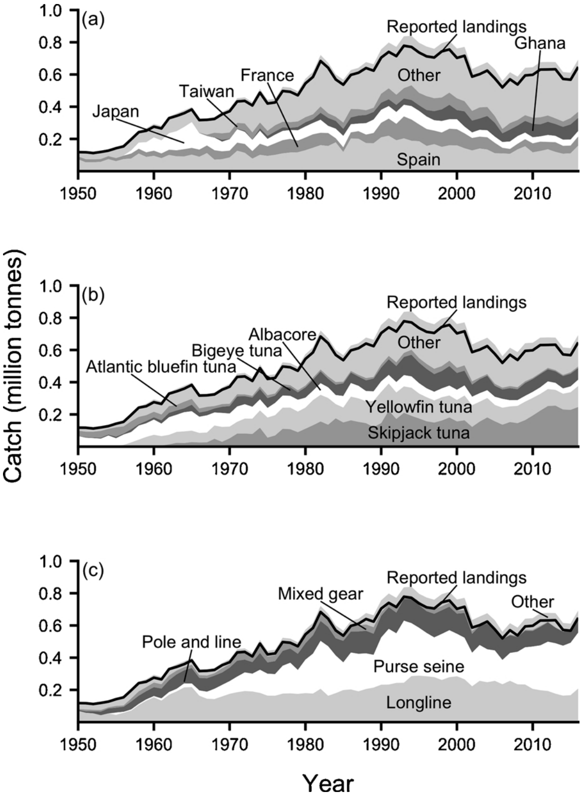

Fig. 4. Catches of tuna and large pelagics in the Atlantic Ocean from 1950 to 2016, by a) fishing country (107 additional countries are pooled in 'Other'); b) taxon (134 additional taxa are pooled in 'Other'); and c) fishing gear (9 additional gear categories are pooled in 'Other').

comprised of Atlantic Bluefin tuna and albacore tuna, while skipjack tuna and yellowfin tuna catches rapidly increased after 1960 (Fig. 4B). More recently, catches are dominated by skipjack (39% or ~230,000 t·year^{-1}), yellowfin (16% or ~100,000 t·year^{-1}) and bigeye tuna (13% or ~75,000 t·year^{-1}; Fig. 4B). The fishing gears primarily used to fish in the Atlantic are longline and purse seine, with a recent strong increase in purse seine fishing (Fig. 4C).

In the Pacific Ocean, Japan has dominated as the main fishing country since 1950, peaking at 900,000 t (40% of total) in 1986, before declining more recently to 10% of total Pacific catches (around 350,000 t·year^{-1}; Fig. 5A). The USA is also a major fishing country in Pacific waters, at its peak in 1987 accounting for 27% of total catches (540,000 t), while catches declined to around 400,000 t·year^{-1} by the mid-2010s (Fig. 5A). Since the 1990s, other Asian countries have contributed significantly to the catch in the Pacific, including Taiwan, Indonesia, South Korea and the Philippines. These four Asian countries accounted for nearly 1.5 million t of catch in 2016 (Fig. 5A).

Skipjack and yellowfin tuna are the main taxa caught in the Pacific Ocean tuna fisheries, together accounting for 76% of total large-pelagic catch in the Pacific over the full time period, and around 3.0 million t·year^{-1} by the mid-2010s (Fig. 5B). Surprisingly (since it is supposedly not a main target species), the fifth most caught large-pelagic taxon in the Pacific Ocean is not a tuna taxon, but blue shark, with 82,000 t being caught in 2016 (Fig. 5B). The fishing gears that are most widespread in the Pacific Ocean tuna fleets are purse seine (69% of the 2016 catch) followed by longline (17%; Fig. 5C).

Catches of large pelagics in the Indian Ocean were dominated by Japan until the late-1960s, but by 2016, Japan only accounted for 2% of total catches (20,000 t, Fig. 6A). The massive growth in catches in the 1980s and 1990s was driven largely by Taiwan, Spain, France and Indonesia, which together accounted for 44% (around 320,000 t) of total catches in 2016 (Fig. 6A).

Unlike in the Atlantic and Pacific Oceans, yellowfin tuna and skipjack tuna were equal contributors over the full time period in the Indian Ocean (~18% each, Fig. 6B), although more recently, catches of skipjack tuna have been higher (23% in the 2010s). The catch of Southern bluefin tuna contributed on average 36% of the catch in the 1960s (Fig. 6B). It is now < 1% of the catch in the Indian Ocean. Longline gears were used almost exclusively in Indian Ocean tuna fisheries up to the late 1960s (Fig. 6C). Subsequently, catching tuna via purse seine, and to a smaller extent gillnet gears, became popular and now constitute 55% of the catch in the Indian Ocean (Fig. 6C).

The reported tuna catches in the Mediterranean Sea presented here show remarkable, and questionable fluctuations across time, most notably due to the biggest fishing countries in the industrial sector, Spain and Turkey (Fig. 7A, see discussion on substantial data reporting issues for these two countries). Unlike in the other ocean basins, Mediterranean tuna fisheries are predominantly a 'local' rather than distant-water fleet affair, with countries such as Italy, France, Turkey and Spain accounting for over 86% of total catches (Fig. 7A).

The taxon with highest cumulative catch in the tuna fisheries in the Mediterranean was Atlantic bonito, accounting for 25% of total time series catch, but more recently only 22% in 2016 (Fig. 7B). Atlantic bluefin tuna and swordfish comprise two other historically important taxa in these waters (Fig. 7B). However, 44% of the total catch across the time period were non-Atlas taxa, including blue shark and Atlantic bonito, which also heavily dominated total catches in the last decade (Fig. 7B). Gear use varied widely over time, with longline and purse seine dominating in recent times, while gillnet, pole-and-line and traps (the last two gears are pooled into 'other') were widely used in earlier decades (Fig. 7C).

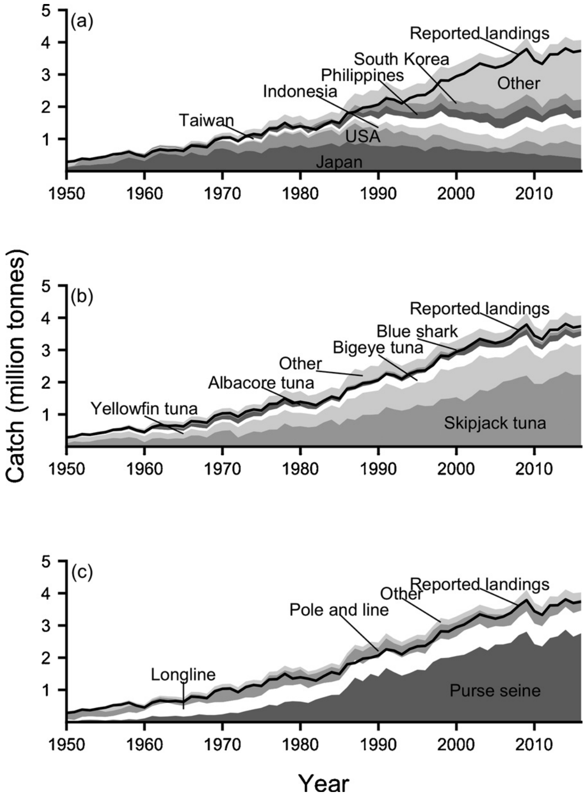

Fig. 5. Catches of tuna and large pelagics in the Pacific Ocean from 1950 to 2016, by a) fishing country (55 additional countries are pooled in ‘Other’); b) taxon (38 additional taxa are pooled in ‘Other’); and c) fishing gear (6 additional gear categories are pooled in ‘Other’).

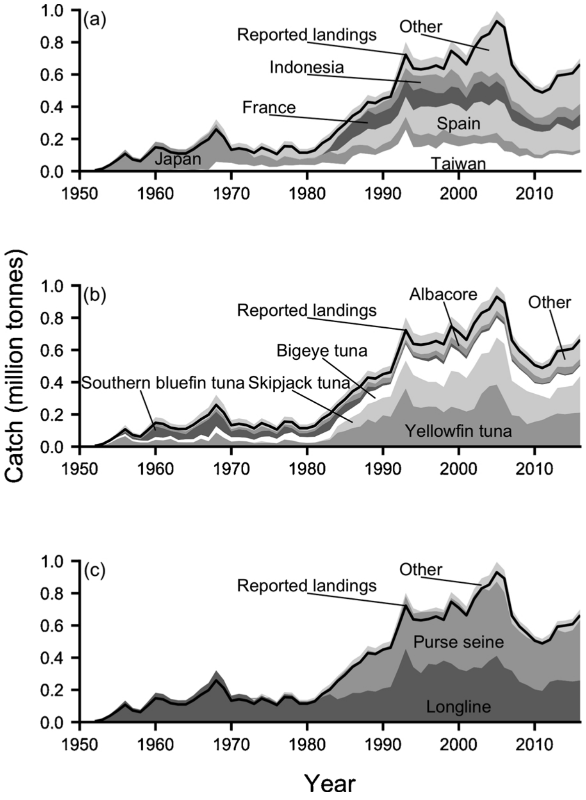

Fig. 6. Catches of tuna and large pelagics in the Indian Ocean from 1950 to 2016, by a) fishing country (54 additional countries are pooled in ‘Other’); b) taxon (83 additional taxa are pooled in ‘Other’); and c) fishing gear (5 additional gear categories are pooled in ‘Other’).

4. Discussion

Here we present a globally harmonized and spatially assigned dataset of catches (reported landings, plus unreported preliminary discard estimates) of large pelagic fishes integrated across all ocean basins for 1950–2016, and include tunas, billfishes, sharks and smaller scombrids. Several separate, individual spatial datasets on large pelagic fisheries catches exist elsewhere, either for subsets of catches by ocean basins reported by RFMOs and globally (Taconet et al., 2017), or globally for the 12 major tuna and billfish taxa as part of the FAO Tuna Atlas (FAO, 2017). However, the present study is the first attempt at harmonizing all datasets across ocean basins, and assigning all nominal catches plus preliminary estimates of discards to spatial tuna data reporting blocks of 1° x 1° to 20° x 20° spatial resolution.

Tuna fisheries, here referring to ‘all large pelagics’ including billfishes, sharks and other large- and medium-sized scombrids, illustrate the greatest spatial expansion in global fisheries (Swartz et al., 2010) due to the highly migratory nature of tuna and other large-pelagic taxa and their wide-spread occurrence in high seas waters, i.e., areas beyond national jurisdiction. However, this expansion is also indicative of the requirement to fish farther offshore as coastal and near-shore areas became increasingly depleted. Today, industrial fishing fleet effort covers at least 55% (Kroodsma et al., 2018) and possibly up to 90% (Tickler et al., 2018b) of the global ocean, and fishing in waters beyond national jurisdiction (i.e., the high seas) is becoming increasingly uneconomical without extensive government subsidies and often questionable cost-cutting labor practices (Sala et al., 2018; Tickler et al., 2018a, b). The scale of this pattern of expansion is troubling, as we have reached the spatial limit for tuna fisheries, with no new fishing grounds remaining, except as provided through species distributional changes due to climate change, which, however, may also lead to loss of previous fishing grounds and catch potential (Cheung et al., 2009, 2010). Thus, the continuation of tuna fisheries and their associated economic benefits at levels similar to the present or recent time periods is dependent on effective and restrictive long-term sustainable management of the fisheries and fleets exploiting these stocks and ecosystems. Given the predominance of a small number of highly developed, wealthy countries as the main (Sumaila et al., 2015) as well as highly subsidized fishing countries (Sumaila et al., 2014, 2016) in the global tuna and large pelagic fisheries, such effective actions are achievable with minimal socio-economic impacts, while increasing global income equality (Sumaila et al., 2015).

4.1. By-catch and discards

With the exception of swordfish, the stock status of many other non-tuna large pelagic taxa is unknown or uncertain (Majkowski, 2007). Industrial tuna fisheries are one of the major threats to pelagic shark populations (Gilman, 2011), which is worsened by the fundamentally different life history dynamics of sharks (Dulvy et al., 2008). While sharks only contributed 5% of the total overall catch presented here, they constituted 12% of the catch caught in tuna longline fisheries. Other studies have also shown that shark longline bycatch is very high (Worm et al., 2013), possibly as high as 25% (Gilman, 2011). Of the catch of sharks reported to the RFMOs, 66% is blue shark. This is potentially worrisome due to this species’ very low resilience and an IUCN Red List Status of ‘near threatened’ (Stevens, 2009). Over 6 million t of shark landings were reported to the RFMOs since 1950 and these were often reported in generic pooled taxonomic groupings such as Elasmobranchii and Selachimorpha, which are highly uninformative taxonomic groupings. Our estimate of taxon-specific discards for the Pacific Ocean alone suggests a further 5.7 million t of sharks were discarded across the time period. Despite contributing a large portion of the catch in tuna fisheries, sharks are often not recorded to the species level

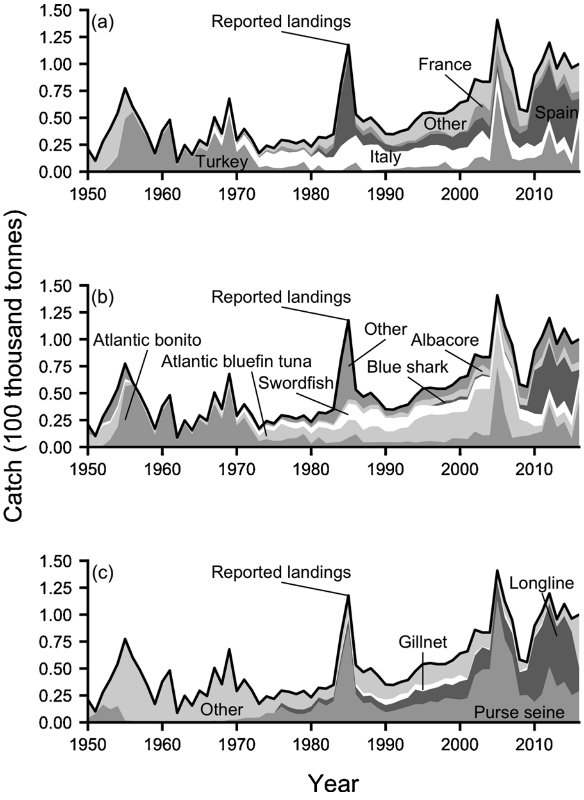

Fig. 7. Catches of tuna and large pelagics in the Mediterranean Sea from 1950 to 2016, by a) fishing country (61 additional countries are pooled in 'Other'); b) taxon (103 additional taxa are pooled in 'Other'); and c) fishing gear (10 additional gear categories are pooled in 'Other').

(Dulvy et al., 2008), which makes managing fishing pressure and conserving threatened species extremely difficult (Dulvy et al., 2000). All of the RFMOs, except the CCSBT, currently have mitigation measures to reduce non-target large pelagic bycatch, such as temporal closures to reduce capture of undersized and non-target tunas, and restrictions on shark finning practices.

However, none of the RFMOs set precautionary catch or bycatch limits for sharks, nor do they require better taxonomic resolution of data (Gilman, 2011), and only the WCPFC requires gear technologies to reduce the capture of sharks (WCPFC, 2010a). Though widely proposed as a mitigation measure, modifications to fishing strategies need agreement between tuna fishing countries and enforcement policies for success (Poisson et al., 2016).

The practice of discarding is wide-spread in commercial fisheries, even though there is agreement that it is both ecologically and economically undesirable (Alverson et al., 1994; Kelleher, 2005; Zeller et al., 2018; Zeller and Pauly, 2005). Discarding involves a conscious decision made by fishers to abandon a portion of their catch for regulatory or economic reasons (Bellido et al., 2011). While discarded catch is often thought of as primarily composed of non-target, unmarketable taxa, including pelagic sharks (Gilman, 2011), there is much evidence that it also includes juveniles of otherwise marketable species (Kelleher, 2005), or species valuable to other fishing sectors such as artisanal fisheries. Just as importantly, 'high-grading', i.e., selective retention of relatively higher-value fish at the expense of previous catch, is very common in tuna fisheries, where vessels prefer to optimize hold space over the course of long voyages (Hall et al., 2000).

To mitigate discarding, fisheries management entities increasingly mandate the landing of all target catch, though this is difficult to implement unless mandatory and independent 100% observer coverage is enforced. Furthermore, this does not address discarding of non-target catch. While the use of at-sea observers for monitoring is costly, this should be considered part of normal operational costs for sustainable fisheries. Observers may be pressured by crew to violate standards to avoid confrontation (Robertson, 1998), which would require immediate responses by RFMOs and the responsible flag state of the offending fishing vessel(s). Observer coverage varies between RFMOs and gear types, with a minimum of 5% agreed upon across RFMOs (WCPFC, 2010b). This extremely low level of coverage is a clear and critical deficit of RFMO governance (Gilman, 2011; WCPFC, 2010b). As technological innovations such as on-board camera coverage and satellite monitoring are now widely available for fisheries monitoring, an industrial tuna fishery with 100% unbiased coverage is readily feasible (McCauley et al., 2016) and should be foundational to any fisheries aiming for sustainability and accountability (Zeller et al., 2011). Pilot projects to implement such technological tools for tuna fisheries have been undertaken, with a positive response from industry members for quite some time (e.g., Piasente et al., 2012). Thus, substantial and intense efforts should be expended by all RFMOs and responsible member countries to implement and enforce such measures for all fleets.

Our estimates of discards for tuna fisheries as presented here should be treated as preliminary in nature and may in many cases underestimate the scale of the wasteful discard problem. The discard rates used here only account for a subset of the literature, and difficulties exist in harmonizing them. Furthermore, IATTC and ICCAT both report some discards in their databases, but the extent of these data are unclear. It appears that FAO may have erroneously counted the discards reported in the ICCAT database as landings in the FAO dataset, as the total landed tonnage reported in FAO's Global Capture Production statistics is equal to the sum of all discards and landings in the ICCAT database (FAO, 2019; ICCAT, 2016). This contradicts FAO's stated data reporting objective to not include discarded catches in their Global Capture Production database. A full and detailed reconstruction of discards for the Atlantic and Indian Oceans, as well as an update and revision of this work for the Pacific Ocean (Schiller, 2014), carefully integrating RFMO reports of discards and scientific literature of discard tonnage and rates, would better capture the global extent of discarding in tuna fisheries. Feedback, input and offers of collaboration from experts is welcome, and will allow us to refine these rates. We welcome such collaborations to improve the quality of global data.

4.2. Comparison to other global analyses

The FAO compiles RFMO data into the FAO FishStat global capture database (FAO, 2019), and reports on the global spatial catch of a selected subset of tuna in their Tuna Atlas (FAO, 2017). Here, our approach builds on these efforts by harmonizing all RFMO datasets and by spatially assigning all nominal reported catch data. Currently, the FAO Tuna Atlas only covers 12 target species of high value tuna and billfishes. While this encompasses much of the economically important catch by global tuna fisheries, it only conveys a partial view of the true scope of the industry. All catch in the FAO Tuna Atlas were also aggregated into 5° x 5° blocks, though much of this information is actually available at a resolution of 1° x 1°. This loss of spatial resolution is problematic in today's context of fisheries management's need to account for ecosystem considerations (Juan-Jordá et al., 2018; Pikitch et al., 2004), and in our view should be avoided.

There have been other excellent efforts to compile global databases for tuna fisheries, many of which contributed to the FAO Tuna Atlas. Fonteneau (1997) published a global atlas, but did not estimate discards, nor scaled up the spatialized data to 100% of the nominal catch. Updates were published later, but at regional scales and without the Pacific Ocean (Fonteneau, 2009, 2010). The recent efforts by the IRD and FAO on harmonizing tuna RFMO data into a single database is akin to our ideal spatialization scenario with matching flag, species, year and gear combinations (Taconet et al., 2017). Unfortunately, just like Fonteneau (1997), they did not scale up the spatialized data to 100% of the nominal catch, as was done in the present study, despite obviously higher data uncertainty, using a set of logical assumptions in the absence of partial parameter match. Finally, the International Seafood Sustainability Foundation (ISSF, 2017) has produced biannual technical reports of the status of the world fisheries for tuna by compiling RFMO data, though they only address the 23 major tuna stocks on the scale of ocean basin (ISSF, 2019).

The spatial data used for our analysis were sourced as public data from the various tuna RFMOs, and we compliment the RFMOs and FAO on the challenging job of annually assembling these data, which correlate well with AIS-derived fishing effort data by the Global Fishing Watch (Kroodsma et al., 2018). Still, the officially reported datasets are subject to misreporting and cover a limited set of the tuna fisheries managed by the RFMOs. Some spatial misreporting was obvious, e.g., when tuna catches were reported at spatial coordinates that occur on land. Public datasets are also subject to confidentiality rules of the RFMOs, which unfortunately leads to incomplete or even entirely missing data components. Most notably, data from the IATTC had a large region of the North Pacific Ocean almost totally devoid of longline fishing data until the early 1990s. Publicly releasing data for this region (even if in aggregated form to mask the identities of fishing enterprises) would facilitate investigations into the spatial extent of historical tuna fisheries and improve transparency and accountability around the use of what is actually a public resource. Besides, hiding data from public view or use does not make sense these days, give the wide public availability of additional data sources, e.g., the satellite-derived data on spatial fishing effort provided by the Global Fishing Watch (Kroodsma et al., 2018). Moreover, vague and qualitative geographic information (i.e., ‘sub-areas’) such as provided in the ICCAT nominal catch database was not usable as these ‘sub-areas’ are not explicitly defined geographically.

The present harmonization was limited by the data reported to the RFMOs. For regions where underreporting is known to occur regularly, for example Spain and Turkey fishing in the Mediterranean Sea (see Fig. 7 and Pauly et al., 2014b), full catch reconstructions (Zeller et al., 2016) are required to complement the incomplete reported data with best estimates of unreported activities to comprehensively account for the extent of global tuna fisheries. Furthermore, the role of China in tuna fisheries will have to be re-assessed, given that its heavily subsidized distant-water fleets, including those targeting tuna, are gradually muscling out those of other distant-water fishing countries (Pauly et al., 2014a). Therefore, future data efforts by tuna RFMOs should emphasize both more comprehensive reporting by all fishing fleets, as well as more detailed spatial reporting efforts by countries.

Improving the state of global tuna stocks is key for sustaining highly valuable fisheries that are particularly important for Small Island Developing States as well as other tropical and subtropical developing countries that have historically benefitted from these species. Transparency and full accountability are vital components for proper management, particularly in the context of supporting these regions, as specifically included in the UN Sustainable Development Goals (SDG 14.7), and more broadly for ensuring a more equitable distribution of benefits from these highly migratory species (Sumaila et al., 2015).

CRediT authorship contribution statement

Angie Coulter: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Tim Cashion:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **Andrés M. Cisneros-Montemayor:** Methodology, Software, Writing - review & editing. **Sarah Popov:** Software, Writing - review & editing, Visualization. **Gordon Tsui:** Software, Writing - review & editing. **Frédéric Le Manach:** Methodology, Software, Writing - review & editing. **Laurenne Schiller:** Writing - review & editing. **Maria Lourdes D. Palomares:** Conceptualization, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Dirk Zeller:** Conceptualization, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Daniel Pauly:** Conceptualization, Writing - review & editing, Supervision, Project administration, Funding acquisition.

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Appendix A. Supplementary data

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