ICES Journal of
Marine Science

ICES Journal of Marine Science (2021), https://doi.org/10.1093/icesjms/fsab135

Original Article

Pre-catch and discard mortality in Northeast Atlantic herring and mackerel fisheries: consequences for stock estimates and advice

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Tenningen, M., Zimmermann, F., and Enberg, K. Pre-catch and discard mortality in Northeast Atlantic herring and mackerel fisheries: consequences for stock estimates and advice. – ICES Journal of Marine Science, 0: 1–12.

Received 27 November 2020; revised 25 June 2021; accepted 29 June 2021.

Unaccounted mortality caused by discarding or pre-catch losses is a major challenge for fisheries management. In pelagic fisheries, a considerable proportion of catches may be lost due to intentional release of unwanted catch (slipping) or net bursts (fishing net tears due to the weight of the catch). Here we review and estimate ranges of discard and pre-catch mortality for two important pelagic fisheries, the Northeast Atlantic (NEA) mackerel and Norwegian spring spawning (NSS) herring, and explore the effects on stock estimates and catch advice. We show that mortality caused by discarding, slipping, and net bursts is unknown but probably corresponds to a considerable percentage of total registered catches. Including estimated unaccounted mortality into assessment models leads to underestimation of the stock levels by 3.7–19.5% and 2.8–6.8% for NEA mackerel and NSS herring, respectively, corresponding to up to several million tonnes of fish that die annually due to fishing without being landed. If discard and pre-catch mortality were eliminated, allowed catches could increase by 10–20%. We demonstrate that unaccounted mortality in pelagic fisheries may be substantial, affecting stock estimates and catch advice. This may undermine the sustainable management and efficient use of pelagic resources.

Keywords: MSY, pelagic, SDG14, slipping, sustainable catch, unaccounted mortality

Introduction

Unaccounted fishing mortality represents a significant share of global fisheries production and undermines the United Nations' Sustainable Development Goals (SDGs) to efficiently use marine resources and secure food supply (Zeller *et al.*, 2018; Costello *et al.*, 2020). Discard and pre-catch mortalities are important sources of unaccounted mortality, and are therefore a major concern for sustainable fisheries management, as they may lead to biased stock assessment if not accounted for (Figure 1) (Crowder and Murawski, 1998; Gilman *et al.*, 2013). Discarding refers to animals that are caught and released back to sea after being brought to deck and is mainly associated with mixed demersal fisheries (see also Box 1: Definitions and terminology). Pre-catch losses are animals that die following encounter with the fishing gear but are not retained by it, likely causing considerable unaccounted mortality in small pelagic fisheries (Gilman *et al.*, 2013; Pérez Roda *et al.*, 2019). Pre-catch losses can include fish escaping through meshes during haul-in (Suuronen *et al.*, 1996a), unwanted catches released before brought on board (slipping) (Lockwood *et al.*, 1983; Stratoudakis and Marcalo, 2002), and fish lost when nets burst (Misund and Beltestad, 1995). Common reasons for discarding and slipping are economic incentives such as to improve value of catch shares by releasing low value individuals in favour of more valuable individuals (high-grading), compliance with regulations on minimum landing size of target species, and quota limitations on

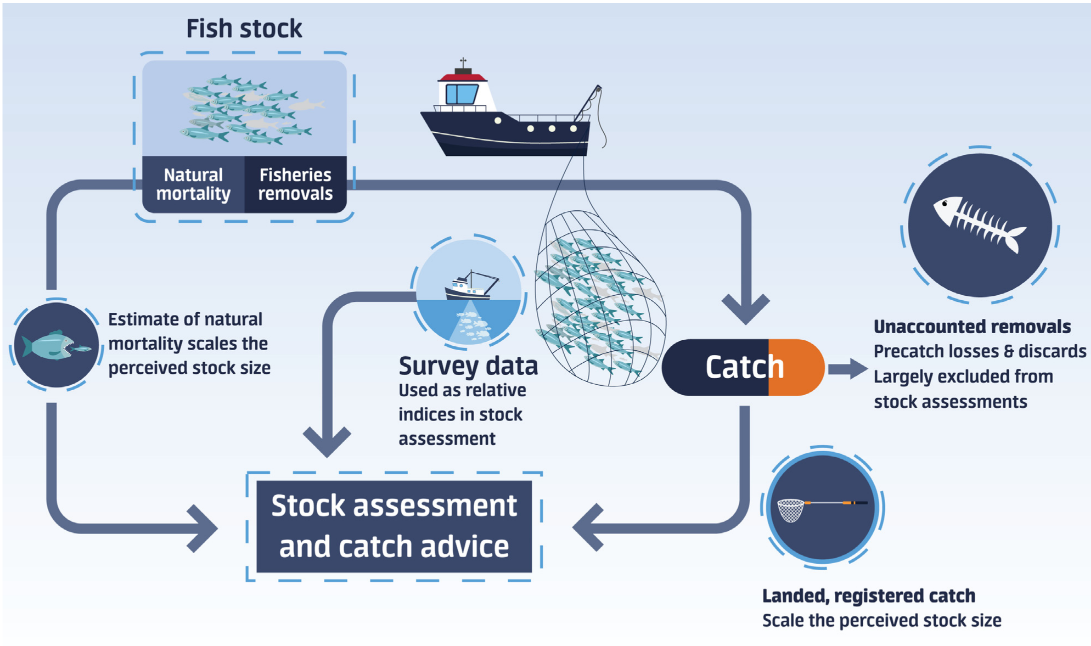

Figure 1. Conceptual representation of the stock assessment process and the role unaccounted removals such as pre-catch losses and discards play in the estimation of perceived stock size.

target or non-target species (Catchpole *et al.*, 2005; Bellido *et al.*, 2011).

Many countries have introduced measures to reduce unwanted catches and discards (Johnsen and Eliasen, 2011; Karp *et al.*, 2019). These commonly include combinations of regulatory measures such as discard bans and real-time area and seasonal closures, technical measures to increase gear selectivity, and monitoring and control by fisheries authorities (Kennelly and Broadhurst, 2002; Suuronen and Sarda, 2007; Suuronen and Gilman, 2020). Consequently, discards have been reduced by 50% since the peak in the late 1980s and the most recent estimate of annual global discards is about 9 million tonnes, representing 10% of the total annual catch (Zeller *et al.*, 2018; Pérez Roda *et al.*, 2019). Pre-catch losses, on the other hand, are largely unknown because fish are lost or released in water, making quantification challenging (Broadhurst *et al.*, 2006; Gilman *et al.*, 2013). The lack of sufficient empirical data on pre-catch losses pose therefore a major bottleneck for determining the degree and implications of unaccounted mortality. Although many stock assessment models are capable of including unaccounted mortality, the underlying data quality is often inadequate (Punt *et al.*, 2006; Fernandez *et al.*, 2010; Cook, 2019). For many fish stocks, pre-catch and discard mortality rates vary between years, fishing fleets, and size classes, and unless this information is available and considered when including data in the assessment, the result may be more uncertain estimates of year class sizes, catch predictions, and advice (Punt *et al.*, 2006; Dickey-Collas *et al.*, 2007; Cook, 2019).

Even in the data-rich, well-managed fisheries for Northeast Atlantic (NEA) mackerel (*Scomber scombrus*) and Norwegian spring spawning (NSS) herring (*Clupea harengus*), data on unaccounted mortality are highly limited and the potential effects on stock assessment are unknown. The stock estimates in the assessments of the NEA mackerel and NSS herring are determined by catch and survey data that inform about the cohort sizes and trends in the stock abundance. In the current stock assessment, no discards are included in the NSS herring assessment, while a 0.3% discard rate is included in the NEA mackerel assessment (ICES, 2019b).

Prior to 2005, unaccounted mortality due to misreporting, slipping, and discarding in the mackerel fishery is considered to have been extensive (ICES, 2013a). It was estimated that the real landings and discards were between 1.7 and 3.6 times higher than reported (Simmonds *et al.*, 2010). An evaluation of the sensitivity of the assessment to past uncertainties in the estimates of removals showed significantly higher spawning stock biomass (SSB) values when misreporting scenarios were added to the data (ICES, 2013b). Except for a study on the effect of escapee mortality in Baltic sea herring fishery on estimates of recruitment, stock biomass, and overall fishing mortality (Rahikainen *et al.*, 2004), to our knowledge, no studies have been published on discard and pre-catch mortality and their effects on herring assessment. Stock assessment models typically scale stock abundance directly with the perceived total mortality from catch data and natural mortality parameters. Consequently, underestimating total mortality leads to underestimated stock biomass and, thus, possibly biased management advice.

In this study, we focus on discard and pre-catch mortality, and their combined effects on stock assessment in pelagic fisheries. Globally, the Food and Agriculture Organization (FAO) (Pérez Roda *et al.*, 2019) estimated a discard rate of 6% in pelagic fisheries corresponding to 2.2 million tonnes fish being discarded annually. The reason for the low discard rates is that pelagic schools are often relatively uniform in species and size compositions, and in many fisheries, there may be little focus on quality and catch value is low (FAO, 2020). However, in pelagic fisheries even relatively low rates of discards result in large quantities of fish being lost because of the large catch volumes and the high mortality associated with small pelagic fish released or lost during the capture process (Lockwood

Box 1. Definitions and terminology.

	(Terms in italics are defined elsewhere in the box.)
Fishing mortality	The sum of all fishing-induced mortalities caused directly through *catch*, or indirectly because of contact with or avoidance of fishing gear. Can include the following subcomponents: official *landings*; illegal, misreported, and unreported *landings*; *discard* mortality; and *pre-catch mortality* (ICES, 1995; Chopin *et al.* 1996), but commonly associated with official *landings* for stock assessment purposes.
Catch	The biomass of marine resources that are *landed*, *discarded*, consumed on board, or used as bait (Pérez Roda *et al.*, 2019). Does not include *pre-catch losses*.
Landings or landed catch	The retained *catch* that is landed for use ashore (Pérez Roda *et al.*, 2019). Typically considered identical with registered *landings* used in stock assessment estimates. Illegal, misreported, and unreported *landings* are often unknown and not used in stock assessment estimates.
Unaccounted fishing mortality	All *fishing mortality* not included in official *landings* and stock assessment estimates.
Discards or discarded catch	The portion of the total *catch*, which is brought onboard but not landed, i.e. dumped at sea. The discarded animals may be dead or alive (Pérez Roda *et al.*, 2019).
Discard rate	The proportion of the total *catch* that is discarded, expressed either as proportion (0–1) or as a percentage (0–100%). The formula to calculate *discard rate* is as follows: Discard rate = Discards / (Landings + Discards) (Pérez Roda *et al.*, 2019).
Pre-catch losses/mortality	Fish that die from the fishing operation but are not brought onboard. Includes fish that die following intentional released prior to being retrieved onboard (*slipped catches*), *net burst*, or other interaction with the fishing gear (Chopin and Arimoto, 1995; Broadhurst *et al.*, 2006; Gilman *et al.*, 2013). Typically, part of the *unaccounted mortality*.
Slipping or slipped catch	Fish deliberately released from nets prior to being brought onboard for commercial or safety reasons, dead or alive (Pérez Roda *et al.*, 2019).
Slipping rate	The proportion of the total catch that is slipped, expressed as proportion (0–1) or percentage (0–100%).
Net burst	An incident where the fishing net tears due to the weight of the catch. The whole catch or a large proportion of it is usually lost.

et al., 1983; Chopin and Arimoto, 1995; Suuronen, 1995; Broadhurst *et al.*, 2006; FAO, 2020). The discard rates reported by the FAO do not account for pre-catch losses, which are likely more relevant than discards in pelagic fisheries (Pérez Roda *et al.*, 2019). Furthermore, even if reported discards are generally low in pelagic fisheries, high rates have been estimated in specific fisheries. Slipping and discard rates in purse seine fisheries targeting small pelagic species have been estimated to be up to 69% of monitored catch weight in Portugal (Stratoudakis and Marcalo, 2002), with large seasonal and spatial variation, including 34% in Madeira (Tejerina et al., 2019), 13% in the Azores (Fauconnet *et al.*, 2019), and 27% in Algarve (Borges *et al.*, 2001). Unaccounted mortality from pre-catch losses and discarding represents, thus, a source of uncertainty that adds to the specific challenges of managing small pelagic fisheries (Siple *et al.*, 2021).

Atlantic mackerel and herring account for 3% of global marine finfish production (FAO, 2020) and are two of the most fished species in European waters. Mackerel is managed as a single stock, the NEA mackerel, and is caught from the northern Norwegian Sea to waters off the Portuguese coast. Herring consists of several stocks, where the NSS herring is the largest (ICES, 2019a). NEA mackerel and NSS herring are well-regulated, very data-rich stocks whose combined annual catch in 2018 exceeded 2.2m t (ICES, 2019a). The stocks are widely distributed and targeted mainly by midwater trawl and purse seine (ICES, 2019b). Discarding of NSS herring and NEA mackerel is forbidden but slipping from purse seines is allowed in the fishing waters of the European Union (EU) and Norway, provided that a set of conditions are followed (EU, 2013; NSFR, 2014). Fish must be released, or the release process started, before a fixed amount of net has been hauled in to avoid detrimental fish crowding densities. In EU waters, the quantities slipped must be reported, while in Norway, no such requirement exists. Despite the discard ban and regulations on slipping from purse seines, anecdotal information indicates that discarding and illegal slipping takes place and is seldom reported (EFCA, 2019; Pérez Roda *et al.*, 2019; ICES, 2019b). Recent research also suggests that a large proportion of slipped fish may die despite regulations that intend to promote survival following slipping (Anders *et al.*, 2019). Unlike many other small pelagic fisheries, NEA mackerel and herring fisheries are quality focused and prices tend to depend on the size of the fish (Zimmermann and Heino, 2013). Mixed species schools and excessively large catches that exceed load capacity or fishing quotas also incentivize for slipping. In addition, large catches can exceed the capacity of gear, and if parts of the catch are not released at an early stage of the catch process the net may burst, resulting in large quantities of fish dying (Misund and Beltestad, 1995). This is a known problem in the Norwegian purse seine fisheries for NSS herring and occurs also in the NEA mackerel fishery. Consequently, fishing grounds are often temporarily closed to avoid further net burst incidents.

The aim of our study is to assess the current knowledge on discard and pre-catch losses in Atlantic herring and NEA mackerel fisheries and explore potential impacts on stock estimates and catch advice. We reviewed the existing empirical information in the literature and developed likely scenarios with different quantities and age distributions of discards and pre-catch losses in both fisheries that were tested within the stock-specific assessment models. Questions we aim to address are: (i) how reliable are the available estimates of discard and pre-catch mortality (i.e. is the mortality low or are the data lacking?); (ii) are the potential impacts on assessment significant; and, subsequently, (iii) is there a need to invest more efforts in reducing and quantifying unaccounted mortality in these fisheries?

Methods

Literature review and range of likely mortality rates

To compile all available information on discards and pre-catch losses in the NEA mackerel and NSS herring fisheries, we included peer-reviewed articles, reports, and anecdotal information from fisheries authorities. The data include information on discards and pre-catch losses in mackerel and herring fisheries in the NEA. First, we summarized available information on discard and pre-catch loss rates, and second, on mortality rates of the discarded or lost fish and possible causes of mortality. Based on the available information, we estimated the range of discard and pre-catch mortality and created possible scenarios for currently unaccounted mortality in NEA mackerel and NSS herring fisheries.

Pre-catch loss and discard rates

Four peer-reviewed articles and five reports with estimates of discards or slipping rates in European herring and mackerel fisheries were identified (Table 1). The estimated discard and slipping rates ranged between 0% and 11% of the monitored catches. Most studies used on-board observers and were carried out between 1993 and 2012. Focus was mainly on discarding in pelagic trawl fisheries, while two studies specifically estimated slipping rates; mackerel and herring slipped by Dutch freezer trawlers (Borges *et al.*, 2008) and mackerel slipped by Norwegian purse seiners (Vold *et al.*, 2013). Net burst rates in NSS herring fisheries were estimated in one study in 1985–1987 (Beltestad and Misund, 1989). No estimates of mesh selection rates or other sources of pre-catch losses were found.

The highest levels of discarding, 11% of the monitored catch weights, were observed in the Scottish trawl fishery for "maatje" herring (herring caught right before their first spawning [May–June] when the fat content is at a specific level and the fish are highly valuable) in 2001 (Pierce *et al.*, 2002) and in the mackerel fisheries in the North western waters between 2010 and 2012 (Anon, 2014). Mackerel was generally discarded and slipped more commonly than herring (Enever *et al.*, 2007; Borges *et al.*, 2008), estimated discard and slipping rates ranging from 1.8% to 11% (Table 1).

In the EU, all member states are obliged to collect, manage, and provide fisheries data including discards for scientific advice. Most of the discard and slipping estimates available are based on data collected under this data collection framework. However, about 50% of NEA mackerel and 95% of NSS herring are caught by countries outside the EU (Norway, Russia, Faroe Islands, and Iceland) (ICES, 2019b). For these fisheries, there have been no dedicated observer-based studies on discards or slipping rates. Norwegian vessels catch about 50% of the NSS herring and 20% of the NEA mackerel quota, and the majority (∼80%) is taken by purse seine (Fiskeridirektoratet, 2021). Slipping is the main method for releasing unwanted catches from purse seines. Data on slipping frequencies are available from one short-term study that aimed to investigate the practical implementation of revised slipping regulations in the mackerel fishery (Vold *et al.*, 2013). Out of 21 monitored purse seine sets 3 sets involved slipping. Based on discussions with the Norwegian Coast guard (pers. comm J. Høgset) and their reports from the mackerel fishing grounds between 2008 and 2018, slipping and net bursts occur with varying rates from year to year. More incidents are observed when schools are large and dense, and when mackerel and herring are caught in mixed schools. Between 0 and 5 incidents have been reported and/or filmed annually since 2008. In single events, several hundred tonnes, sometimes exceeding 1000 t, of fish can be lost or slipped. Not all incidents are detected by the coast guard and there are indications that their presence reduces the number of slipping events.

Table 1. Discard and slipping rates of mackerel and herring in NEA fisheries.

Species	Source	Fishery	Discard rate %	Slipping rate %	Years	Sampling effort
Scomber scombrus	Pierce *et al.* (2002)	Scottish trawl	4	Included in discards	2001	1% of annual fishing effort
	Ulleweit *et al.* (2010)	German pelagic freezer trawlers	2.8	NA	2002–2008	5% of annual fishing hours
	Enever *et al.* (2007)	English and Welsh trawl	3.7×10^6 †	NA	2003–2005	8–32 hauls annually
	Morizur *et al.* (1996)	UK trawl	9	Included in discards	1993–1994	36 hauls in total
	Napier *et al.* (1999)	Northern EU waters; trawl and purse seine	2.7	Included in discards	1996	193 hauls
	Borges *et al.* (2008)	Dutch freezer trawl	9	1	2002–2005	4–9% of annual fleet activity
	Vold *et al.* (2013)	Norwegian purse seine	NA	4.2 (of catch weight) 14.3 (of sets)	2011–2012	21 sets in total
	Quirijns and Pastoors (2014)	North Sea	4	NA	2010-2012	NA
	Anon (2014)	North western waters	11	NA	2010-2012	<1%
Clupea harengus	Ulleweit *et al.* (2010)	German pelagic freezer trawlers	2.2	NA	2002–2008	5% of annual fishing hours
	Pierce *et al.* (2002)	Scottish trawl	0	Included in discards	2001	5% of annual fishing effort
	Pierce *et al.* (2002)	Maatje purse seine / trawl	11	Included in discards	2001	5% of annual fishing effort
	Morizur *et al* (1996)	Celtic Sea trawl	4.7	Included in discards	1994–1995	78 hauls in total
	Napier *et al.* (1999)	Northern EU waters; trawl and purse seine	2.7	Included in discards	1996	193 hauls
	Borges *et al.* (2008)	Dutch freezer trawl	9	1	2002–2005	4–9% of annual fishing effort
	Quirijns and Pastoors (2014)	North Sea	0	NA	2010-2012	NA
	Anon (2014)	North Western waters	3	NA	2010-2012	<1%

†number of individuals discarded per year raised to fleet level

Reporting net burst incidents is mandatory in Norway. Catch data from the Norwegian Fisheries Directorate show that 11–32 and 1–21 gear-related problems were reported annually between 2011 and 2018 in the Norwegian fisheries for herring and mackerel, respectively. Annually, between 0 and 5 of these were specifically reported as burst net or hole in the net in each fishery. This represents a small proportion of the 1000–3000 reported catch events annually, and there are strong indications that the reported numbers of burst nets are substantial underreports of the true numbers, especially in the NSS herring fishery. Beltestad and Misund (1989) estimated the net burst rate in the NSS herring fishery between 1985 and 1987 and found that in 7 of 49 purse seine sets, the net burst. Net bursts were more common in daytime (6 of 14 sets) compared with nighttime (1 of 35 sets). When extrapolating the observations to the whole fishery the authors estimated that 44100 t of fish was lost during the study period.

Mortality rate of discarded, slipped, and lost mackerel and herring

In addition to the frequency of slipping and discarding events, their impacts on the fish stocks depend on the mortality rate of the slipped or discarded fish. Small pelagic species are vulnerable to contact with fishing gears and may have high mortalities if released or discarded (Suuronen, 1995; Broadhurst *et al.*, 2006). NEA mackerel mortality following crowding and slipping from purse seines has been estimated to range between 28% and 100% depending on crowding density and duration in Northern European waters (Lockwood *et al.*, 1983; Huse and Vold, 2010). In Spanish fisheries, the mortality of mackerel crowded in the purse seine, pumped on board, and monitored in onboard tanks ranged from 0% to 97% (Marcalo *et al.*, 2019). The mortality of mackerel passing through grids in purse seines was estimated at 44% to 68% (Misund and Beltestad, 2000). Herring mortality was estimated to range between 28% and 52% depending on crowding density (Tenningen *et al.*, 2012), 95–100% following simulated net bursts (Misund and Beltestad, 1995), and 68–100% following mesh and grid selection in trawls (Suuronen *et al.*, 1996b). The mortality rates can vary greatly with capture method, environmental conditions, catch size, haul duration, and the size and condition of the individual fish (Davis, 2002; Broadhurst *et al.*, 2006). Smaller individuals tend to be more vulnerable (Suuronen *et al.*, 1996b; Tenningen *et al.*, 2012). The causes of mortality are still not fully clear but are likely to be due to skin injuries and infections, exhaustion and lack of oxygen, injuries from crowding and physical pressure, and synergistic and accumulated effects of these (Pawson and Lockwood, 1980; Suuronen *et al.*, 1996a; Olsen *et al.*, 2012).

Estimated proportion of unaccounted catches

Based on the available data, we concluded that discarding accounts for a minor proportion of unaccounted mortality in mackerel and herring fisheries, whereas slipping and net bursts are likely more significant, but data are lacking. Based on the available empirical (Tables 1 and 2) and anecdotal information on quantities discarded, slipped and lost through net bursts, and the estimated mortality rates, we estimated that possible quantities correspond to a range from 1% up to 50% of total catches, and the mortality rate of these fish to be between 10% and 50% for herring and 30% and 100% for mackerel. In addition to real variation in pre-catch loss and discard rates and mortalities, the wide range represents the lack of accurate data and, thus, the underlying uncertainty, covering also possible worst-case scenarios.

The unaccounted mortality caused by discarding and pre-catch losses is a combination of the number of fish affected by discarding, slipping, and net burst, and their expected mortality rate. Given the scarcity of information to assign probabilities to frequency and quantity of discards, slipping, and net bursts, and the event-specific survival rates, we assumed an even distribution across the entire range that averages out possible overweighting of lower and upper boundary cases. Both proportion and mortality were therefore assumed to have continuous uniform distributions with minimum and maximum values equal to the corresponding ranges. Combining the two uniform probability distributions for each species (i.e. multiplying all elements with each other to derive the outer product) allowed us to estimate probability distributions of net burst, slipping, and discard mortality to sample from in the subsequent runs of the assessment models (Figure 2). Although both assumptions on the upper limits of possible losses as well as their mortality affect the resulting probability distribution and their mean, the outcome is more sensitive to the assumption on possible loss rates (Supplementary Figure S1).

Assessment simulations

Assessment model

For both stocks, the current stock assessment is based on the state-space assessment model (Nielsen and Berg, 2014), with some modifications in the case of herring (Aanes, 2016). For herring, we applied the assessment model and configurations as they were reported in the 2018 assessments (ICES, 2018). For mackerel, the mark-recapture data were excluded from the operating model due to uncertain tag mortality and recapture rates, resulting in problematic influence on the assessment (ICES, 2019b). To test the sensitivity of results to effects of assessment inputs, we excluded sequentially other survey indices used in the assessments. All assessment runs and analysis were conducted in R 4.0.2 (R, 2020) and ggplot2 (Wickham, 2016) was used for graphics.

Assessment runs

For each run, a value from the probability distribution of unaccounted mortality (Figure 2) was randomly drawn, multiplied with catch and added as age-specific discard and pre-catch losses x_a to the reported annual catches at age C_a to calculate the input catches at age $\hat{C}_a$ corrected for assumed unaccounted mortality. This was done according to four different scenarios, two of them age-dependent (1 and 2), reflecting that discard and pre-catch losses can be linked to small-sized individuals in the catch, and two of them independent of age (3 and 4):

1. Only the youngest fish selected to the fishery are affected: $\hat{C}_a = C_a \cdot (1 + x_a)$ for a between 4 and 7 for herring and a between 2 and 5 for mackerel, $\hat{C}_a = C_a$ for all other ages.
2. Young age classes are more affected than older ages (additional mortality decreases linearly with age a in respect to maximum age a_{max}): $\hat{C}_a = C_a \cdot ((1 + x_a) \cdot a \cdot \frac{1}{a_{max}})$.
3. All ages equally affected: $\hat{C}_a = C_a \cdot (1 + x_a)$.
4. Frequency of pre-catch losses is affected by fishing activity, using total catch as proxy for fishing activity: $\hat{C}_a = C_a \cdot (1 + x_a) \cdot q_c$, where q_c is a factor based on the quartiles of total catches that re-

Table 2. Survival experiments of mackerel and herring following contact with fishing gears (crowding, grid, and mesh selection).

Species (stock)	Source	Summary of experiment	Level and type of stressor	Mortality rate (%)
Scomber scombrus (NEA mackerel)	Lockwood *et al.* (1983)	Fish were caught by purse seine, transferred to tanks on board fishing boat, and crowded at high (1 000–1 500 fish m^{-3}), medium (127–141 fish m^{-3}), and low (100–148 fish m^{-3}) densities between 10 and 30 minutes. Mortality was estimated 2 days post-crowding.	Density: high	74–99
			Density: medium	35–45
			Density: low	5–10
	Misund and Beltestad (2000)	Fish were caught by purse seine, transferred to a net pen, and forced to pass through a rigid sorting grid to another net pen (small scale) or directly from the purse seine to a net pen (full scale). Mortality was estimated 1 month post-treatment.	Grid selection (small scale)	1–2
			Control (small scale)	1–2
			Grid selection (full scale)	44–64
			Control (full scale)	5–44
	Huse and Vold 2010)	Fish were caught by purse seine, transferred to free floating net pens at fishing ground, and crowded 10–15 minutes at high and medium densities. Mortality was estimated 3–6 days post-crowding.	Density: high	84–100
			Density: medium	28
			Control	0–46
	Marcalo *et al.* (2019)	Fish were caught by purse seine, crowded in the net for 0–50 minutes, pumped on board, and monitored in water tanks on deck. Mortality was estimated 2–6 days post-crowding.	Crowding and pumping	0–97
Clupea harengus (NSS herring)	Misund and Beltestad (1995)	Fish were caught by purse seine, transferred to net pens, and exposed to simulated net burst. Small scale: 60 kg herring in a 30 m^3 net pen. Large scale: 700 kg herring in a 1 000 m^3 net pen. Mortality was estimated 5 to 9 days post-treatment.	Small scale	100
			Control (small scale)	98
			Large scale	95
			Control (large scale)	12
Clupea harengus (Baltic sea herring)	Suuronen *et al.* (1996)	Fish caught by trawl were allowed to escape through 36 mm diamond mesh codend or a rigid sorting grid (12 mm bar spacing). Control groups were seine and handline caught herring. Mortality was estimated 14-days post-treatment.	Diamond mesh selection	85–100
			Grid Selection	68–100
			control	9–55
Clupea harengus (NS herring)	Tenningen *et al.* (2012)	Fish were caught by purse seine, transferred to free floating net pens at fishing ground, and crowded 10–15 minutes at high (220–478 kg m^{-3}) and medium (58–142 kg m^{-3}) densities. Mortality was estimated 4–5 days post-crowding.	Density: high	28–52
			Density: medium	< 2
			Control (3–7.3 kg m^{-3})	< 2

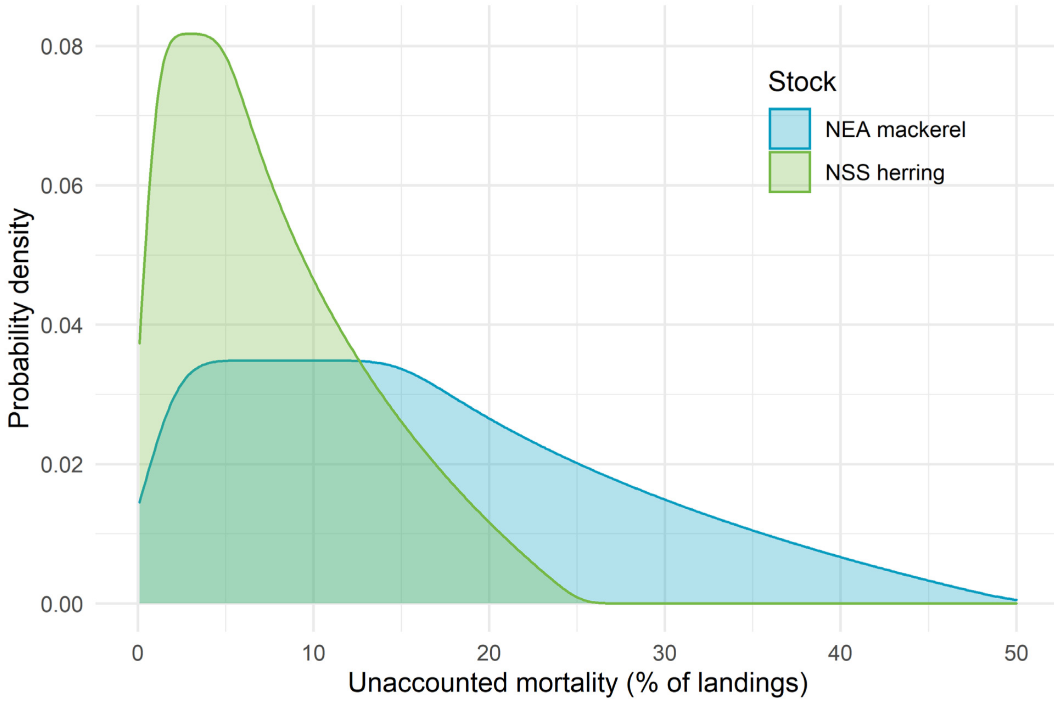

Figure 2. Probability densities of unaccounted mortality (net burst, slipping, and discard mortality) for NEA mackerel (blue) and NSS herring (green) as percentage of landings based on studies presented in Tables 1 and 2 and anecdotal evidence.

sults in doubled effect size $q_c = 2$ for years when total catches were in highest quartile (larger than 75% of catches over entire time series), $q_c = 1$ for total catches in intermediate quartiles (25–75%), and $q_c = 0.5$ for total catches in lowest quartile (<25%). This implies that the occurrence of pre-catch losses is four times higher in years with very high fishing activity and catches compared to years with low fishing activity.

The rationale behind the scenarios 1 and 2 is that fish size is a common reason for discarding and slipping, while the risk for net bursts and slipping events is typically linked with the fishing activity and, thus, presumably occur more often when catches are high (scenario 4). Scenario 3 serves as intermediate case that applies no additional assumptions beyond the proportion of unaccounted mortality.

We conducted a short-term forecast only in the final assessment year (2018) to estimate the advised catches for the subsequent year (2019) to avoid confounding effects caused by retrospective patterns, in contrast to analysis that specifically address retrospective patterns (Hurtado-Ferro *et al.*, 2015). F_{MSY} as currently defined for each stock (0.23 for mackerel, 0.157 for herring) and geometric mean of recruitment were used in all forecasts as input parameters, and we considered the resulting catch forecast as what the responsible stock assessment working group would advise as total allowable catch (TAC).

For each scenario, the process of randomly selecting the level of unaccounted discard and pre-catch mortality, running the assessment and generating the catch advice was repeated 1000 times. From the resulting stock estimates, we calculated the mean annual SSB with 95% confidence intervals (CIs), as well as the TAC advice for the year following the assessment year (here 2019). All results were standardized to the mean estimates of the baseline assessment run of the assessment, in which no additional mortality was included. CIs for the unaccounted mortality scenarios are presented as means of the upper and lower CIs over all runs.

Results

Impact of unaccounted mortality on stock estimates

The estimated SSB was higher for both stocks in almost all runs and years when unaccounted mortality was included, resulting in a statistically significant ($p < 0.001$, linear model) increase of SSB estimates in all scenarios compared to the baseline assessment run (Figure 3a). The median increase over all runs and years was between 3.7% and 19.5% for NEA mackerel and 2.8 and 6.8% for NSS herring depending on scenario (Figure 3a), corresponding to a median deviation in SSB of 109–474 and 146–367 thousand tonnes, respectively. The increases in SSB were on average slightly above the median probabilities of unaccounted mortality (median 14.8% for mackerel and 6.5% for herring across each stock's probability distribution). Generally, the median deviation in SSB showed a clear link to the assumed unaccounted mortality (Supplementary Figure S2), increasing in all scenarios linearly with increasing unaccounted mortality (however, with the slope depending on the scenario).

For both stocks, the effects on SSB were strongest when the unaccounted mortality was age-independent, i.e. when all ages were equally likely to be affected, with little difference between the catch-independent and catch-dependent scenarios. The ranges of CIs were also larger compared to the baseline run of the assessment where the unaccounted mortality of pre-catch losses and discards is ignored (Supplementary Figures S3 and S4), with an increase in the range between absolute SSB at lower and upper 95% CI that was

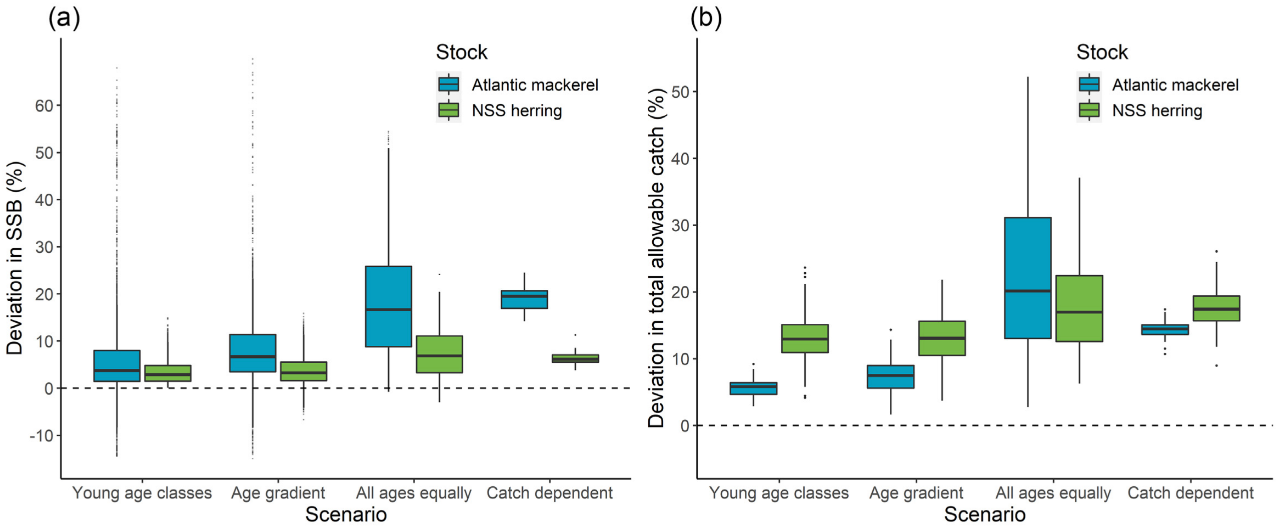

Figure 3. Boxplots of percentage deviations in annual SSB (a) and total allowed catch (b) for NEA mackerel (blue) and NSS herring (green) between scenarios with increased mortality and baseline run without increased mortality. Deviations in SSB were summarized over the entire time series and all bootstrap runs, whereas deviations in TAC are shown for the year following the last assessment year (here 2018). TAC forecasts are based on the Fmsy-rule ($F = 0.23$ and $F = 0.156$, respectively, for mackerel and herring) for each stock. Two of the scenarios were age-dependent (only the youngest age classes or a decreasing effect with age), while two were age-independent (i.e. all ages affected equally), including on where the effect strength is affected by total annual catches. The boxplots show median (solid black line), first and third quartiles (lower and upper bounds of the boxes), 1.5 times the interquartile range (whiskers), and the outliers outside of this range (dots), over all bootstrapped runs for each scenario.

proportional to the increase of mean SSB, indicating a potential increase in uncertainty.

The additional mortality were fully absorbed by the abundance estimates, whereas the fishing mortality (Supplementary Figure S5) estimated by the assessment model showed virtually no deviations from the baseline run. In contrast, increased abundance was reflected in increased recruitment of a near identical magnitude as increases in SSB (Supplementary Figure S6).

Impact of unaccounted mortality on TAC

The increases in SSB were reflected in higher TAC estimates for the following year (Figure 3b). The increases in TAC were more pronounced than the increases in SSB (Figure 3b). Herring showed a stronger effect compared to mackerel in all but one scenario (scenario 3: all ages affected equally). Median TAC increased by 5.2–20.1% for mackerel and 12.9–17.4% for herring depending on scenario, representing 55–213 and 98–133 thousand tonnes, respectively.

Sensitivity to assessment input data

The configuration of the assessment model, notable the inclusion of survey indices, had only minor impacts on the effects of including discard and pre-catch mortality into the assessments (Supplementary Figure S7). Reducing the configuration to only one or no index in case of mackerel did not affect the observed patterns (Supplementary Figure S7). The notable exception was the catch-dependent scenario in mackerel, where the exclusion of survey indices, especially the swept area survey, resulted in significant deviations compared to the assessment that includes all three survey indices.

Discussion

Our results show that even though unaccounted mortality due to discarding and pre-catch losses in the NEA mackerel and NSS herring fisheries can be only partially quantified, it likely represents a significant proportion of the fisheries removals. Including unaccounted mortality into the stock assessment models can, thus, have considerable effects on estimates of stock biomass and TACs. The effects on SSB were slightly higher or of the same magnitude as the estimated probable range of unaccounted mortality, confirming the expectation that SSB increases proportionally to the additional mortality in most assessment models. Higher SSB estimates translated into elevated TAC by similar or higher percentages, which represents the previously unaccounted losses allocated as share of the TAC. The impacts were stronger when pre-catch and discard mortality was evenly distributed over all age classes than when mortality was concentrated on the younger age classes.

Quantitative impacts on stock estimates are determined by the assumed rates of discarding, slipping, and net burst events and the probable range of survival of the affected fish. Reliable estimates of discard and pre-catch losses in these (and many other) fisheries are lacking and, subsequently, the potential mortality rates in our study covered a very large range (0.3–50% and 0.1–25% for mackerel and herring, respectively). Nevertheless, our results show that the effects can be relevant even for relatively low rates, as the assessment impacts were mostly determined by the relatively low ranges of pre-catch and discard mortality proportion around the median (14.8% in mackerel and 6.5% in herring). This demonstrates the importance of obtaining estimates of unaccounted mortality, both to reduce uncertainty and to obtain more accurate reference values.

Reliable estimation of slipping and net burst rates would require considerable effort. Pelagic stocks are commonly targeted by many fleets, and the fisheries range over large geographical areas. Discard, slipping, and net burst rates show strong spatial and temporal variation due to different regulations, fish schooling behaviors, species and size compositions, fishing methods, and market demands (Stratoudakis and Marcalo, 2002; Borges *et al.*, 2008). This complicates monitoring and control, making extrapolation of observed discard and slipping rates to the whole fishery problematic (Stratoudakis and Marcalo, 2002; Rochet and Trenkel, 2005; Borges *et al.*, 2008).

Fisheries in many countries are extensively controlled and monitored, often requiring the vessels to report electronically about their fishing activity and catches. In addition, the coast guard monitors fishing grounds and there are controls at the landing sites. Information about discards is mainly obtained through observer programs as part of the EU data collection regulation (Suuronen and Gilman, 2020). However, observer programs are expensive, and usually only cover a small proportion of the fishery. Despite efforts to estimate mackerel and herring discard and slipping rates, the estimates are likely underestimates of the true figures due to low quality of discard information. There is also a concern that the exemption from the landing obligation in herring and mackerel purse seine fisheries could be a significant source of unaccounted mortality, especially for mackerel (Fitzpatrick and Nielsen, 2016). Having observers on board has also been shown to affect the fishermen's behavior. In Northern Portugal, higher slipping rates were registered when observers were onboard (Stratoudakis and Marcalo, 2002). This is expected when fish are slipped due to regulatory reasons. The Norwegian fisheries authorities believe slipping events are fewer in their presence; a likely scenario when slipping is related to catch value. Electronic monitoring is discussed as an option in many fisheries (Hall et al 2017) and several fisheries, e.g. tropical tuna purse seine fisheries, have fully implemented electronic monitoring programs (van Helmond *et al.*, 2020). Clear, practically implementable and controllable regulations, e.g. how the net should be rigged for slipping, reporting system, and further improvement of methods and instruments to identify school biomass, individual size and species composition prior to catch are necessary for successful reduction of net burst, slipping and discard events.

Fisheries-dependent data are fundamental input of almost all analytical stock assessment models, and estimated stock biomasses are largely or entirely determined by the catches and other removals. This issue is exacerbated by the common assumption of many assessment models that catch data contains no observation errors, giving a large weight to catch information. Any assessment model shows a perception of the stock given the model, its configuration and input data, while the true stock size will remain unknown. Including previously unaccounted mortality in an assessment does, therefore, not change the true stock size. Removals that are not known nor included (e.g. illegal, unregistered, or unreported catches, discards, and pre-catch losses) may therefore pose a challenge to sustainable management of fisheries. Our results show that this may also be an issue for well-monitored and managed pelagic fisheries where discarding is typically not considered as a major concern. Ignoring the estimated pre-catch and discard mortalities underestimated the SSB and the forecasted TAC in both NEA mackerel and NSS herring substantially. The increase in forecasted TAC is a direct result of the underestimation of SSB and implies that unaccounted mortality is removed and instead included as catch (landed and reported), i.e. fishing mortality and thus reference points such as Fmsy are unaffected (in contrast to biomass reference points). Fishing-independent data provide information about trends in the stock but not about absolute stock size and as expected our results show that survey data do very little to mitigate this problem. This can contribute to disputes between fishermen and scientists, when the experience the fishermen have (higher "true" stock level) differs from the one scientists derive based on the lower SSB estimate provided by stock assessment model (perceived stock) that ignores pre-catch and discard mortality.

The effects on SSB estimates increased linearly with the proportion between unaccounted mortality (net bursts, discarded, and slipped catches) and official landings, implying that the product of discard, slipping, and net burst frequency and their respective survival rates may provide a good predictor for the impacts on stock abundance estimates. However, the effects of including discards or discard survival can be difficult to generalize and any quantification requires therefore stock-specific analysis (ICES, 2021). Furthermore, including such information in an assessment requires sufficiently accurate knowledge on the probable range of the unaccounted mortality, which is typically lacking even in data-rich fisheries. Knowledge gaps on the frequency of slipping events and net bursts currently prevent a more informed evaluation of the possible impacts on stock estimates, and our results may therefore represent over- or underestimates of the true impacts. Furthermore, except for the catch-dependent scenario, we assumed time-invariant effects that result in systematic bias in the assessment, which may be less problematic due to limited impacts on relative trends in abundance estimates. Slipping and discard rates can, however, be much more variable, for instance when they are driven by external factors such as changes in prices or regulations. Such temporal patterns in discarding are more challenging to assess and could be a possible explanation for poor performance of and retrospective patterns in the assessments for both of our focal stocks in the past.

Including discard data in assessment has been shown to reduce bias in estimates of stock size, recruitment, and exploitation rates and provide more reliable short-term catch predictions (Punt *et al.*, 2006). However, this requires that the nature of discarding (e.g. size or quota related) and between year and fleet variation is known and reflected in the way the data are used in the assessment model (Punt *et al.*, 2006; Cook, 2019). Because of low sampling effort, such data are often not available and estimates of pre-catch losses and discards are less precise compared with landings (Dickey-Collas *et al.*, 2007), introducing additional uncertainty that may counteract the increased accuracy due to including them. To determine the costs and benefits of including pre-catch losses and discards in an assessment, case by case analysis is required to estimate likely pre-catch and discard mortalities and potential dynamics over time, and test their effects on stock estimates. Obtaining accurate data on pre-catch losses and discards requires a great amount of effort, both experimental evidence on survival rates of slipped and discarded fish, and data on the occurrence of slipping, net bursts, and discarding in the fishery, with no guarantee that the data will be reliable. The key question is therefore whether the additional mortality is substantial enough to affect stock estimates and quota advice to a degree that outweighs the additional data requirements and model complexity. Our analysis suggests that the effects are potentially large enough to call for a future inclusion of discarding in the assessment of both NEA mackerel and NSS herring, especially when considering the intermediate to high range of possible discard mortalities. Further research to narrow down the true discard mortality is therefore advised, such as improved pre-catch school identification (Peña *et al.*, 2021), slipping methods (Marcalo *et al.*, 2018; Anders *et al.*, 2019), and other modifications to fishing practices and gear that increase selectivity and survival of fish selected from the gear (Hall *et al.*, 2017; Suuronen and Gilman, 2020).

Our estimates of the discarding, slipping, and net bursts in the NEA mackerel and NSS herring fisheries allow us to calculate how much more could be sustainably caught in these fisheries if these wasteful practices where stopped. Fishing opportunities could improve by more than 50 and up to 200 thousand tonnes annually, worth €83–341 million for mackerel and €41–55 million for NSS herring, based on the firsthand values in 2019 in Norway. Even without the monetary benefits, improving fisheries management by removing the pre-catch and discarding losses would contribute towards providing more food for the growing human population (SAPEA, 2017; Costello *et al.*, 2020). Furthermore, stopping the wasteful practices would contribute directly towards United Nations SDG 14, Life Below Water, target 14.4, of *effectively regulating harvesting and ending overfishing, illegal, unreported, and unregulated fishing*, as well SDG 2, Zero Hunger (UN, 2015). Pre-catch and discard losses can be further reduced by continued development of mitigation measures in close cooperation with stakeholders, continued and increased surveillance at the fishing grounds, and new and increased efforts to obtain estimates of mortality rates. Quantifying potential impacts is essential for a common agreement between fishermen, authorities and scientists on the magnitude of the problem and a key for the motivation needed to develop efficient mitigation measures. Unaccounted mortality is a major concern both for the one third of the global fisheries that remain overexploited (FAO, 2020; Palomares *et al.*, 2020) and the increasing number of stocks that are sustainably managed (Zimmermann and Werner, 2019; Hilborn *et al.*, 2020), as unaccounted mortality may severely undermine rebuilding efforts while representing particularly large losses in yield when stock sizes are high.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Data availability statement

The data produced in this study are available from the authors upon request.

Acknowledgements

The authors thank M. Breen for discussion and J. Høgset for valuable information from the fishing grounds. FZ and KE acknowledge funding from the Norwegian Research Council (grant no. 243735). FZ and MT acknowledge funding from the Norwegian Research Council (grant no. 203477).

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Handling Editor: Christos Maravelias