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REVIEW

Discards in global tuna fisheries

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ABSTRACT: Monitoring live and dead discarded catch contributes to effective fisheries management and ecological and socioeconomic sustainability. We determined contemporary rates and levels of discards in global tuna fisheries. An estimated 265 279 t (52 283 to 478 275 t 95 % CI) is annually discarded by global tuna fisheries, composing about 5 % of the weight of the total catch. Pelagic longline and purse seine fisheries contributed about 64 and 36 % of discards, respectively. Other gear types composed <1 % of discards. Discards in tuna fisheries are now 63 % lower than estimated 1 decade earlier, mainly due to large declines in discards in longline tuna fisheries, possibly from increased retention of formerly discarded species and sizes of catch and increased gear selectivity. The decline also resulted, in part, from employing different methods to categorize caught sharks whose fins were retained and carcasses discarded following processing. Discard rates were greater in shallow- than deep-set longline fisheries, and higher in purse seine sets associated with fish aggregating devices and other floating objects than in other purse seine set types. The quality and availability of data on discards in global tuna fisheries were extremely limited. Filling gaps in monitoring, improving observer data fields and collection protocols, and providing public access to amalgamated discard data held by fisheries management organizations will improve the certainty of future discard estimates, supporting effective management of discards in global tuna fisheries.

KEY WORDS: Discards · Fisheries · Regional fisheries management organization · RFMO · Tuna

INTRODUCTION

Discard rates and levels are a fundamental component of a suite of indicators that track trends in manageable pressures from fishing and of inputs to stock assessment and ecosystem models used to understand direct and collateral effects of fishing (Fulton et al. 2004, Link 2005, Punt et al. 2006, Piet et al. 2007, Gilman et al. 2017). Fishery pressures on marine ecosystems have conventionally been monitored using data on landed catch. However, landed catch can be a small component of total fishing mortality (Botsford et al. 1997). Extending pressure indicators to encompass the entire catch (retained, released alive and discarded dead catch) enables a more comprehensive, albeit still incomplete estimate of total fishing mortality (ICES 2005, Gilman et al. 2013).

Discards in marine capture fisheries can have profound socioeconomic and ecological effects (Goñi 1998, Baum & Worm 2009, Oro et al. 2013, Fondo et al. 2015, Batsleer et al. 2016, Borges et al. 2016). International guidance has called for the reduction of discards, considered a waste of natural resources (FAO 1995, 2011). In addition to food security issues, discards can also affect fisheries' socioeconomic sustainability. Discards can reduce recruitment to a fishery when large numbers of juveniles of marketable species are discarded (Jensen et al. 1988). Discards in

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one fishery can reduce target species catch and revenue in others (Sumaila & Bailey 2011). It is operationally inefficient for vessels to catch and handle organisms that will not be retained (FAO 2011, Gilman et al. 2014b). Reducing discards by increasing retention, incentivized through the development of new markets for these currently undesirable species and sizes, could reduce pressure on overexploited stocks of current target species (Gilman et al. 2014b).

Discards can also have direct and collateral effects on ecosystem food web processes and structure. For example, discards can alter scavengers' foraging behavior, distribution and diet. Discards can also alter competition amongst species of scavengers and community composition (Wassenberg & Hill 1987, Evans et al. 1994, Hall 1996, Goñi 1998, Hall et al. 2000, Bugoni et al. 2010). Some direct ecological effects of discards are detrimental, such as reducing scavenger population fecundity due to density-dependent effects, while others are positive, such as improving the viability of populations of endangered species when discards are an important food subsidy (Oro et al. 2013, Fondo et al. 2015).

Discards can alter distributions of biomass within and between ecosystems. The transfer of biomass from benthic to pelagic ecosystems by demersal fisheries has been documented (e.g. Evans et al. 1994, Blaber et al. 1995). There is comparatively limited knowledge of biomass transfer between ecosystems caused by pelagic fisheries (Hall et al. 2000). Discards can increase levels of organic material in benthic ecosystems (Wassenberg & Hill 1987, Evans et al. 1994). In fisheries where discards are spatially concentrated and in areas of low current flow, discards may cause hypoxia or anoxia of the seabed. If prolonged, this can cause substantial mortalities and alter benthic community processes and structure (Goñi 1998, Hall et al. 2000, Gray et al. 2002, Haselmair et al. 2010). This is potentially problematic not just for discharges occurring in coastal areas, but also for discharges occurring in very deep regions of the ocean (Stockton & DeLaca 1982, Smith 1985, Hall et al. 2000).

Some fisheries, including pelagic longline, purse seine and driftnet fisheries for tuna and tuna-like species (Scombroidei) and billfishes (Xiphioidei), incidentally catch relatively vulnerable species, including elasmobranchs, seabirds, sea turtles, marine mammals and some bony fishes, which compose a proportion of non-retained catch (Hall et al. 2000, Gilman et al. 2010, Gilman 2011, Hall & Roman 2013, Clarke et al. 2014). As a result of their life history characteristics, these taxa have low resistance and resilience to even low levels of anthropogenic mortality (Musick 1999, Stevens et al. 2000, Dulvy et al. 2008). There has been substantial progress in identifying effective and in some cases economically viable gear technology mitigation measures for some of these bycatch problems (Gilman 2011, Clarke et al. 2014). However, there has been limited uptake of bycatch mitigation methods in most fisheries, in part, due to deficits in key elements of management systems (Gilman 2011, Gilman et al. 2014b).

There are numerous reasons why fishers decide to discard part of their catch, most of which are responses to market conditions and regulatory measures. For example, fishers may discard species and sizes lacking markets or with relatively low value, damaged catch with low or no value, and species that can damage the rest of the catch during storage. Quality, including catch that is unfit for human consumption due to spoilage or toxicity, provides another reason to discard part of the catch.

High-grading, where fishers discard lower value catch to make room in the hold for higher value catch, when the perceived difference in net value between discards and retained catch is greater than the cost of replacing the discard, is another cause for discarding (Alverson et al. 1994, Arnason 1994, Hall 1996, Kelleher 2005). Fishers may also discard catch during the final set of a trip if there is insufficient room to retain all the catch from that set (IOTC 2009), where high-grading may also occur.

Output controls can also create incentives for discarding. Quota-induced high-grading occurs when a vessel reaches a species-based quota and discards lower value grades and replaces them with higher value grades. Over-quota discarding occurs in multispecies fisheries when a quota for one species is reached, but quotas for other species are not in place or have not been reached, where the vessel discards additional catch of the species for which the quota has been reached. Fishers may discard sublegal individuals in fisheries with measures on minimum landing sizes. Fishers may discard to meet prescribed catch composition (e.g. measures setting limits on the percent catch composition by species). Discarding may occur in response to restrictions on retention by sex, such as exists in some crab fisheries (Alverson et al. 1994, Arnason 1994, Hall 1996). Retention bans for specified species, such as oceanic whitetip sharks *Carcharhinus longimanu* and silky sharks *C. falciformis* in western and central Pacific Ocean tuna fisheries (WCPFC 2011, 2013), are another regulatory-driven reason for discarding.

Discard bans, to be effective, may require broad industry support, flexibility in output controls, and extensive surveillance and enforcement (Hall et al. 2000, Poos et al. 2010, Batsleer et al. 2013). In some fisheries, measures such as overcatch provisions, quota substitution, species-based quotas by grades, and deemed value effectively reduced incentives for discarding. These measures also created incentives for increased selectivity, in order to reduce catch rates of species subject to full retention requirements (Arnason 1994, Peacey 2003, Hall & Mainprize 2005, Iceland Ministry of Fisheries 2011).

This study benchmarked contemporary discard rates and extrapolated levels in global tuna fisheries. Commercial fisheries for tuna and tuna-like species and billfishes supply some of the most valuable globally traded fishery products and provide substantial economic revenue, employment and food security to flag and coastal states (Gillett 2009, Bell et al. 2011, 2015, FAO 2014, Williams & Terawasi 2015). The study also documented the state of availability and quality of information on discards in tuna fisheries. This discard estimate updates 2 previous studies (Alverson et al. 1994, Kelleher 2005). Regional-level estimates of discards available for a subset of the fishing methods from public domain materials of tuna regional fisheries management organizations (RFMOs, regional fishery bodies with the competence to establish binding conservation and management measures) were synthesized and compared with raised estimates extrapolated from discard rates from a sample of individual fisheries. The degree of variability in discards within and among tuna fishing methods was assessed. Current and accurate estimates of discards in tuna fisheries contribute to identifying opportunities to augment responsible fisheries conduct and management, thereby avoiding and reducing adverse socioeconomic and ecological effects.

METHODS

Covered fisheries and definition of discards

The study estimated discard levels in main fisheries capturing tuna and tuna-like species and billfishes, which are the main resources managed by the 5 tuna RFMO conventions and agreements (Gilman et al. 2014b). Purse seine, longline, pole-and-line and troll are the main gears used to catch these highly migratory pelagic and neritic species. Several other gear types, including handline, drift gillnet (driftnet), ringnet, set net and trap, are also used to catch tunas and billfishes, primarily by small-scale, coastal fisheries (Miyake et al. 2010, FAO 2015a, SPC 2015a).

The term 'tuna and tuna-like species' refers to species of the suborder Scombroidei (Collette et al. 2001, 2006, Orrell et al. 2006). There are 7 principal market species of 'true' tunas: albacore *Thunnus alalunga*, Atlantic bluefin *T. thynnus*, bigeye *T. obesus*, Pacific bluefin *T. orientalis*, skipjack *Katsuwonus pelamis*, southern bluefin *T. maccoyii* and yellowfin *T. albacares* (Majkowski 2005). These 7 species of market tunas, as well as billfishes, are all pelagic. Other tunas and some tuna-like species are mainly neritic, occupying waters primarily over continental shelves (Majkowski 2005, 2007). There are 15 genera with 51 species currently recognized in the Scombridae (Collette et al. 2001). Tuna-like species include, for example, kawakawa *Euthynnus affinis*, frigate *Auxis thazard*, bullet *A. rochei* and longtail tunas *T. tonggol*, wahoo *Acanthocybium solandri*, and narrow-barred Spanish *Scomberomorus commerson* and king mackerels *S. cavalla* (Collette et al. 2001, Majkowski 2005, 2007). Billfishes (suborder Xiphioidei) comprise marlins *Makaira* spp., sailfishes *Istiophorus* spp., spearfishes, white and striped marlins *Tetrapturus* spp. and swordfish *Xiphias gladius* (Collette et al. 2006).

The terms discards and discarded catch were used here to include all non-retained catch, including both live released and dead discarded catch (Alverson et al. 1994, Kelleher 2005, FAO 2011, Gilman et al. 2013). In both cases, the organism is released or discarded whole (i.e. no part of the organism is retained).

This definition of discards excludes other sources of organic matter that is returned to the sea by tuna fishing vessels, such as bait that falls from gear during fishing operations, spent bait discarded by crew, discharges of chum, and discharges of offal (waste from processed catch, including heads, gills and viscera). It also excludes processed sharks where fins were removed before returning the remaining carcass back to the sea. The definition also excludes discharges of live baitfish used for chumming in pole-and-line tuna fisheries to aggregate target tunas (Majkowski 2003a, IPNLF 2012). Catch that were retained on the vessel but later discarded at port, such as fish that were rejected due to poor quality and fish that were landed due to a government ban on discarding at sea but had no available market (Gilman et al. 2013) were also not accounted for in estimating discarded catch.

Fishery-level records of discard rates

Published and grey literature reporting discard rates in individual tuna fisheries (i.e. fishery-level discard rates) were compiled for longline (Gamblin et al. 2007, Ward et al. 2008, Huang & Liu 2010, Acroyd et al. 2012, NMFS 2014, 2015, Fernandez-Carvalho et al. 2015, Gascoigne et al. 2015, Gilman et al. 2015, Patterson et al. 2015), purse seine (Amande et al. 2008, 2010, Banks et al. 2011, Hall & Roman 2013, Republic of the Marshall Islands 2015), troll (Bugoni et al. 2008, Holmes 2013, 2014, Criquet et al. 2015, Holmes & Chen 2015), gillnet (Rogan & Mackey 2007) and trap (Neves dos Santos et al. 2002) fisheries. We employed both structured and unstructured literature searches. The structured search was conducted using various combinations of the following Boolean search terms and operators in Google Scholar: discard, fisheries, fishery, longline, purse seine, gillnet, driftnet, troll, handline, pole, line, pole-and-line, trap, bycatch, tuna, pelagic. An unstructured literature search was conducted by reviewing reference lists of relevant publications and reports and via polling an informal network of fisheries professionals to identify relevant publications. Fishery-level discard rates using the same units were then used to calculate mean rates and estimates of error by tuna RFMO area and gear type, and by set type for longline and purse seine fisheries.

Fishery-level discard rate records were compiled for the following gear types, categorized by set type for purse seine fisheries, and categorized by soak depth for longline fisheries, resulting in the following 10 fishing method categories: (1) Shallow-set pelagic longline, where the majority of hooks between 2 floats were reported to soak shallower than 100 m, and/or there were <15 hooks between 2 floats (Gilman et al. 2006a, Williams et al. 2009); (2) Deep-set pelagic longline, where the majority of hooks between 2 floats were reported to soak deeper than 100 m, and/or there were ≥15 hooks between 2 floats (Gilman et al. 2006a, Williams et al. 2009); (3) Purse seine free school (unassociated) sets (see definition by Hall & Roman 2013); (4) Purse seine associated sets (sets on logs, anchored and drifting fish aggregating devices [FADs], other floating objects) (see definition by Hall & Roman 2013); (5) Purse seine dolphin school sets (see definition by Hall & Roman 2013); (6) Pole-and-line; (7) Troll; (8) Handline; (9) Driftnet; and (10) Trap.

Fishery-level records were compiled only for those that reported discard rates for an individual gear type. In some fisheries, however, vessels use multiple gear types, in some cases simultaneously (e.g. Bugoni et al. 2008, IOTC 2016a,b). Many small-scale driftnet fisheries, and possibly industrial driftnet fisheries, which are typically multispecies fisheries where the proportion of the total catch that comprises tuna can range from minimal to large, may use additional gear types simultaneously but still be recorded as a driftnet fishery (Gillett 2011, Ardill et al. 2012). Few compiled fishery-level records contained information to enable categorizing them as being derived from locally based versus distant water fisheries, information that can be used to infer vessel size classes and trip durations (e.g. Miyake et al. 2010), which may influence discard rates (Kelleher 2005). Also, few studies contained information on the country or territory where the fishing vessels were based, principal retained species or principal caught species, preventing use of these factors to categorize the records.

The study periods of the compiled publications from which fishery-level discard rate records were obtained had a mean date of 2007.4 (95% CI ±1.6 yr, range 1996 to 2014). The average of annual mean discard rates for the most recent 5 yr period was used, if available, for each fishery-level discard rate record. For studies that reported only amalgamated discards data for a multiple-year period, or reported data only for a single year, then data for the available period reported were used. This method was selected to employ estimates that were most likely to characterize contemporary fisheries, but using the average of recent years instead of just the most current 1-yr period when available in order to account for inter-annual variability.

Fishery-level records were based on data collected from onboard (human and electronic) observer programs, logbook programs, port-sampling programs, scientific fishing surveys, and control groups (i.e. fishing using conventional gear and methods, does not receive the variable being tested) of experiments (FAO 2015b, Gilman et al. 2016a). For records derived from experiments, only data from studies that included a control group of conventional fishing gear and practices were included, as discard rates under experimental treatments may not accurately characterize discard rates in commercial fisheries. Records from interviews of fishers were not included. While social surveys can provide a critically important first-order qualitative characterization of a fishery, especially when little or no information was previously available (e.g. Moore et al. 2010), information on bycatch and discard rates from this source may have large uncertainty relative to the other data sources.

Fishery-level discard rate records were based on data from sampled fishing effort and not extrapolated fleet-wide estimates.

Catch and effort data from tuna regional fisheries management organizations

Data on regional-level estimates of catch (total, retained and discarded) and effort by gear type, where available, were obtained from public domain materials of the Inter-American Tropical Tuna Commission (IATTC) (IATTC 2015a,b), Western and Central Pacific Fisheries Commission (WCPFC) (WCPFC 2016), Pacific Community (SPC, the science provider to WCPFC) (Harley et al. 2015, SPC 2015a,b), International Commission for the Conservation of Atlantic Tunas (ICCAT) (ICCAT 2016), and Indian Ocean Tuna Commission (IOTC) (IOTC 2013, 2016a,b). Fisheries for southern bluefin tuna covered by the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) currently all occur within the convention areas of IOTC, WCPFC and ICCAT (R. Kennedy pers. comm.). As a result, the regional-level data on tuna fisheries conducted in IOTC, WCPFC and ICCAT convention areas covered the fisheries catching southern bluefin tuna.

The tuna RFMO data on regional catch and effort by gear type for the most recent 5 years available were used. These data were through 2014 or 2015 except IOTC handline, troll and trap effort data were through 2010, IOTC pole-and-line market tuna catch data were through 2012, and IATTC pole-and-line and troll retained catch data were through 2013 (Harley et al. 2015, IATTC 2015a,b, SPC 2015a,b, ICCAT 2016, IOTC 2016a,b, WCPFC 2016).

Regional and global discard estimates

Catch and effort data from public domain materials from tuna RFMO secretariats and SPC were used to produce regional-level estimates of mean annual discard rates and levels (IOTC 2013, 2016a,b, IATTC 2015a,b, SPC 2015b, ICCAT 2016, WCPFC 2016).

Estimates of mean discard rates by gear type were used to estimate regional raised discard levels. We extrapolated mean rates and error intervals from fishery-level discard rates observed from a sample of fisheries using tuna RFMO regional catch and effort data, by RFMO area and gear type. This method assumed a linear relationship exists: the discard rate of a sample of fisheries of a gear type was applied, linearly, to the annual mean total amount of effort, catch and/or retained catch of a tuna RFMO area for that fishery category. In estimating raised regional discard levels, statistical areas and not convention areas were used in the Pacific Ocean in order to avoid double counting in an overlap area of 2 tuna RFMO convention areas (IATTC & WCPFC 2011).

The delta method (Oehlert 1992, Jackson 2011) was used to combine regional RFMO area discard level estimates to produce global-level estimates by gear type and for combined tuna fishery gear types. The average of annual discard levels raised from 2 discard rate estimates for ICCAT purse seine fisheries was also calculated using the delta method. The raised global annual discard levels by tuna fishery gear type were compared to estimates made by Kelleher (2005).

RESULTS

Regional discard estimates from public domain data of tuna regional fisheries management organizations

Tables 1 & 2 present mean annual discard levels and rates, respectively, by gear type and RFMO area. These levels and rates were estimated from regional-level catch (total, retained, discarded) and effort data from public domain tuna RFMO materials.

Fishery-level records of discard rates

Table 3 provides mean discard rates derived from fishery-level records, by tuna RFMO area and gear type, for pelagic longline, purse seine, troll, driftnet and trap fisheries. No discard rate records were found for pole-and-line and handline tuna fisheries.

Mean pelagic longline discard rates for combined records of shallow- and deep-set fisheries are presented in Table 3. A total of 19 discard rate records were compiled for longline fisheries: 9 from shallow-set fisheries and 10 from deep-set fisheries. Discard rates were presented in 3 units: number of individuals per 1000 hooks, percent of the weight of the total catch, and percent of the number of total catch. With all 3 units, shallow-set fisheries had higher mean discard rates than deep-set fisheries, but mean rates of the same discard rate units were not significantly different ($p > 0.05$, 2-sample *t*-test for unequal variance).

Table 1. Summary of mean annual discard levels from available tuna regional fisheries management organization (RFMO) materials, reported by tuna RFMO area and gear type (IOTC 2013, 2016a,b, IATTC 2015b, SPC 2015b, ICCAT 2016). ND: no data

Tuna RFMO	Annual mean discard levels (±95% CI) (t)						
	Longline	Purse seine	Pole-and-line	Troll	Handline	Gillnet	Trap
IATTC[a]	ND	7954 (±2179)[b]	ND	ND	ND	ND	ND
ICCAT[c]	1001 (±222)	4672 (±2312)	0	0	ND	ND	0
IOTC	ND	ND	ND	ND	ND	ND	ND
WCPFC	ND	ND	ND	ND	ND	ND	ND

[a] Annual mean 2011–2015

[b] Raised from large purse seine to total purse seine effort using the observed large purse seine discard rate

[c] Annual mean 2011–2014

Of 11 discard rate records compiled for purse seine fisheries, 4 were from associated sets, 1 from dolphin sets, 4 from free school sets, and 2 from mixed set types. Six records used units of tonnes per set, 3 were in units of tonnes per 1000 t of landed tuna and 2 used units of percent of the weight of the total catch (Table 3). Associated sets had higher discard rates than the 2 other set types, but the mean rates were not significantly different ($p > 0.05$, 2-sample *t*-test for unequal variance).

For troll fisheries, discard rates were available from records from a single fishery, the Canadian north Pacific albacore troll fishery, from logbook data (Table 3). Discard rates were in units of number per

Table 2. Mean discard rates (±95% CI) (live released plus dead discarded catch) from public domain tuna RFMO materials for (a) IATTC statistical area: large purse seine mean annual discard rate 2011–2015 for vessels with carrying capacity >363 t, combined set types (IATTC 2015b); (b) ICCAT convention area: mean annual rates 2011–2014 (ICCAT 2016); (c) WCPFC statistical area: mean annual rates 2010–2014 (Harley et al. 2015, SPC 2015a,b, WCPFC 2016). IOTC data on discards were unavailable (IOTC 2013, 2016a,b)

(a) IATTC statistical area large purse seine

Species group	Discards/set (t)
Market tunas	0.18 (±0.08)
Billfishes	0.0011 (±0.0004)
Other teleosts	0.075 (±0.030)
Elasmobranchs	0.017 (±0.006)
Combined species	0.27 (±0.10)

(b) ICCAT convention area

Discard rate unit	Purse seine[a]	Longline	Trap	Pole-and-line	Troll
Discards (t) / total catch (t)	0.017 (±0.007)	0.005 (±0.0009)	0	0	0
Discarded market tunas (t) / total catch t	5.8×10^{-5} (±2.6×10^{-5})	0.0016 (±0.0006)	0	0	0
Discards (t) / catch of market tunas (t)	0.017 (±0.007)	0.013 (±0.002)	0	0	0
Discarded market tunas (t) / catch market tunas (t)	5.9×10^{-5} (±2.6×10^{-5})	0.004 (±0.002)	0	0	0
Discards (t) / retained market tunas (t)	0.017 (±0.007)	0.013 (±0.002)	0	0	0
Discarded market tunas (t) / retained market tunas (t)	5.9×10^{-5} (±2.6×10^{-5})	0.004 (±0.002)	0	0	0

[a] Several of the purse seine discard rates using different units produced the same estimate due to rounding. For example, for the discard rate in units of tonnes of discarded market tunas per tonnes of total catch of market tunas, the estimate was $5.87146 \times 10^{-5} \pm 2.63315 \times 10^{-5}$ 95% CI, and in units of tonnes of discarded market tunas per tonnes of retained market tunas the estimate was $5.87183 \times 10^{-5} \pm 2.63348 \times 10^{-5}$ 95% CI

(c) WCPFC statistical area

Discard rate unit	Purse seine combined set types	Longline
Discarded market tunas (t) / catch of market tunas (t)	0.016 (±0.009)[a]	0.0088 (±0.012)[b]
Discarded market tunas (t) / effort[c]	0.24 (±0.16)[a]	2.0×10^{-3} (± 2.6×10^{-3})[b]

[a] Bigeye, skipjack and yellowfin tunas

[b] Albacore, bigeye and yellowfin tunas

[c] Units of effort: days fishing and searching for purse seine; 1000 hooks for longline

Table 3. Fisheries discard rates and raised annual mean estimated levels by tuna RFMO area and gear type (Neves dos Santos et al. 2002, Gamblin et al. 2007, Rogan & Mackey 2007, Amande et al. 2008, 2010, Bugoni et al. 2008, Ward et al. 2008, Huang & Liu 2010, Banks et al. 2011, Acroyd et al. 2012, Hall & Roman 2013, Holmes 2013, 2014, NMFS 2014, 2015, Carvalho et al. 2015, Criquet et al. 2015, Gascoigne et al. 2015, Gilman et al. 2015, Holmes & Chen 2015, Patterson et al. 2015, Republic of the Marshall Islands 2015). ND: no data

Mean rates		Raised annual discard levels				
Rate	Unit	Unit	IATTC	ICCAT	IOTC	WCPFC
Longline						
5.7 (±5.2)	no./1000 hooks	No.	934 409 (±852 443)	ND	1 300 367 (±1 186 299)	6 361 464 (±5 803 441)
7.5 (±28.7)	% of weight of total catch	t	16 951 (±64 868)[a]	13 554 (±51 866)	23 590 (±90 273)	115 404 (±441 619)[a]
18.8 (±21.1)	% of no. of total catch	No.	ND	ND	ND	ND
Purse seine						
33.4 (±51.6)	t/1000 t of landed tunas	t	18 909 (±29 213)	9081 (±14, 029)	ND	53 022 (± 81 914)
3.5 (±16.6)	% of weight of total catch	t	ND	9679 (±45 907)	14 440 (± 68 485)	ND
4.78 (±8.90)	t/set	t	140 811 (±262 180)	ND	ND	ND
Troll						
1.6	no./1000 fishing days	No.	ND	ND	937	ND
0.00098[b]	% of weight of total catch	t	ND	0.05	0.81	ND
0.001[a]	% of weight of market tuna catch	t	2.36[a]	0.06	0.38	0.46
Gillnet						
46.18	no./set	No.	ND	ND	ND	ND
Trap						
<1	% of weight of total catch	t	0	<25.5	<0.4	0

[a] Rough estimate, based on assumptions explained in 'Results; Discard levels extrapolated from fishery-level estimates'

[b] Because >98 % of the weight of the catch was target albacore tuna (Criquet et al. 2015) there was a nominal difference in rates when using the weight of the total catch vs. weight of the market tuna catch

1000 fishing days, percent of the weight of the total catch and percent of the weight of the market tuna catch. There was 1 discard rate record for an Irish albacore driftnet fishery in a unit of number per set (Table 3). A single tuna trap fishery discard rate record from a fishery in Algarve, Portugal, was identified, reporting a discard rate in a unit of percent of weight of the total catch (Table 3) (Neves dos Santos et al. 2002).

Discard levels extrapolated from fishery-level estimates

Table 3 reports regional and global discard levels by tuna RFMO area produced by extrapolating fishery-level discard rates. As no discard rate records were found for pole-and-line and handline tuna fisheries, it was not possible to estimate raised discard levels for these gear types. There were no estimates of tuna driftnet fishery effort for IATTC, ICCAT or WCPFC, and IOTC reported gillnet effort in a unit of number of days at sea and not number of sets, needed to extrapolate from the 1 discard rate record (IATTC 2015b, ICCAT 2016, IOTC 2016a,b, WCPFC 2016). This prevented estimating regional and global raised discard levels for tuna driftnets.

In Table 3, raised annual mean estimated discard levels by longline tuna fisheries, by tuna RFMO area are not broken down by shallow-set and deep-set fisheries, as regional-level catch and effort data were not available to produce raised estimated levels categorized by longline soak depth. For the IATTC statistical area, the regional longline annual mean effort estimated to represent >97 % of total effort was used (IATTC 2015b). As a result, the raised estimated levels based on this effort value may be a slight underestimate, by ≤3 %. There were no estimates available from the tuna RFMOs of total catch in units of number of individuals, and thus Table 3 does not include a raised discard level from the estimated discard rate in units of percent of the number of total catch. Due to a lack of data on the weight of total longline catch for IATTC and WCPFC (Harley et al. 2015, IATTC 2015a,b, SPC 2015a), it was also not possible to directly estimate raised discard levels in units of percent of the weight of total catch for IATTC and WCPFC. Rough estimates of the weight of discards for these 2 regions were calculated using the IOTC ratio of number of discarded individuals to weight of discards and applying this to the estimated number of discarded individuals for IATTC and WCPFC. The sum of the regional raised discard levels from using the discard rate of percent of the weight of the total catch produces a global raised discard level by longline fisheries of 169 499 t yr^{-1} (95% CI: 0 to 378 451 t yr^{-1}).

For raised annual mean estimated discard levels by purse seine fisheries, by RFMO area, levels are reported for combined set types (Table 3). No data were available for ICCAT, IOTC and WCPFC for number of sets, weight of landed catch and weight of total catch by set type, preventing estimating extrapolated estimates by set type (IOTC 2013, 2016a,b, Harley et al. 2015, SPC 2015a,b, ICCAT 2016, WCPFC 2016). The sum of the regional raised discard levels produced a global raised discard level by purse seine fisheries of 95 751 t yr^{-1} (95% CI: 54 442 to 137 060 t yr^{-1}). For ICCAT, the average of annual discard levels raised from 2 discard rate estimates was used. For IATTC, the raised level from the discard rate in units of tonnes per 1000 t of landed tunas was used. The raised discard level from the tonnes per set discard rate was not used as it was deemed to have relatively higher uncertainty due to the influence of an outlier discard rate record from a study with a relatively small sample size (Amande et al. 2010).

For troll fisheries, an estimate of total market tuna catch by troll vessels in the IATTC statistical area was not available to estimate a raised discard level for this region (Table 3) (IATTC 2015a,b, SPC 2015b). To estimate the total weight of discards in troll fisheries operating in the IATTC statistical area, we used the ratio of troll vessel albacore catch in the WCPFC to IATTC statistical area and the estimated discard weight by troll vessels in the WCPFC area. The 5 year (2010–2014) mean albacore tuna catch by troll vessels in the IATTC statistical area (21 257 t) was 5.37 times that in the WCPFC statistical area (3336 t) (SPC 2015a). Using this ratio, the estimated IATTC annual mean troll vessel discard level was 2.34 t. The sum of the regional raised discard levels from using the discard rate of percent of the weight of market tuna catch produces a global raised regional discard level by troll fisheries of 3.30 t yr^{-1} (Table 3), with no estimate of error due to the discard rate used to produce the estimated raised regional levels having come from a single record.

Using the single identified estimate of a discard rate for a tuna trap fishery, Table 3 estimates raised discard levels in trap fisheries for the ICCAT and IOTC areas. A lack of data on total tuna trap fishery catch for the other 2 tuna RFMO convention areas (Harley et al. 2015, IATTC 2015a,b, SPC 2015a) prevented raising discard levels for these regions.

Comparison of raised estimates of discard levels and RFMO estimates

Annual discard levels (Table 3) estimated from fishery-level discard rate records are compared to estimates derived from tuna RFMO materials (Table 1) by gear type and RFMO area as follows:

Longline: Based on data from ICCAT (2016), longline fisheries annually discarded 1001 t (±222 t 95% CI) (Table 1). Annual discards in longline fisheries in the ICCAT convention area raised from fishery-level discard rate records were 13 554 t (±51 866 t 95% CI) (Table 3).

Purse seine: Based on data from IATTC (2015b), purse seine vessels annually discarded 7954 t (±2179 t 95% CI) (Table 1). ICCAT (2016) estimated 4672 t (±2312 t 95% CI) was annually discarded in regional purse seine fisheries (Table 1). The IATTC statistical area annual purse seine discard level raised from fishery-level records was 18 909 t (±29 213 t 95% CI) based on raising the level from a discard rate in units of tonnes of discards per 1000 t of landed tunas, and 140 811 t (±262 180 t 95% CI) when extrapolating from a discard rate in units of tonnes of discards per set (Table 3). Explained previously, the latter estimate was influenced heavily by an outlier from a study with a relatively small sample size (Amande et al. 2010). Annual purse seine discards in the ICCAT area were 9081 t (±14 029 t 95% CI) when raising from a discard rate in units of tonnes of discards per 1000 t of landed tunas, and 9679 t (±45 907 t 95% CI) when raised from a discard rate in units of percent of weight of the total catch made up of discards (Table 3).

Troll: ICCAT (2016) reported 0 discards in troll fisheries each year from 2011 to 2014 (Table 1). Extrapolating from fishery-level discard rates, troll fisheries discarded 0.05 to 0.06 t yr^{-1} in the ICCAT convention area (Table 3).

Trap: ICCAT (2016) reported 0 discards in trap fisheries each year from 2011 to 2014 (Table 1). Using a single discard rate estimate from a Portuguese tuna trap fishery produced a raised ICCAT area annual discard level of <25.5 t (Table 3).

Estimated global annual discard levels by tuna fishery gear type and comparison to Kelleher (2005) estimates

Table 4 presents estimated global annual discard levels by tuna fishery gear type raised from fishery-level discard rates and compares these estimates to tuna fishery discard estimates by Kelleher (2005). A lack of data prevented estimating raised discard levels for any tuna RFMO area for both pole-and-line and driftnet fisheries. For trap fisheries, it was possible to estimate raised regional maximum discard level estimates for 2 of the 4 tuna RFMO areas, and we assumed that there are no discards in tuna trap fisheries in WCPFC and IATTC statistical areas (Table 3). The sum of the ICCAT and IOTC maximum tuna trap fishery discard level estimates was used to estimate the global tuna trap fishery raised discard level (Table 4). Tuna trap fisheries may not occur in the other 2 regions (western and central and eastern Pacific Ocean). For example, there are Japanese and Korean coastal trap fisheries where juvenile Pacific bluefin tuna are a small (<1 % of the catch) but economically important bycatch (Suzuki & Kai 2012).

Based on data from SPC (2015a) on total landed albacore, bigeye, skipjack and yellowfin tunas in global tuna fisheries in 2014 (the most current year for which this estimate was available), and the estimate here that 265 279 t is annually not retained by global tuna fisheries produces the very rough estimate that the ratio of non-retained catch to retained market tunas is 0.056. Thus, for every 1 t of landed tuna, 0.056 t of catch is not retained, i.e. is either released alive or discarded dead. No estimate of total retained catch by global tuna fisheries (or total retained catch of non-principal market tunas) was available, preventing estimating the percent of total catch that is not retained. We are however able to estimate an upper threshold using the mean annual discard level, which indicates that <5.3 % of the weight of the total catch by global tuna fisheries in 2014 was not retained, i.e. total non-retained catch was 5.3 % of total retained market tunas plus total non-retained catch. This rate would have been lower if we had been able to account for the total retained non-market tunas. Given that landings from purse seine fisheries make up a large majority of total tuna fisheries landings (Miyake et al. 2010, SPC 2015a,b) and that a small proportion of the weight of the retained catch of purse seine fisheries comprises species other than main market tunas (Amande et al. 2008, 2010, Dagorn et al. 2013, Hall & Roman 2013), it is likely that the discard rate in total tuna fisheries is close to this upper threshold. This rough estimate does not account for discard levels from some gear types (pole-and-line, handline, driftnet) (Table 4), which are assumed to contribute nominal annual discard levels relative to purse seine and longline fisheries.

Kelleher (2005), based on tuna fishery records obtained from publications with study periods from an average year of 1999.3 (95 % CI ±0.5 yr, range 1986 to 2000), estimated that discards were 22.0 % of the total catch of longline fisheries targeting tuna and other highly migratory species, 5.1 % of tuna purse seine fisheries, 2.0 % of handline fisheries, 0.4 % of tuna pole-and line fisheries and <1 % of trap fisheries. For combined records from longline, purse seine, pole-and-line and trap tuna and other highly migratory species fisheries, discards were 14.4 % of the weight of the total catch. Kelleher (2005) states that troll, handline, fixed fish trap, and coastal gillnet fisheries have a 'low or negligible discard rate', but did not provide estimates of discard rates or levels for troll or gillnet tuna fisheries. The global estimated level of discards from tuna fisheries here was 63 % lower than the estimate of 710 903 t made by Kelleher (2005).

Table 4. Summary of estimated raised global annual discard levels by tuna fishery gear type in this study (for sources see citations in legends of Tables 3 & 5) and corresponding estimates from Kelleher (2005). ND: no data

Longline	Purse seine	Pole-and-line	Troll	Handline	Gillnet	Trap	Total
Raised estimate (95 % CI) (t)							
169 499	95 751	ND	3.3[b]	ND	ND	25.9[c]	265 279
(0–378 451)	(54 442–137 060)[a]						(52 283–478 275)
Kelleher (t)							
560 481	144 152	3121	ND	3149	ND	0	710 903

[a] For ICCAT, based on the average of annual discard levels raised from 2 discard rate estimates. For IATTC, based on raised level from t/1000 t of landed tunas discard rate estimate; was not based on the raised IATTC discard level estimated from the t/set discard rate due to there being relatively high uncertainty associated with this rate estimate

[b] Based on raising from a single discard rate record (no estimate of error)

[c] Based on raising from a single discard rate record (no estimate of error), and assumimg that there are no tuna trap fisheries in the Pacific Ocean

DISCUSSION AND CONCLUSIONS

Discard rates and levels

Extrapolating from fishery-level records, an estimated 265 279 t of catch is annually not retained by global tuna fisheries (Table 4). Pelagic longline fisheries contribute almost 64% of the non-retained catch, followed by purse seine at 36%. The other gear types for which global raised levels could be estimated (troll and trap tuna fisheries) made up only 0.01% of the total (Table 4).

These estimates were based on limited data and several assumptions and therefore should be considered a first order estimate with very high uncertainty. For example, in raising mean discard rates from a sample of tuna fisheries to estimate discard levels for the regional population of tuna fisheries, the assumed linear relationship between effort and discards and between catch and discards may not be correct (e.g. Trenkel & Rochet 2001, Kelleher 2005). Also, the sample of fisheries from which mean discard rates and error intervals were calculated and extrapolated to regional populations may not have been a random sample: the tuna fisheries for which discard rates were available for each gear type may not have been representative of global tuna fisheries of that gear type. This is particularly true for gear types where small sample sizes of discard rate records were compiled and for which the total global number of fisheries of that gear type is large (i.e. the sample was a small proportion of the population).

It is likely that combined discards from tuna fishery gear types other than longline and purse seine are much less than 1% of the weight of total tuna fishery discards. One basis for this hypothesis is that there are likely a small number of driftnet fisheries where tunas are a major component of the catch (Gillett 2011, Ardill et al. 2012). As a result, even if the high discard rates documented in some driftnet tuna fisheries (e.g. high rate of discarded sharks in an Irish albacore driftnet fishery; Rogan & Mackey 2007) are characteristic of all tuna driftnet fisheries, this still likely results in a small cumulative discard level relative to those from longline and purse seine fisheries. A second basis for this hypothesis is that there are nominal discard levels in the other tuna fishery gear types, based on quantitative estimates for troll and trap tuna fisheries (Table 4) and based on qualitative estimates for pole-and-line and handline fisheries, discussed below.

Available qualitative information suggests that nominal discard rates and levels occur in pole-and-line tuna fisheries (FAO 1997a, Gilman 2011, Anderson et al. 2012, Ardill et al. 2012). Incidental catch in Indian Ocean pole-and-line fisheries supply local markets or are consumed by crew, with very small numbers of catch discarded (Anderson et al. 2012, Ardill et al. 2012). An estimated 1 to 2 fish of non-marketable species, such as oceanic triggerfish *Canthidermis maculata*, caught when fishing at natural and artificial floating objects (versus fishing in the open ocean where catch is almost exclusively target species), were discarded per trip, based on expert opinion (Anderson et al. 2012). Similarly, available qualitative information suggests that there are nominal discards in handline tuna fisheries, and like driftnet fisheries, small-scale handlining is used largely in multispecies fisheries where tunas can be a minor component of the catch (Majkowski 2003b, Gillett 2011).

The global estimated level of discards from tuna fisheries was 63% lower than the estimate made by Kelleher (2005). Kelleher (2005) estimated that discards from fisheries for tuna and tuna-like species and billfishes contributed about 10% of total global discards based on data from 1986 to 2001. Based on the updated estimate presented here, contemporary discards from global tuna fisheries likely continue to contribute a relatively small proportion of total global fisheries discards.

An estimated 5.3% of the weight of the total catch of global tuna fisheries was not retained. This is also 63% lower than the rate estimated by Kelleher (2005) of 14.4% of the weight of the total catch, for about a decade earlier than the present study.

When comparing discard rates in units of weight of non-retained catch to the weight of the total catch, longline was the highest, for which 7.5% of the weight of the catch was discarded, followed by purse seine at 3.5%, then troll at 0.001%. One record for a trap tuna fishery estimated that discards were <1% of the weight of the total catch. Largely consistent in rank order, Kelleher (2005) estimated that discards were 22.0% of the weight of the total catch of longline fisheries, 5.1% of purse seine fisheries, 2.0% of handline fisheries, 0.4% of pole-and line fisheries and <1% of trap fisheries, and that troll and coastal gillnet fisheries have 'low or negligible' discard rates. While providing a useful metric to compare discard rates across fisheries, it is important to consider that different products, end markets and volumes are supplied by the different tuna fishery gear types. There were no quantitative data for other tuna fishery gear types to calculate comparable discard rates.

The main cause of the reduction in the estimated discard rate and level between the present study and Kelleher (2005) was a decline in the rate and level of discards by pelagic longline fisheries: 88% of the reduction in weight of discards in global tuna fisheries was due to a reduction in discards from longline fisheries. The estimated purse seine discard rate and level also declined by 31 and 34%, respectively, accounting for 11% of the reduction in the global tuna fishery discard level estimated by Kelleher (2005).

Kelleher (2005) estimated a longline discard rate, in part, using 2 analyses of observer data (Bailey et al. 1996, Lawson 1997). Bailey et al. (1996) and Lawson (1997) reported that large-scale Asian-flagged longline fleets operating in the western and central Pacific Ocean had a discard rate of about 11% of the weight of the total catch if caught sharks that were finned and carcasses discarded are not considered discarded catch. The discard rate increases to about 28% if finned sharks are considered discarded catch[1]. While Kelleher (2005) included sharks that were finned and their carcasses discarded as part of the discarded catch, this was treated as retained catch in the present study, as explained in the section 'Defining catch and discards' below. Based in part on Bailey et al. (1996) and Lawson (1997), Kelleher (2005) applied a discard rate of 40% of the weight of the catch to distant water longline fisheries, and 15% to smaller, locally based longline fisheries that lacked available estimates of discard rates. Kelleher (2005) also accounted for regional expert advice in deriving these estimated discard rates, including that discarded catch that had been damaged via depredation by sharks and whales may not have been recorded as discarded catch (K. Kelleher pers. comm.). Discards of damaged catch are currently recorded as discarded catch by some longline observer programs (e.g. SPC & FFA 2014a).

Assumptions made by Kelleher (2005), such as using an estimate for the proportion of caught sharks that were finned with carcasses discarded that was larger than determined by Bailey et al. (1996) and Lawson (1997), may also have contributed to the different longline discard rates of the present study and Kelleher (2005). The difference may also be a result of the extremely high uncertainty in the estimates due to the methods employed of raising estimates from a small sample of records, as well as uncertainty of estimates of total retained catch. There may also have been increased retention of formerly discarded species and sizes of catch. For example, retention and market demand for opah *Eumegistus illustris* and monchong *Taractichthys steindachneri* caught by the Hawaii longline fishery have increased by an order of magnitude over the past 2 decades (Chan et al. 2014).

Changes in regional and domestic regulatory measures that require or prohibit discarding and that require fishing gear or methods to increase gear selectivity to reduce catch rates of species of conservation concern may also have contributed to changes in tuna fishery discard rates and levels. For example, measures requiring purse seine full retention of tunas came into effect for WCPFC and IATTC parties in 2010 and 2009, respectively (WCPFC 2008, 2009, IATTC 2009, 2013). Bans on retaining silky and oceanic white tip sharks, which would increase discards, came into effect for WCPFC parties in 2014 and 2013, respectively, and a ban on the retention of oceanic whitetip sharks came into effect for IATTC parties in 2012 (IATTC 2011, WCPFC 2011, 2013). Recent measures restricting shark finning practices would be expected to increase discards of sharks in tuna fisheries (e.g. Gilman et al. 2015). However, in some fisheries there may have been nominal changes in shark finning rates and shark fishing mortality levels (Clarke 2013, Clarke et al. 2013). Other restrictions on gear designs and fishing methods to mitigate bycatch of species of conservation concern have also been adopted by tuna RFMOs (e.g. see reviews by Clarke et al. 2014, Gilman et al. 2014b).

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[1] Lawson (1997) analyzed observer data from 1992 to 1997 for longline fisheries operating in the western and central Pacific Ocean, finding that 42% of the weight of the catch was made up of non-target 'bycatch' species (species other than albacore, bigeye and yellowfin tunas). More than half of the bycatch was made up of sharks (primarily blue shark *Prionace glauca*). Lawson (1997) explained that several of these 'bycatch' species, including billfishes and sharks, had market value and were typically retained. In the case of sharks, for some species, such as blue shark, which was >17% of the weight of the total catch and >75% of the shark catch, only fins were retained. However, for other shark species (e.g. mako *Isurus oxyrhinchus*) the trunks were also retained in some fisheries (Bailey et al. 1996, Lawson 1997). Lawson (1997) reported a discard rate for target tuna species of 3.8%. Lawson (1997) did not, however, report an estimated regional rate for total discarded catch. Bailey et al. (1996) also analyzed longline observer data for the same region for a similar period (1983–1994). Bailey et al. (1996) estimated that Asian-flagged vessels discarded about 20% of the weight of the total non-target catch. If 3.8% of the target tuna catch was discarded, 20% of the bycatch was discarded, and bycatch was 42% of the total weight of the catch, this produces a rough discard rate of 10.6% of the weight of the total catch. Sharks were 23% of the total catch, and as stated, over 75% were blue sharks, which were typically finned and the carcass discarded.

As one example, bans on the use of wire leaders in some pelagic longline fisheries reduced catch rates of sharks, as the sharks bite through or abrade and sever leaders made of weaker materials and escape (Gilman et al. 2015, 2016a).

Degree of variability within fishery categories

The higher discard rate in shallow- versus deep-set longline fisheries may be due, in part, to differences in shark catch rates. Shallow-set fisheries can have an order of magnitude higher shark catch rate than deep-set fisheries (Clarke et al. 2006, Gilman et al. 2008). There is a growing body of literature from electronic tagging and longline catch studies indicating that pelagic species, and in some cases individual age classes and sexes of a species, partition themselves vertically, by depth as well as geospatially, by temperature, dissolved oxygen and prey availability (Musyl et al. 2003, Beverly et al. 2009). This causes the depth of longline gear soak to result in variability in susceptibility to pelagic longline capture by individual species, as well as by age class and sex (Gilman & Hall 2015).

The finding that highest discard rates occurred in associated (FAD and log) purse seine sets is likely due to associated sets having the highest species diversity and catch per set of non-tuna species, with many of these non-tuna species having low or no market value (Williams et al. 2009, Dagorn et al. 2013, Hall & Roman 2013). Furthermore, associated sets have the highest catch of small market tunas. In some regions these smaller tunas may have been discarded due to low or no market value; however, tunas compose a small proportion of the discarded catch (WCPFC 2010, Hall & Roman 2013).

Public domain RFMO materials enabled a single comparison of discard rates between regions, showing consistent estimates for IATTC and ICCAT purse seine fisheries, and low dispersion in the rate estimates within the 2 regions. This consistency in discard rates suggests that purse seine discard rates are somewhat spatially uniform, at least in these 2 regions. The relatively low coefficient of variation (CV) for the estimates derived from RFMO materials indicates that there was small inter-annual variability in discard rates for the recent sampled years. This suggests that raised discard estimates based on a sample of purse seine fishery records will not introduce a large degree of uncertainty by not having balanced representation of all regions and all years in the study period.

There was high dispersion in many estimates of discard rates from fishery-level records. Longline discard rates had CVs of 74% (number of discarded organisms per 1000 hooks), 155% (percent of the weight of the total catch) and 106% (percent of the number of the total catch). Purse seine discard rates had CVs of 62% (tonnes discards per t of landed tunas), 52% (percent of the weight of the total catch) and 150% (tonnes per set). The high degree of variability relative to the mean discard rates based on fishery-level records is likely due to averaging rates of records from fisheries making different longline and purse seine set types.

As a result of the observed high dispersion in discard rates within some tuna fishery gear types, including by set type for purse seine fisheries and for shallow- versus deep-sets for longline fisheries, raising estimated levels based on rates from a small sample of fishery-level records as conducted here can reduce the accuracy of estimates.

Alternative units for discard rates

Numerous units have been used for effort and for discard rates in tuna fisheries (Table 3). Discard rates have used units of number or weight of discards per: unit of effort, total catch, total catch of principal market tunas, total retained catch, and total retained catch of principal market species (Hall 1996, FAO 1997b, Borges et al. 2001, Kelleher 2005, Rogan & Mackey 2007, Bartram et al. 2010, NMFS 2016). Standardizing units for discard rates would improve opportunities to pool and compare records between and within fisheries (Gilman et al. 2016b).

In some fisheries, especially multispecies fisheries with numerous retained market species, use of reported landings of a single principal market species or target species may have a weaker correlation than using total landings or total catch (Matsuoka 1997, Kelleher 2005).

Comparison of discard levels estimated from raised fishery-level rates vs. from RFMO materials

Few comparisons were possible between regional discard levels estimated from raising fishery-level records and levels derived from RFMO public domain materials. For longline fishery discards in the ICCAT region, the lower mean estimate from ICCAT materials was likely due, in part, to no teleosts other than tunas and billfishes recorded as having been discarded for each year in the study sample, as well as no data for discarded rays (ICCAT 2016). The raised estimate was based on only 3 fishery-level records, with very high variability relative to the mean discard rate estimate (CV = 155%). There is low certainty in both discard estimates as a result of these data quality issues.

As with the ICCAT longline estimates, both the IATTC and ICCAT purse seine discard levels estimated from raising fishery-level discard rate records had large dispersion in estimates. In particular the IATTC estimate derived from extrapolating from a discard rate in units of tonnes of discards per set had very high variability (CV = 150%) due to inclusion of an outlier from a study with a relatively small sample size.

Based on ICCAT public domain materials, discard levels in ICCAT troll and trap tuna fisheries were reported to be 0 from 2011 to 2014 (ICCAT 2016). ICCAT does not require onboard observer coverage of troll or trap tuna fisheries (or any other gear type besides purse seine and longline) (reviewed in Gilman et al. 2014b). Therefore, discard data from these gear types reported to ICCAT are likely from logbook data, which have high uncertainty (see section 'Relative certainty of alternative sources of discard data' below). The raised discard levels from fishery-level records resulted in very low annual discard levels in regional ICCAT convention area troll and trap tuna fisheries, but these were based on a single discard rate record for each gear type. The section 'Quality of fishery-level records' provides a more detailed discussion of discards in troll and trap tuna fisheries.

Quality and availability of RFMO public domain data

Table 5 summarizes the availability of amalgamated data on discard levels from tuna RFMO public domain materials. Table 5 also identifies the availability of information on catch and effort by gear type, needed to raise discard rates regionally. Several large gaps in information from public domain tuna RFMO materials (Tables 1 & 5) prevented estimating regional or global tuna fishery discard levels. The tuna RFMOs lack observer data for tuna fishery gear types other than purse seine and longline tuna fisheries (Gilman et al. 2014b). Most tuna RFMOs also lack basic catch and effort data for these other gear types (Table 5). Improved monitoring of tuna fisheries to fill these gaps would support producing more robust estimates of discards. Improving observer data fields and data collection protocols, where needed, would also contribute to more effective monitoring and management of discards (Gilman & Hall 2015).

Of the tuna RFMOs, ICCAT has produced the most comprehensive publicly available discard data for purse seine and longline fisheries (Tables 1 & 5). WCPFC, through its science provider SPC, is the custodian of observer data for purse seine and longline fisheries of the western and central Pacific Ocean, where more than half of global tuna landings occur (ISSF 2012, 2015, SPC 2015a). However, unlike ICCAT, WCPFC and SPC have not produced public domain summaries of amalgamated data on discards (Tables 1 & 5). Making amalgamated discard data

Table 5. Availability of tuna RFMO public domain amalgamated data on annual discard levels and information on regional catch and effort by gear type, needed to extrapolate discard rates regionally (IOTC 2013, 2016a,b, Harley et al. 2015, IATTC 2015a,b, SPC 2015a,b, ICCAT 2016, WCPFC 2016). IA: IATTC; IC: ICCAT; IO: IOTC, W: WCPFC

	Longline	Purse seine	Pole-and-line	Troll	Handline	Gillnet	Trap
Total effort[a]	IA[b], IO, W	IA[c]	W				
Weight of catch	IC, IO	IC, IO	IC, IO	IC, IO	IO	IO	IC, IO
Weight of catch of market tunas	IC, IO, W	IC, IO, W	IC, IO, W	IC, IO, W	IO	IO	IC, IO
Weight of retained catch	IA[d], IC	IC	IC	IC			IC
Weight of retained market tunas	IA, IC, W	IA, IC, W	IA, IC	IA, IC			IC
Weight of discards (total non-retained catch)	IC[e]	IA[c], IC[e]	IC[e]	IC[e]			IC[e]

[a] WCPFC (2016) reported purse seine effort in a unit (number of days fishing and searching) that did not support regionally raising discard rate estimates (Table 4)

[b] Effort is for a subset of IATTC longline fisheries, by vessels flagged to China, Japan, Korea, French Polynesia, Taiwan and USA (which together represent >97% of total effort; N. Vogel pers. comm.)

[c] For IATTC large purse seine vessels only (vessels with carrying capacity >363 t)

[d] Excludes retained rays (N. Vogel pers. comm.)

[e] See the section 'Discussion; Discard rates and levels' for a discussion of discard data of ICCAT (2016), which reported no discards by pole-and-line, troll and trap fisheries, no discarded non-tuna teleosts or sharks in purse seine fisheries, and contained no data on ray purse seine discards

publicly available from WCPFC and other existing tuna RFMO materials would contribute to improved future efforts to estimate discards in regional and global tuna fisheries.

Quality of fishery-level records

Relative to purse seine and longline fisheries, there were extremely small sample sizes to support estimates of discard rates for pole-and-line, troll, handline, gillnet and trap fisheries. Most of the rates for these gear types were based on single estimates, preventing estimates of error. There were no records found on discards for any pole-and-line or handline tuna fishery.

Consistent with the recommendations to address poor data quality available from tuna RFMO public domain materials, there is a need for improved data on discard rates in individual tuna fisheries. There was relatively better data quality on discards in longline and purse seine tuna fisheries. These are the main gear types supplying global tuna products and very likely contribute the largest proportions of discards relative to the other tuna fishery gears. Therefore, improved data quality on discards is a highest priority for longline and purse seine tuna fisheries.

Relative certainty of alternative sources of discard data

The certainty of estimates of discards may be highest for those derived from observer data, lower for scientific surveys and control groups of research experiments, and lowest for logbook program data and fisher interviews/surveys. Scientific surveys and control groups of research experiments may employ gear and fishing methods that results in discard rates and levels that are not characteristic of a fishery, such as from fishing at grounds not typical of the fishery in order to maximize relative abundance and concomitant sample sizes of a taxa of interest to the study. Data from logbook programs are of low certainty as crew may lack the time and training to meet needed data reporting protocols (e.g. inaccurate species identification; Walsh et al. 2007), and may have an economic or social disincentive to record accurate data (FAO 2002, Walsh et al. 2002). Information obtained from fisher and other social survey methods is of relatively low certainty (Gilman et al. 2010, Podsakoff et al. 2012). Data from observer programs also have sources of uncertainty, including from an 'observer effect' where crew may implement methods and gear designs that deviate from conventional practices when an observer is not assigned to their vessel, and where low coverage rates and unbalanced sampling designs can result in low certainty in estimates (Hall 1999, Lennert-Cody 2001, Lawson 2006, Amande, et al. 2012).

Defining catch and discards

Inconsistent definitions of catch and discards complicate pooling records and reduce the certainty of estimates. Some records may have included as part of the catch organisms that crew released in the water, while others may consider these to be pre-catch and not part of the catch (ICES 2005, Gilman et al. 2013). For example, for purse seine sets made on aggregations of tunas and other species associated with dolphin schools or with live large marine organisms (whale sharks, manta rays, whales), where crew removed dolphins or other large organisms from the net in the water, there may have been inconsistent categorization of these interactions by different monitoring programs, some including them as part of the catch and others not. For example, Hall & Roman (2013) did not include as part of the catch interactions with dolphins for purse seine sets on schools of dolphins for dolphins that crew released alive using the backdown maneuver. Released mobulids, however, were included as part of the catch. This was based on the rationale that released dolphins were expected to survive while released mobulids were predicted to die (M. Hall pers. comm.). Similarly, IATTC (2015a,b) included records of purse seine dead discarded sea turtles and dolphins but not records of live released turtles and dolphins or dolphins released during backdown.

There may also be inconsistent treatment of events where an organism freed itself from the gear (e.g. threw the hook, broke the line or became untangled from line). Some monitoring programs may categorize these as a catch event, while others consider it to be pre-catch escapement (Gilman et al. 2013). For example, records of seabird captures in the US observer program database for Hawaii pelagic longline fisheries include events where seabirds were observed hooked or entangled in gear during retrieval and the seabird escaped or fell from the gear prior to being brought on deck or handled by crew (Gilman et al. 2014a). Conflicting with this protocol, IATTC directions for observers when an organism falls from a hook, escapes or falls back into the sea is to not record it as part of the catch (IATTC 2014, Gilman & Hall 2015). Moreover, for example, organisms released from longline gear in the water, such as when a large hooked shark or entangled leatherback sea turtle is brought to the side of the vessel where the crew cuts the branchline, are recorded as released catch events by some observer programs (e.g. Hawaii longline; NMFS 2010) but not others (Gilman & Hall 2015). Similarly, organisms that were partially depredated by predators during the gear soak, where the portion of the organism remaining on the gear was landed on deck and discarded, may inconsistently be counted as part of the discarded catch depending on how much of the organism was retrieved upon gear haulback (Gilman et al. 2006b, 2008).

The definition of discards used here may cause the findings to be misinterpreted as referring only to dead discards. This incorrect interpretation would overestimate fishing mortality as a proportion of live released catch survive (e.g. Musyl et al. 2011, 2015). Most data sources do not identify the condition of non-retained catch, and post-release mortality rates are not well understood in most fisheries and for most species. These limitations make defining discards as the combination of live released and dead discarded catch the best available option.

Sharks with fins removed and carcasses returned to the sea were categorized as part of the retained catch. The rationale is that the shark carcass is offal following processing of the fish, just as other processed fish are treated as retained despite a portion of the fish (heads, gills and viscera) being returned to the sea following processing. Kelleher (2005), however, included finned sharks as part of the discarded catch. His rationale was that a large part of the edible portion of the fish is not retained, and this increases attention to the social issue of waste resulting from shark finning.

As explained in 'Methods', the definition of discards used here excluded various additional sources of organic matter that crew routinely return to the sea, including lost and discarded bait, discharges of chum and offal, and catch discarded at port. Furthermore, collateral, indirect mortalities were not included in the discard estimate, as discussed in the following section.

Unaccounted 'cryptic' sources of fishing mortality

Several cryptic or not readily detectable sources of fishing mortality were not included in the discard estimate. These components of fishing mortality are typically not accounted for due to a lack of adequate data, and for some components, a lack of accurate estimation methods (ICES 2005, Broadhurst et al. 2006, Gilman et al. 2013, 2016b, Uhlmann & Broadhurst 2015). These cryptic, not readily detectable sources of fishing mortality are: (1) pre-catch losses, where catch dies from the fishing operation but is not brought onboard upon gear retrieval; (2) ghost fishing mortalities when abandoned, lost or discarded fishing gear continues to catch and kill organisms; (3) post-release mortalities of catch that was retrieved and released alive but later died as a result of injuries sustained during the interaction; (4) collateral mortalities indirectly caused by various effects of fishing, such as from an organism avoiding gear, and from habitat degradation such as anoxia from fishery discards and habitat loss caused by fishing gear; (5) losses due to synergistic effects of multiple sources of stress and injury from fishing operations; and (6) mortalities from cumulative stress and injury caused by repeated sub-lethal fishery interactions (Chopin et al. 1996, ICES 2005, Gilman et al. 2013).

Depredation, the partial or complete removal of catch from the gear by predators, occurs in numerous fisheries. For instance, sharks and cetaceans depredate catch from pelagic longlines, and predators such as crabs and octopuses depredate catch from traps and gillnets. Captured organisms may not be present upon gear haulback because a predator completely removed it from the gear; this is a form of pre-catch fishing mortality (Visser 2000, Gilman et al. 2008, 2013, Ramos-Cartelle & Mejuto 2008).

Sharks, sea turtles and other organisms can become entangled in the appendages and surface components of FADs used in purse seine and other tuna fisheries (e.g. Filmalter et al. 2013). This is not accounted for as part of the catch. This can occur in both active and derelict FADs, constituting pre-catch and ghost fishing mortalities, respectively.

Ghost fishing is understood to be most problematic in gillnets, traps and other passive fishing gears, where the capture process relies on the movement of organisms into the gear (Gilman et al. 2016b). When derelict nets become entangled on 3-dimensional objects, and are in a location where environmental conditions, such as currents and weather, and interactions with other fishing gear do not damage the gear, including in very deep water, gillnets can maintain high ghost fishing catch rates for years (Kaiser et al. 1996, Matsuoka et al. 2005, Brown & Macfadyen 2007). While the ghost fishing catching efficiency of derelict gillnets on flat substrate in relatively shallow water declines rapidly over a few days, they can retain a small proportion (ca. 5%) of its original catching efficiency for years (Kaiser et al. 1996). Organisms caught in derelict fishing gear can attract scavengers, which subsequently are caught, contributing to long-term ghost fishing efficiency due to this self-baiting (Kaiser et al. 1996, Matsuoka et al. 2005, Gilman et al. 2016b).

As discussed in the previous section, a portion of live released organisms survive. Post-release survival rates are influenced in part by the level of stress while captured before being handled by crew, environmental conditions (e.g. air temperature, sea surface temperature, thermocline steepness), and handling and release methods (Davis 2002, Musyl et al. 2011). The amount and location of fishing gear remaining attached when released also can significantly affect post-release survival rates (e.g. for longline-caught-and-released sea turtles; Parga 2012). The probability of post-release mortality varies by species, and by size and sex within a species (Broadhurst et al. 2006, Ryder et al. 2006). Information to support robust estimates of post-release fishing mortality exists for only a small number of taxonomic groups and tuna fishery gear types (Stevens et al. 2000, Weng et al. 2005, Moyes et al. 2006, Campana et al. 2009, Musyl et al. 2011, Poisson et al. 2014).

Drifting FADs used in purse seine tuna fisheries, which aggregate biomass from a surrounding area, provide an example of a collateral mortality source. FADs may alter the survival probability of organisms associating with the floating object by altering their spatial distributions, modifying their diet composition and changing their behavior, such as horizontal movements and diel vertical migration cycles (Marsac et al. 2000, Hallier & Gaertner 2008, Dagorn et al. 2010). In some regions, FADs also have the potential to trap organisms in areas of low productivity (Marsac et al. 2000, Hallier & Gaertner 2008).

There are a few examples of management programs for tuna fisheries that monitor some typically unaccounted sources of fishing mortality. For example, some observer programs collect data on indicators of degree of injury (condition and vitality) of organisms that are released alive, which can inform estimates of the probability of post-release survival (e.g. in longline tuna fisheries; SPC & FFA 2014a,b). Observer programs of some fisheries record abandoned, lost and discarded fishing gear, which can be used to estimate ghost fishing mortality rates and quantities (Gilman 2015, Gilman et al. 2016b).

To produce higher certainty estimates of discards, management authorities should account for these not readily detectable sources of fishing mortality. Improvements in methods to estimate unaccounted fishing mortality sources and in monitoring methods will likewise contribute to improved certainty of discard estimates.

Main conclusions and next steps

An estimated 265 279 t of catch is annually not retained by global tuna fisheries, which was 5.3% of the weight of the total catch. In addition to concern over the large volume of discards, the composition of tuna fishery discards, including at-risk taxa, warrants attention (Gilman 2011, Clarke et al. 2014). Pelagic longline and purse seine fisheries contributed 64 and 36% of the total non-retained catch, respectively. Other tuna fishery gear types made up only 0.01% of total discards. The discard estimates were highly uncertain due to extremely limited data quality, including small sample sizes, and employment of methods to raise estimates that were necessarily based on various assumptions.

Kelleher (2005) estimated that discards from fisheries for tuna and tuna-like species and billfishes contributed about 10% of total global discards. Contemporary discards from global tuna fisheries likely continue to contribute a relatively small proportion of total global fisheries discards.

The discard rate and level estimated here were both 63% lower than estimates by Kelleher (2005), largely due to a decline in the estimated discard rate by longline tuna fisheries. The longline discard rate decline was due, in part, to the use of different definitions of discards, and a possible overestimation by Kelleher (2005) of the proportion of caught sharks that were finned and the carcasses discarded. The decline in longline discard rate also possibly resulted from increased retention and gear selectivity.

Discard rates were higher in shallow-set versus deep-set longline tuna fisheries. The higher discard rate in longline shallow-sets may be due, in part, to the higher shark catch rate, where shallow-set fisheries can have an order of magnitude higher shark catch rate than deep-set fisheries, and where sharks can make up over half of the catch in shallow-set pelagic longline (Clarke et al. 2006, Gilman et al. 2008).

Higher discards occurred in purse seine associated FAD and log sets than in free school and dolphin sets. Associated sets have the highest species diversity and highest catch rate of non-tuna species and small tunas, which have low or no market value in some regions (Williams et al. 2009, Dagorn et al. 2013, Hall & Roman 2013).

The study also revealed the state of availability and quality of information on discards in tuna fisheries. There were very few records documenting discard rates, in particular, for tuna fishery gear types other than purse seine and longline. Improved data for purse seine and longline tuna fisheries are the highest priority as these gear types contribute >99.9% of global discards from tuna fisheries. Major gaps in information from public domain tuna RFMO materials prevented estimating regional or global tuna fishery discard levels from these sources for any individual tuna gear type. Filling gaps in monitoring of all tuna fishery gear types to enable robust estimates of discards, improving observer data fields and data collection protocols where needed to support effective monitoring and management of discards, and making publicly available amalgamated discard data from available tuna RFMO resources will enable the use of this information by a broader group of scientists and managers, and contribute to improved future estimates of discards in regional and global tuna fisheries.

In addition to improvements in tuna fisheries monitoring, employing standardized definitions of discards and standardized units for discard rates will improve the ability to make comparisons between fisheries and pool data for regional and global estimates. Furthermore, several sources of fishing mortality are not accounted for in estimates of discards. These include pre-catch losses, post-release moralities, ghost fishing mortalities, mortalities from repeated sub-lethal interactions, and losses from indirect effects of fishing. Improvements in monitoring to supply adequate data and, for some components, developing accurate estimation methods are needed.

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