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REVIEWS

A review of bycatch reduction in demersal fish trawls

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Abstract Otter trawling for fish is one of the world's most productive yet problematic fishing methods due to its bycatch and discards; issues that have been mitigated in some fisheries by developing more selective trawls. This paper systematically reviews efforts published in international peer-reviewed papers over the past 30 years to identify beneficial (and limiting) factors and propose a way forward in this field. In total, 203 papers were assessed, encompassing many of the world's fishing regions, and involving > 147 species, although 74% of efforts occurred in Europe mainly focussing on haddock (*Melanogrammus aeglefinus*) (64 papers) and cod (*Gadus morhua*) (59 papers). Common, simple modifications have involved increasing lateral-mesh openings to match the morphology of unwanted catches via larger diamond-shaped mesh, or simply turning meshes 45° or 90°, either throughout codends or as strategic windows in the posterior trawl. In some fisheries, more complex grids have improved size or species selection. Fewer attempts have been made to modify the anterior trawl, but varying sweep/bridle lengths, horizontal separator panels and longer headropes have realized benefits depending on species-specific behavioural responses. While the utility of many modifications is indisputable, experimental designs (mostly involving covers, but also alternate hauls and paired comparisons) have, in many cases, suffered low replication and/or confounding variables. These deficits may have compromised some results and contributed to repeated efforts in particular fisheries. We conclude that rigorous empirical assessments, initially focusing on the posterior trawl, but eventually encompassing anterior changes, combined with straightforward interpretation of results for stakeholders, are as important as the simplicity and reliability of modifications. Finally, by assessing the utility, applicability, advantages and disadvantages of the modifications developed, we provide a framework which could be followed in future work to reduce bycatch in these fisheries.

Keywords Bycatch · Discard · Demersal fish trawl · Multi-species · Selectivity

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Introduction

The problem

Despite many years developing more selective fishing methods, bycatch (i.e. organisms that are unintentionally caught) remains a key issue for fisheries management, policy and science (FAO 2011; Gilman et al. 2020). Demersal otter trawling for fish (hereafter referred to as 'fish trawling' and the gear as 'fish trawls') is a major contributor to global seafood production; but is also responsible for 25% of the world's discarded bycatch (estimated at 9.1 million t in total; Pérez Roda et al. 2019). Concerns from the public and interacting fisheries regarding impacts associated with large collateral mortalities of discards, eco-labelling certification initiatives like the Marine Stewardship Council, and the recent implementation of the European Union's Landing Obligation (or 'discard ban'), have placed fish trawling at the forefront of mitigation efforts, with hundreds of studies being done—especially in the past few decades (Broadhurst et al. 2006; Uhlmann et al. 2019).

Many of the world's fisheries jurisdictions seek to reduce bycatch from fish trawls, but most research has occurred at relatively few locations, and in many cases concentrated on technological modifications to conventional trawls designed to improve either size or species selectivity. While there exist several regional reviews (e.g. Kennelly 1995; Pol and Carr 2000; Valdemarsen and Suuronen 2003; Graham et al. 2004a, b; Graham 2006; Madsen 2007; Suuronen and Sarda 2007; Madhu 2010; Feekings et al. 2013), there has been no systematic, global synthesis of the many fish-trawl studies that have been done. Such a review should prove useful to those jurisdictions/fisheries beginning work in this area and/or that fall outside the regions where research has concentrated, and complement broader efforts to reduce the wastage and environmental impacts of fishing gears in general (e.g. Broadhurst 2000; Wenger et al. 2017; McHugh et al. 2017; Pérez Roda et al. 2019).

Our objective in this review was to address the above shortfall by detailing and critically evaluating the various technical and experimental approaches used throughout the world to improve the species and/or size selectivity of fish trawls (and so reduce bycatch) via gear modifications. We then use this information to suggest a way forward for future work in this field.

Methods

Fish-trawl catching mechanisms

Any review of technical approaches to improve the selectivity of fishing gears first requires some overview of the associated catching mechanisms (McHugh et al. 2017). There are many different configurations of fish trawls, but like for other otter trawls, all adhere to a generic plan which can be separated into various zones according to the underlying catching process (McHugh et al. 2017; Melli et al. 2020; Fig. 1).

For the purposes of this review, and following previous definitions (e.g. McHugh et al. 2017), the first zone ('spreading mechanisms') includes the otter boards (or hydrovanes which are dragged along or very close to the seabed and angled so that they spread all of the rigging aft), sweeps (typically > 100 m) and bridles (Fig. 1). These non-netting components exploit the behavioural responses of most fish to herd them from the area in front of the entire trawl and into the netting components (Wardle 1989). The second zone can be defined as the entry point to the netting components and encompasses the weighted ground gear and foot rope (which keep the trawl on the seabed), and a headline with floats or kites that assist the mouth of the trawl to open vertically (Fig. 1). These zone-2 components are configured to stop the escape of fish under or over the trawl. Behind this rigging are the trawl wings and body (zone 3) which usually comprise sequentially smaller meshes, with the body following a long-tapered section designed to concentrate swimming and tiring fish towards their retention in the extension and codend. The latter is zone 4 and is usually not tapered, although the codend can have variable circumferences (within or between the extension) to accommodate catches.

Due to the size of the rigging involved in fish trawls, especially the lengths of sweeps, most configurations are towed as single rigs and only occasionally as twin (or 'dual') rigs comprising two outside otter boards and a centre weight or sled (e.g. Graham et al. 2003; O'Neill et al. 2006). Further, while there is considerable variability in fish-trawl designs within and among fisheries, in many cases the extension and codend are

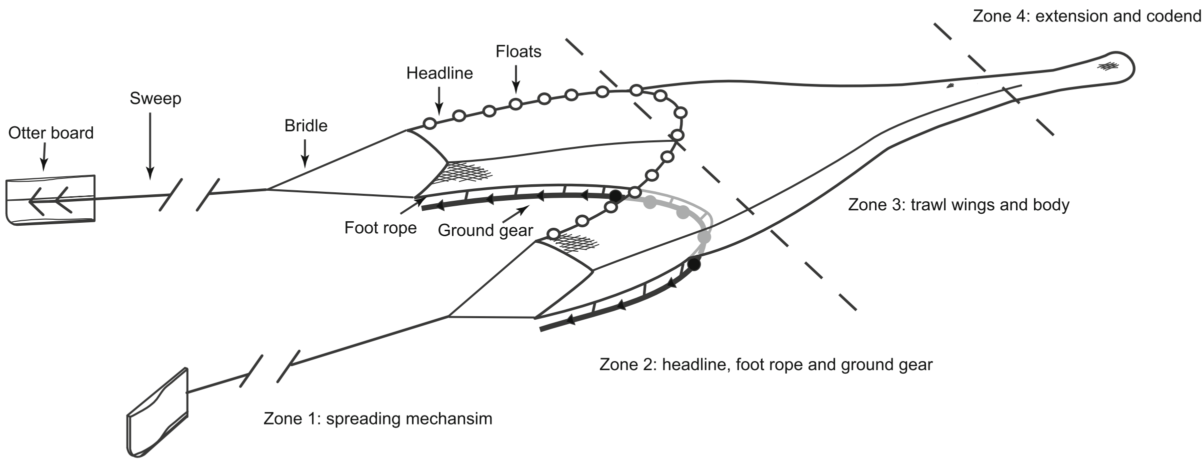

Fig. 1 A typical demersal otter trawl showing the four categorized zones

fairly homogenous, and are often the focus of input controls such as minimum mesh sizes due to the assumption that they are key areas affecting selection (Millar and Fryer 1999).

Scope of the review

This review focusses on empirical experiments done at sea to quantify modifications designed to improve the size or species selection of demersal otter trawls targeting fish (teleosts), and so excludes similar work with beam trawls or directed trawling for cephalopods, molluscs or crustaceans. Nevertheless, we acknowledge that at least some of these other species groups, and especially crustaceans, are retained and harvested as so-called 'by-product' in many fish-trawl fisheries (Kunjipalu et al. 2001; Aydin et al. 2014; Madhu et al. 2015; Brčić et al. 2018a, b).

Further, while there exist hundreds of national and international reports, magazine articles and other 'grey' literature describing research on modifications to fish trawls, this paper focusses only on papers in international, refereed journals. This approach ensures our critical consideration of the anonymously peer-reviewed empirical science used in this field. In any case, it was apparent that in many instances where modifications presented in the grey literature had merit, these were subsequently published in international journals. We also restricted our study to papers that were written in English.

Acquired material and synthesis

In this review, we followed a systematic approach with consideration to the 'preferred reporting items for systematic reviews and meta-analyses' (PRISMA) method (Liberati et al. 2009). To ensure the publications examined were as inclusive as possible, we began with $\sim$ 150 papers describing experiments to test modified fish trawls gathered by us over the past 30 years. From these papers we derived 22 common words/phrases, including: 'selectivity', 'codend', 'square mesh', 'trawl,' 'grid', 'catch', 'bottom/demersal trawl', 'diamond mesh', 'bycatch reduction', 'square mesh', 'T0', 'T45', 'T90', 'discard', 'behaviour/behavior', 'twine', 'windows', 'multi-species', 'separating', 'ground gear', 'sweep' and 'twin trawl'. These terms and their combinations were incorporated into searches of the ISI Web of Science, Proquest and Google Scholar. We established an historical search window of January 1988 to October 2020, starting with the study by Robertson and Stewart (1988). The earliest boundary aligns with the findings of Millar (1992) and Millar and Walsh (1992) who detailed problems with the early analyses of selectivity studies involving paired-gear comparisons, and proposed a more rigorous approach (i.e. 'Share Each Length Catch Total' (SELECT) methodology) (Millar and Fryer 1999). While we do not comment on specific issues in papers prior to 1988, it became apparent that all useful earlier modifications were encapsulated in the later papers.

The search produced some 300 papers, which were then filtered and cross-referenced against our original 150. We excluded papers where fish were not the primary target, or those that did not investigate applied modifications to fishing gears at sea, such as theoretical or laboratory studies (for which there are many excellent works dating back to Sainsbury (1984) and more recently Tokaç et al. (2018)).

Papers that satisfied the search criteria were then examined in detail and partitioned into categories according to the four zones of the trawl in which they were focused (or combinations thereof), and whether the modifications were relatively 'simple' or 'complex' as described by Uhlmann and Broadhurst (2015). Specifically, simple modifications were those that were familiar to fishers and could be made within conventional configurations, including changes to: diamond-shaped mesh (also termed 'T0') simply by turning it 45° ('T45' by hanging it on the bar to make it 'square mesh') or 90° ('T90'); twine diameters; ground gears; or headline heights. We anticipated that such modifications might be more easily accepted by fishers than complex modifications, which extended beyond conventional configurations and involved often new (unfamiliar to fishers), retroactively fitted components such as separator panels, grids, light-emitting diodes or new trawl designs.

After categorising all papers, each was qualitatively summarized according to its defining characteristics. These included: where and when the study was done (including when the data were collected); up to six key target and bycatch species (the latter comprising either undersized targets and/or other species) and their general body type ('roundfish' that were fusiform or laterally compressed vs 'flatfish' that were dorsoventrally compressed); the specific modifications tested and the testing method (i.e. how modifications were assessed in trawls, along with ancillary equipment like net monitoring equipment or cameras); selectivity and/or efficiency improvements of modifications; and any stated or potential confounding/beneficial factors of the experimental designs or analyses (with reference to recommended approaches detailed in the literature, including Fryer 1991; Wileman et al. 1996; Millar and Fryer 1999).

Results

In total, 203 papers published in 36 journals and focussing on > 147 species across > 49 families satisfied the objectives of the search criteria (Tables 1 and 2). The journal Fisheries Research published 94 papers (i.e. 46% of the total), while a further 59 papers (29%) were distributed among seven journals: ICES Journal of Marine Science/Journal du Conseil (16 papers); Journal of Applied Ichthyology/Archive of Fishery and Marine Research (11); Scientia Marina (8); Aquatic living Resources (7); Turkish Journal of Fisheries and Aquatic Sciences (6); Fishery Technology (6); and the Canadian Journal of Fisheries and Aquatic Sciences (5).

Spatio-temporal patterns and species assessed

Most research (74%) to reduce fish-trawl bycatch has occurred in Europe (with 20% in the North Sea alone) (Fig. 2) and focused on haddock (*Melanogrammus aeglefinus* Gadidae), cod (*Gadus morhua* Gadidae), whiting (*Merlangius merlangus* Gadidae), hake (*Merluccius merluccius* Merlucciidae) and European plaice (*Pleuronectes platessa* Pleuronectidae)—species that were either individually or collectively assessed > 190 times in papers (Table 1). Other substantial European efforts have occurred in the Mediterranean Sea (particularly off Turkey and Italy) for multi-species fisheries, but often also with hake and/or red mullet (*Mullus barbatus* Mullidae), blue whiting (*Micromesistius poutassou* Gadidae), common pandora (*Pagellus erythrinus* Sparidae) and Atlantic horse mackerel (*Trachurus trachurus* Carangidae) (Table 1). Both round and flatfishes were often collectively assessed, but the former were the focus in four times more studies (79 vs 21%; Table 1).

Fewer papers (17%) were done off North America—despite extensive fish-trawl fisheries occurring there targeting cod and haddock, along with flatfish like American plaice (*Hippolossoides platessoides* Pleuronectidae); Pacific halibut (*Hippoglossus stenolepis*), various flounders and soles (Pleuronectidae) (Fig. 2). The remaining regions with multiple efforts were restricted to Australia (3%) and India (4%). There were no papers from South America and only one from each of Africa and Asia.

Irrespective of geographic location and species, 187 of the 203 papers described modifications within a

Table 1 Families and common and Latin names of species assessed in more than one published paper (January 1988 to October 2020) describing modifications to reduce bycatch in demersal fish trawls

Family	Common name	Latin name	No of papers
Anoplopomatidae	Sablefish	*Anoplopoma fimbria*	4
Bothidae[F]	Mediterranean scaldfish	*Arnoglossus laterna*	3
Callionymidae	Dragonets	*Callionymus* spp.	2
Carangidae	Atlantic horse mackerel	*Trachurus trachurus*	14
	Mediterranean horse mackerel	*Trachurus mediterraneus*	2
Gadidae	Silvery pout	*Gadiculus argenteus*	2
	Alaskan pollock	*Gadus chalcogrammus*	3
	Atlantic cod	*Gadus morhua*	59
	Haddock	*Melanogrammus aeglefinus*	64
	Whiting	*Merlangius merlangus*	24
	Blue whiting	*Micromesistius poutassou*	12
	Saithe	*Pollachius virens*	9
	Pouting	*Trisopterus luscus*	2
	Poorcod/Capelin	*Trisopterus minutus*	11
Hexagrammidae	Lingcod	*Ophiodon elongatus*	4
Leiognathidae	Ponyfish	*Leiognathus* sp.	2
Lophiidae	Blackbellied angler	*Lophius budegassa*	2
	Angler	*Lophius piscatorius*	5
Lotidae	Shore rockling	*Gaidropsarus mediterraneus*	2
Merlucciidae	Silver hake	*Merluccius bilinearis*	4
	European hake	*Merluccius merluccius*	33
	North Pacific hake	*Merluccius productus*	2
Moronidae	European seabass	*Dicentrarchus labrax*	2
Mullidae	Red mullet	*Mullus barbatus barbatus*	30
	Surmullet	*Mullus surmuletus*	6
	Goldband goatfish	*Upeneus moluccensis*	6
Nemipteridae	Randall's threadfin bream	*Nemipterus randalli*	3
Nephropidae	Norwegian lobster	*Nephrops norvegicus*	7
Pentanchidae	Blackmouth catshark	*Galeus melastomus*	3
Phycidae	Greater forkbeard	*Phycis blennoides*	6
Platycephalidae	Tiger flathead	*Neoplatycephalus richardsoni*	2
Pleuronectidae[F]	Arrow-tooth flounder	*Atheresthes stomias*	10
	Witch flounder	*Glyptocephalus cynoglossus*	2
	Rex sole	*Glyptocephalus zachirus*	4
	Flathead sole	*Hippoglossoides elassodon*	5
	Pacific halibut	*Hippoglossus stenolepis*	4
	American plaice	*Hippolossoides platessoides*	9
	Rock sole	*Lepidopsetta bilineata*	3
	Yellowfin sole	*Limanda aspera*	3
	Yellowtail flounder	*Limanda ferruginea*	5
	Common dab	*Limanda limanda*	3
	Lemon sole	*Microstomus kitt*	7
	Dover sole	*Microstomus pacificus*	11
	English sole	*Parophrys vetulus*	4

Table 1 continued

Family	Common name	Latin name	No of papers
	European flounder	*Platichthys flesus*	2
	European plaice	*Pleuronectes platessa*	15
	Winter flounder	*Pseudopleuronectes americanus*	3
	Common sole	*Solea solea*	2
Pomatomidae	Bluefish	*Pomatomus saltatrix*	2
Scophthalmidae[F]	Four-spot megrim	*Lepidorhombus boscii*	2
Scyliorhinidae	Lesser spotted dogfish	*Scyliorhinus canicula*	2
Sebastidae	Blackbelly rosefish	*Helicolenus dactylopterus*	2
	Widow rockfish	*Sebastes entomelas*	2
	Shortspine thornyhead	*Sebastolobus alascanus*	4
Sparidae	Bogue	*Boops boops*	2
	Annular seabream	*Diplodus annularis*	7
	Axillary seabream	*Pagellus acarne*	4
	Common pandora	*Pagellus erythrinus*	12
	Blotched picarel	*Spicara maena*	3
	Picarel	*Spicara smaris*	4
Synodontidae	Greater lizardfish	*Saurida tumbil*	2
	Brushtooth lizardfish	*Saurida undosquamis*	5
Trichiuridae	Largehead hairtail	*Trichiurus lepturus*	4
Zeidae	John dory	*Zeus faber*	3

[F]denotes flatfish

single zone of the trawl, with just 16 assessing modifications at multiple zones, including four papers describing modifications at all zones. Attempts at modifying each zone dated back to the earliest papers, but more recently there were clear temporal differences (Fig. 3). Efforts to address modifications within zones 1 (7% of the total), 2 (11%) and 3 (11%) remained temporally similar at averages of 0.4 to 0.7 studies year^{-1}. In contrast, cumulative efforts towards zone 4 (71% of the total) were substantially greater ($\sim$ 4.2 studies year^{-1}). Notwithstanding these differences, there has been a consistent trend towards simple, rather than complex modifications across all zones (Table 2, Fig. 3).

Experimental methodologies

In many papers, experimental methodologies were determined by the assessed zone and/or trawl configuration examined. Nevertheless, the basic approach involved at least one of three categories: (1) covers (over codends or escape exits, behind ground gears or as liners in codends); (2) alternate hauls (where treatments were deployed in sequences, usually by the same vessel); and/or (3) simultaneous paired comparisons, either by two vessels each towing a trawl side-by-side ('parallel haul'), one vessel towing paired trawls ('twin trawl'), or a single trawl with the codend split into side-by-side legs ('trouser trawl') (Wileman et al. 1996; Millar and Fryer 1999).

Reflecting the dominant focus of work on zone-4 modifications, the most common approach (104 papers or 51%) involved installing covers over the entire codend, and sometimes extension, to retain escaping fish. This approach was most prevalent in European fisheries. Cover designs varied but, to limit confounding effects, in many studies (like Campos and Fonseca 2003; Tosunoğlu et al. 2003) researchers followed the general recommendations of Wileman et al. (1996) with a mesh size approaching 50% of the

Table 2 Summary of the zone of the trawl, modifications assessed (and complexity) to improve selectivity, their impacts and reference(s)

Zone in trawl	Modification(s) and complexity	Impacts	Reference(s)
Zone 1 (spreading mechanisms)	Raising sweeps off the bottom (simple)	Reduced catches of some species (especially flatfish), but no major effects on sizes caught. Lowered sweeps had greater effect in daytime and raised sweeps had little effect at night	Rose et al. (2010), Ryer et al. (2010), Sistiaga et al. (2015), Lomeli et al. (2019)
	Changing warp, sweep or bridle lengths and angles (simple)	Longer warps, sweeps and bridles caught more. Catches of some small fish decreased with longer sweeps	Engås and Godø (1989b), Ramm et al. (1993), Lauth et al. (1998), Fiorentini et al. (1999), Somerton and Munro (2001), Somerton (2004), Sistiaga et al. (2016b)
	Changing spread ratio (simple)	Greater catches of all sizes with lower spread ratio	Rose and Nunnallee (1998)
Zone 2 (headline, foot rope and ground gear)	Long, cutaway headropes (including the 'topless trawl') (complex). Lowering the headline (simple)	Reduced catches of unwanted sizes of certain species, especially roundfish, but less so for flatfish. Lower headline reduced catches of cod but maintained catches of flatfish	Thomsen (1993), King et al. (2004), Hannah et al. (2005), Chosid et al. (2008), Krag et al. (2015), Eayrs et al. (2017), Earys et al. (2020)
	Raising foot rope using floats, weights, spokes, rubber discs and/or wide spacing of discs (simple)	Reduced bycatches of unwanted fish and benthic infauna	Engås and Godø (1989a), Ramm et al. (1993), Brewer et al. (1996), Dahm (2000), Guyonnet et al. (2008), Krag et al. (2010)
	Rockhopper, 'semicircular spreading ground gear (SCSG)' and alternate light (rubber) ground gears (complex)	The SCSG caught more larger fish. Lighter ground gear caught less overall	Brinkhof et al. (2017), Lauth et al. (1998), Larsen et al. (2018a)
	Rollers or large rubber discs on ground gear or with/without tickler chains (simple)	Discs increased catches of flatfish and reduced catches of cod. Rollers decreased catches of invertebrates and debris with some reduction in smaller sizes of targets. Removing a tickler chain reduced catches of unwanted elasmobranchs but also targeted flatfish	Ball et al. (2003), Reid et al. (2012), Kynoch et al. (2015)
	Light emitting diodes or fibre-optic lights along headline or foot rope (complex)	Variable, but some species-specific changes in behaviour at night	Lomeli et al. (2018), O'Neill and Summerbell (2019)
Zone 3 (trawl wings and body)	Increase mesh size throughout conventional T0 netting (simple)	Reduced catches of unwanted sizes of certain species, while maintaining target catches	Broadhurst and Kennelly (1995), Beutel et al. (2008), Campbell et al. (2010), Kynoch et al. (2011)
	Horizontal separator panels/frames in the trawl; some from the headline through to extension (complex)	Good at separating species with different vertical orientations (e.g. cod and haddock)	Cotter et al. (1997), Engås et al. (1998), Ferro et al. (2007), He et al. (2008, Holst et al. (2009), Krag et al. (2009), Park et al. (2012)
	Windows in various parts of trawl body (simple); some with guiding panels (complex)	Reduced catches of unwanted sizes while maintaining target catches; especially for flatfish depending on location of panel	Ball et al. (2003), Milliken and DeAlteris (2004), Madsen et al (2006), Bayse et al. (2016), Santos et al. (2016b), Bonanomi et al. (2020)

Table 2 continued

Zone in trawl	Modification(s) and complexity	Impacts	Reference(s)
Zone 4 (extension and codend)	Increase codend mesh size throughout conventional T0 netting (simple)	Increasing T0 mesh size typically improved L_{50}s across comparable, but sometimes with increased and/or variable SRs	Reeves et al. (1992), Broadhurst and Kennelly (1995), Galbraith et al. (1994), Perez-Comas et al. (1998), Campos and Fonseca (2003), Campos et al. (2003), Tosunoğlu et al. (2008), Joksimovic et al. (2009), Sala and Lucchetti (2011), Hunt et al. (2014), Wienbeck et al. (2014), Madhu et al. (2015), Pol et al. (2016a, 2016b)
	Different codend circumferences and lengths (simple). Single vs double codends (simple)	Smaller codend diameters and lengths increased L_{50}s with usually minimal effects (or a slight increase) on SRs for T0 codends. Single codends also had higher L_{50}s than double, with similar SRs	Reeves et al. (1992), Galbraith et al. (1994), Özbilgin and Tosunoğlu (2003), Tosunoğlu et al. (2003), Özbilgin et al. (2005), O'Neill et al. (2008), Graham et al. (2009), Sala and Lucchetti (2011), Wienbeck et al. (2011), Eryasar et al. (2014), Herrmann et al. (2015a), Sala et al. (2016), Demirci et al. (2017), Ilkyaz et al. (2017), Veiga-Malta et al. (2019)
	Different codend twine materials, thickness (including single vs double), colour and flexibility (simple)	Thinner, single and more flexible twine increased L_{50}s with reduced or unchanged SR. Colour had no effect. Similar effects for Dyneema and slight improvements for polyamide twines. No effects of knotless twine	Lowry and Robertson (1996), Madsen et al. (1998), Kynoch et al. (1999), Tokaç et al. (2004), Sala et al. (2007), Graham et al. (2009), Herrmann et al. (2013a), O'Neill et al. (2016), Cheng et al. (2019)
	Removing or changing strengthening bags, chafing gear, or lastridge ropes (simple)	Strengthening bags/chafing gear or increasing their circumference had variable effects on L_{50} and SR. In some studies L_{50} was decreased or unchanged with increases in SR, but in some L_{50} increased with no effect on SR. Shortening/removing lastridge ropes had similar variable effects	Lök et al. (1997), Dahm (1998), Halliday and Cooper (2000), Tosunoğlu et al. (2003), Kynoch et al. (2004), Aydin et al. (2014), Demirci et al. (2019)
	T45 mesh codends instead of T0 (simple)	T45 meshes in codends usually reduced SRs across comparable L_{50}s as similar-sized T0 meshes for roundfish, but less so for flatfish	Robertson and Stewart (1988), Millar and Walsh (1992), Walsh et al. (1992), Wallace et al. (1996), Petrakis and Stergiou (1997), Stergiou et al. (1997), Dahm (1998), Perez-Comas et al. (1998), Tokaç et al. (1998), Halliday et al. (1999), Stergiou (1999), Halliday and Cooper (2000), Kunjipalu et al. (2001), Campos and Fonseca (2003), Campos et al. (2003), Bahamon et al. (2006), Ordines et al. (2006), Sardá et al. (2006), He (2007), Lucchetti (2008), Prakash et al. (2008, 2013), Sala et al. (2008), Ateş et al. (2010), Aydin et al. (2011), Özbilgin et al. (2012, 2015), Rajeswari et al. (2013), Tokaç et al. (2014), Dereli and Aydin (2016), Madhu et al. (2016), Düzbastilar et al. (2017), Demirci and Akyurt (2017), Brčić et al. (2018b), Joshy et al. (2018), Ceylan and Sahin (2019), Eryasar and Özbilgin (2015), Zengin et al. (2019)

Table 2 continued

Zone in trawl	Modification(s) and complexity	Impacts	Reference(s)
	T90 or hexagonal-mesh codends instead of T0 (simple)	T90 usually increased L_{50}s with reduced or unchanged SRs for similar T0 mesh sizes; but less so for flatfishes. Hexagonal mesh similarly affected the size selection of Atlantic horse mackerel	Kunjipalu et al. (1994), Moderhak (1997), Moderhak (1999), Moderhak (2000), Aydin and Tosunoglu (2010), Digre et al. (2010), Wienbeck et al. (2011), Herrmann et al. (2013a), Dereli and Aydin (2016), Ilkyaz et al. (2017), Lomeli et al. (2017a), Kaykaç et al. (2018), Veiga-Malta et al. (2019)
	T45 or T0 windows in conventional codends (simple)	T45 windows usually increased L_{50}s with reduced or at least unchanged SRs, especially for round fish. T0 windows also similarly improved selectivity for some species	Moderhak (2000), Zuur et al. (2001), Madsen et al. (2002), Metin et al. (2005), Özbilgin et al. (2005), Madsen et al (2006), Bullough et al. (2007), Grimaldo et al. (2007), Kaykaç (2010), Tokaç et al. (2010), Özdemir et al. (2012, 2014), Wienbeck et al. (2014), Alzorriz et al. (2016), Sistiaga et al. (2018), Ceylan and Sahin (2019)
	Positioning of T0/T45/T90 panels/windows/cylinders in extensions and codends (simple)	Moving T45 windows aft improved L_{50}s with reduced or unchanged SRs. Having windows on the top of the codend was usually better than on the sides, but for some species having panels on the bottom was better. Having T45 or T90 as a full cylinder in the extension improved L_{50}s while maintaining SRs for some species	Graham and Kynoch (2001), Graham et al. (2003), Madsen and Staehr (2005), O'Neill et al. (2006), Herrmann et al. (2015b), Brčić et al. (2016,2018a), Kopp et al. (2018), Sola and Maynou (2018), Ceylan and Sahin (2019), Mouchet et al. (2019), Cuende et al. (2020b)
	Assessment of stimulation/guiding devices inside codend and/or extension to direct fish to escape panels/windows (complex)	Reduction in catches of most unwanted species with little loss of targets. Inserting solid black panels in codends evoked some behavioural responses, but LEDs had few effects	Glass and Wardle (1995), He et al., (2008), Lomeli and Wakefield (2012), Herrmann et al. (2015b), Fraser and Angus (2019), Cuende et al. (2020a, 2020b)
	Size-selective grids, including the sort-X, sort-V, FRESWIND or flexi-grids (rigid or flexible) (complex)	Mostly reduced SR for any required L_{50}. Angles of grids affected selectivity. Few diurnal effects. Main advantage of flexible grids is ease of handling	Larsen and Isaksen (1993), Rose (1999), Sardá et al. (2004, 2005, 2006), Jørgensen et al. (2006), Bahamon et al. (2007), Aydin et al. (2008), Herrmann et al. (2013b), Larsen et al. (2016), Santos et al. (2016a), Özvarol (2016a, 2016b), Gamaza et al. (2018), Larsen et al. (2018b), Brinkhof et al. (2020), O'Neill et al. (2008), Sistiaga et al. (2009, 2016a, 2018),

Table 2 continued

Zone in trawl	Modification(s) and complexity	Impacts	Reference(s)
	Species-selective grids, including the Nordmøre or super-shooter grids (rigid or flexible) (complex)	Reduced key megafauna by up to 100%, with no loss of targeted fish. Main advantage of flexible grids is ease of handling	Chosid et al. (2012), Eigaard et al. (2012), Brčić et al. (2015), Lomeli and Wakefield (2013, 2016), Lucchetti et al. (2016), Lomeli et al. (2017b), Vasapollo et al. (2019)
	Assessment of certain lifting/guiding panels/funnels/deflectors to direct fish (complex)	Significantly improved selectivity (i.e. increased L_{50}s with reduced or constant SRs).in most studies and for many species	Halliday and Cooper (1999), Rose and Gauvin (2000), Maartens et al. (2002), Kvamme and Isaksen (2004), Kvalsvik et al. (2006), Sistiaga et al. (2008, 2009, 2012), Herrmann et al. (2013c), Grimaldo et al. (2015)
	Combinations of grids and T0/T45 mesh windows (complex)	Improved L_{50}s with reduced or constant SRs for most species examined	Eigaard and Holst (2004), Graham et al. (2004a, b), Fonseca et al. (2005), Coll et al. (2008), Grimaldo et al. (2008, 2009), Wakefield et al. (2017), Vogel et al. (2017), Herrmann et al. (2019)
	Mechanisms to release fish at certain depths or when catches reach a certain level using acoustic releases, weak-links or pre-set holes (complex)	Expensive and complex systems that did not seem to perform better than other modifications	Grimaldo et al. (2014), Brinkhof et al. (2019)
Other modifications	Comparisons of trawls, often modified with different sweep and bridle lengths, headline heights, floats, ground chains, and/or mesh sizes in various parts of the wings, body and codend (complex)	Significant species-specific differences due to modified trawls, but causes are often difficult to determine due to combinations of modifications within each	Fiorentini et al. (1999), Cartes et al. (2009), Holst and Revill (2009), Reid et al. (2012), Manjarres-Martinez et al. (2015)
	Single vs twin trawls (simple)	Standardized catches of some species were greater in twin gear	Sangster and Breen (1998)
	Overall size of gear (simple)	No effects of total net size on standardized catches	Dahm et al. (2002)

T0, diamond shaped; T45, square shaped; T90, turned 90°

Fig. 2 Map showing the locations and numbers of studies assessing technical modifications to demersal otter trawls targeting fish during 1988 to 2020

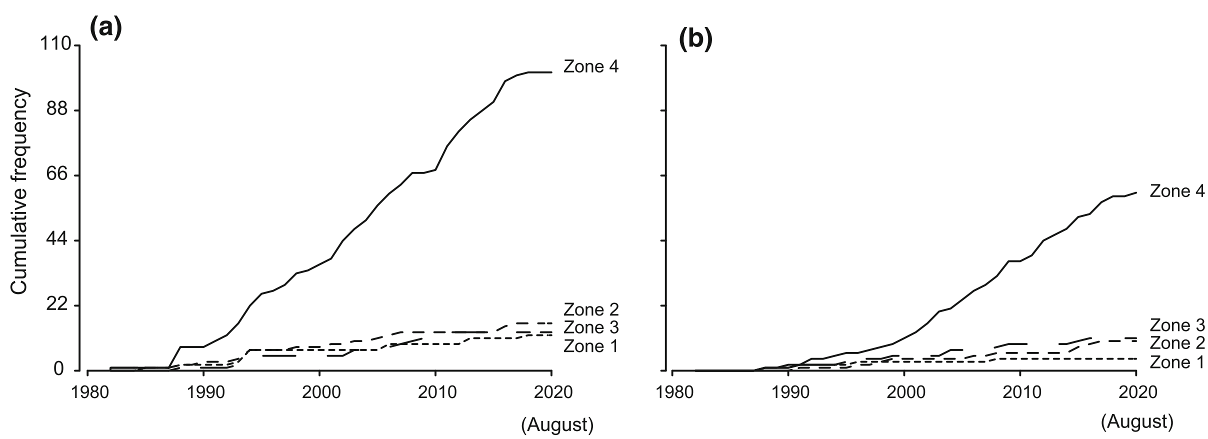

Fig. 3 Cumulative frequency of papers through time (1988 to 2020) describing **a** simple and **b** complex modifications to the defined four zones of demersal fish trawls

smallest treatment, and hooped circumferences and lengths 1.5 and 2.0 times the largest treatment codend. Nevertheless, very few studies (e.g. Madsen et al. 2002) formally tested for confounding effects as described by Madsen and Holst (2002), although cameras were sometimes used (Campos and Fonseca 2003; Kvalsvik et al. 2006).

Smaller covers were used over the escape exits of several zone-4 modifications (Zuur et al. 2001; Maartens et al. 2002; Sistiaga et al. 2010, 2016a; Herrmann et al. 2013c; Aydin et al. 2014; Ceylan and Sahin 2019; Brinkhof et al. 2020), or on their own (Eigaard and Holst 2004; Sardá et al. 2005, 2006; Aydin et al. 2008; Eigaard et al. 2012) and/or with small-mesh codend liners (Larsen and Isaksen 1993; Maartens et al. 2002; Sistiaga et al. 2016a, 2018; Mouchet et al. 2019). Typically, a covered treatment was assessed in isolation, and without concomitant testing of a conventional configuration (e.g. Metin et al. 2005; Park et al. 2012; Lomeli and Wakefield 2016; Larsen et al. 2016, 2018b). Other covers or collecting bags were occasionally used in zone-2 or -3 modifications to retain organisms escaping under the foot rope/ground gear (Pol et al. 2016b; Kaykaç et al. 2018) or through anterior trawl panels (Park et al. 2012; Santos et al. 2016b; Larsen et al. 2018a).

Data describing catch-at-length for individual species were collected from the codend and cover and typically analysed using various parametric selection curves via maximum likelihood to produce parameter vectors of interest, including the 50% size at selection (L_{50}) and selection range (SR; defined as 70% size at selection—25% size at selection). Such analyses usually incorporated between-haul variation (Fryer 1991) and assessments of model fits (discussed by Millar and Fryer 1999), but not always (Rose 1999; Sardá et al. 2004; Prakash et al. 2013; Rajeswari et al. 2013). Occasionally, additional fixed effects like catch weight (O'Neill et al. 2016) or towing speed (Sala et al 2007) were included in models, and often with variable effects. Any stated selectivity improvements by modified vs conventional configurations were mostly based on either maintaining or increasing L_{50} with a reduced SR, or a constant SR but improved L_{50}. In recent years, several cases of more complex models were used to partition estimated selectivity parameters among different modifications in codend/extensions, and so provide greater detail about the relative efficacy of components (e.g. Sistiaga et al. 2010, 2018; Herrmann et al. 2013c; Brinkhof et al. 2020).

Due to the analyses involved, using covers typically means that studies done in multi-species fisheries have selectivity assessments limited to fewer than seven or eight species (He 2007; Özbilgin et al. 2015; Özvarol 2016b; Brčić et al. 2018a; Kopp et al. 2018), but often only one (e.g. Lowry and Robertson 1996; Moderhak 1997, 1999, 2000; Kynoch et al. 2004; Özvarol 2016a) or two (Reeves et al. 1992; Larsen and Isaksen 1993; Grimaldo et al. 2009; Larsen et al. 2018a, b), or even precipitated separate papers based on data from the same cruise but for different species (Özvarol 2016a, b; Larsen et al. 2016, 2018b) or analyses (Demirci et al. 2017; Cuende et al. 2020a; Brčić et al. 2016, 2018a). The numbers of replicate deployments among treatments have varied considerably, with many involving between 10 and 30 (Kynoch et al. 1999; Campos and Fonseca 2003; Bahamon et al. 2006; Ateş et al. 2010; Krag et al. 2010; Demirci and Akyurt 2017), but some were as low as two (Moderhak 1997; Özdemir et al. 2012; Herrmann et al. 2013c) and as high as 60 or 70 (Gamaza et al. 2018; Campos et al. 2003).

Alternate-haul approaches were presented in 45 papers (22%), and often where treatment trawls encompassing zone 1–3 modifications were compared against control (unmodified) trawls in single-rigged fisheries (e.g. Ramm et al. 1993; Madsen et al. 2006; Grimaldo et al. 2015; Sola and Maynou 2018). Alternate hauls were also used for testing various zone-4 modifications and, in contrast to cover-based experimental designs, were more popular among non-European fisheries (e.g. Wallace et al. 1996; Perez-Comas et al. 1998; He et al. 2008; Graham et al. 2009; Chosid et al. 2012; Wakefield et al. 2017). In some papers assessing zone 1–3 changes, alternate hauls were complemented with ancillary equipment, including trawl-monitoring gear to account for variable spread ratios (defined as the wing-end spread divided by the headline length; e.g. Lauth et al. 1998; Somerton 2004; Lucchetti et al. 2016) and therefore headline height, or cameras (Glass and Wardle 1995; Ferro et al. 2007; He et al. 2008; Wakefield et al. 2017); but not always (Broadhurst and Kennelly 1995; Manjarres-Martinez et al. 2015). Simultaneous paired comparisons were only slightly less common (in 36 papers) and also popular in non-European fisheries, with nine involving trouser trawls (e.g. Millar and Walsh 1992; Pol et al. 2016a), 21 with twin trawls (e.g. Cotter et al. 1997; Graham et al. 2004a, b) and six using parallel hauls (e.g. Pol et al. 2016a, b). Paired comparisons were used to assess modifications across all zones and, as for alternate hauls, often used with ancillary techniques to validate consistent inter-trawl geometries (Pol et al. 2016a, b; Reid et al. 2012; Krag et al. 2015).

Where a small-meshed control codend was used in alternate-haul or simultaneous paired-comparison approaches, catch-at-length data were similarly analysed for parametric selection curves as above for covered approaches, but usually accounting for different probabilities of retention in the treatment and control gears (e.g. via the SELECT method; Halliday et al. 1999; Sistiaga et al. 2008). Additional fixed factors such as catch weight were also occasionally modelled (O'Neill et al. 2006; Pol et al. 2016a, 2016b). However, unlike covered codend work, assessments were usually done over a greater number of replicate deployments, reflecting the likelihood of increased between-haul variability. Specifically, alternate-haul experiments nearly always involved at least 10 to 30 replicate tows of individual trawls (Galbraith et al. 1994; Eayrs et al. 2017,2020; Fraser and Angus 2019; Lomeli et al. 2019) up to > 80 (Bullough et al. 2007), while paired-comparison approaches had between 5 and 40 replicates (Graham et al. 2003; Graham et al. 2004a, b; Madsen and Staehr 2005; Veiga-Malta et al. 2019; Krag et al. 2009; Kynoch et al. 2011; Campbell et al. 2010; Bonanomi et al. 2020), but as many as 100 (Beutel et al. 2008). Similar detail required in analyses has meant that, as for covered codends, data collected during the same paired-comparison cruises appear to have sometimes been presented in separate papers (e.g. Pol et al. 2016a, 2016b).

More recently, where small-meshed controls were not used in alternate-haul or paired-gear comparisons, but rather treatments were compared against conventional gears, relative selectivity estimates have been made via catch comparisons described by Holst and Revill (2009) and others (e.g. Krag et al. 2015). These approaches produce model estimates of the expected proportions of fish at size and catch ratios in the treatment trawl (Eryasar and Özbilgin 2015; Lomeli et al. 2018, 2019; Fraser and Angus 2019). Also, unlike covered-codend studies, in some cases (mostly off North America and Australia) broader categories of catch data (numbers and weights of species) from alternate-haul or paired-gear comparisons in multi-species fisheries have been analysed using linear (often mixed) models or ANOVA (Brewer et al. 1996; Rose and Nunnallee 1998; Hannah et al. 2005; Graham et al. 2009), and very occasionally simple t-tests or non-parametric approaches (King et al. 2004; Milliken and DeAlteris 2004). These approaches produced mean percentage reductions of bycatch species or unwanted sizes.

Zone-specific modifications

Irrespective of the methodological approach, each of the four zones in the trawl were subjected to various modifications (often with more than one assessed in a particular study) designed to exploit either the perceived behavioural responses and swimming capacities of the key species (especially zones 1 to 3), their sizes (especially zone 4) and/or their morphology (i.e. round vs flatfish) (Table 2). And because researchers are unlikely to publish null results, in all papers at least some aspects of the assessed modification(s) explained variability in the catches of focal species; albeit with substantial variations of influences. Reflecting the work done in each zone, modifications increased in diversity from the anterior to the posterior of the trawl (Table 2).

Zone 1 (spreading mechanisms)

The relatively few attempts at modifying spreading mechanisms were mostly simple, unless as part of changes to other zones (where 50% of modifications were complex) and designed to mostly exploit broad inter-specific behavioural differences (Fig. 3; Table 2). Within the former, variable warp, sweep or bridle lengths were common and often showed quite strong positive and negative impacts on catches of larger and smaller species, respectively (e.g. Engås and Godø 1989b; Sistiaga et al. 2016b). Simply raising sweeps off the bottom decreased the catches of some species (especially flatfish, Pleuronectidae), and often with greater impacts during daylight, while maintaining target catches (Rose et al. 2010; Ryer et al. 2010; Sistiaga et al. 2015; Lomeli et al. 2019) (Table 2). As for penaeid trawls (McHugh et al. 2017), optimising spread ratio for specific designs of fish trawls is important and was clearly illustrated by Rose and Nunnallee (1998) who observed greater catches of arrowtooth flounder (*Atheresthes stomias*, Pleuronectidae), flathead sole (*Hippoglossoides elassodon*, Pleuronectidae) and Alaskan pollock (*Gadus chalcogrammus*, Gadidae) as spread ratio decreased (via a constraining line) in Alaskan trawls.

Zone 2 (headline, foot rope and ground gear)

Modifications at the headline, foot rope and ground gear, whilst also few in number, improved trawl selectivity and/or efficiency for both round (e.g. haddock and cod) and flatfish (flounder, *Platichthys flesus* Pleuronectidae, plaice and dover sole, *Microstomus pacificus* Pleuronectidae) via behavioural mechanisms and also reduced benthic infauna and debris in the trawl (Table 2). Of particular note were improvements generated by using relatively longer (cutaway) headropes (including the 'topless trawl'; Chosid et al. 2008) which were designed to exploit the behavioural response of fish that rise up and increased the escape of haddock, but less so for flatfish (Thomsen 1993; King et al. 2004; Hannah et al. 2005; Eayrs et al. 2017). Similarly, Eayrs et al. (2020) showed that lowering the headline significantly decreased cod catches by a substantial amount (but not flatfish).

Other common zone-2 modifications involving raising the foot rope and other changes to ground gears have mostly maintained target catches, while reducing bycatches of several roundfish including, but not limited to, lutjanids (Brewer et al. 1996), grey gurnard (*Eutrigla gurnardus* Triglidae), whiting, saithe (*Pollachius virens* Gadidae) and Atlantic horse mackerel (Dahm 2000). Such modifications have also reduced the amounts of debris and benthic infauna caught (Ramm et al. 1993; Rose and Nunnallee 1998; Krag et al. 2010). In particular, several studies have compared rockhopper ground gear with alternatives, including the so-called 'semicircular spreading ground gear' which improved catching efficiency for larger cod and haddock, while reducing drag (Brinkhof et al. 2017; Larsen et al. 2018a). Other, simpler, modifications to ground gear have involved exploiting species-specific responses to herding stimuli. For example, Kynoch et al. (2015) demonstrated that removing tickler chains reduced catches of elasmobranchs without affecting targeted haddock, whiting and flatfish. The utility of light emitting diodes (LEDs) as stimuli for exploiting behaviour in zone 2 was tested in some studies with variable selectivity improvements, although, not surprisingly, greater nocturnal effects for certain species (Lomeli et al. 2018; O'Neill and Summerbell 2019).

Zone 3 (trawl wings and body)

Within this anterior-netted section, simply increasing lateral-mesh openings via larger T0 mesh towards the tapering end to match the desired sizes of target species generally improved size selection for roundfish, mostly maintaining commercial catches while reducing unwanted sizes of species such as haddock, whiting and devil anglerfish (Beutel et al. 2008; Holst and Revill 2009; Campbell et al. 2010; Kynoch et al. 2011) (Table 2). A particularly successful suite of modifications has involved horizontal separator panels throughout the trawl to separate downwards-orientating (cod and most flatfish) from upwards-rising species (haddock, whiting and saithe), with possibilities for better selectivity via other compartment-specific modifications in either the trawl body or codend (Cotter et al. 1997; Engås et al. 1998; Ferro et al. 2007; Holst et al. 2009). Short horizontal panels restricted to the aft section of the trawl body also appear to have utility (He et al. 2008). Horizontal separator panels have also extended towards directing jellyfish (Scyphozoa) from trawls through escape exits; albeit with some loss of targeted fish (Park et al. 2012).

Zone-3 modifications have also included various lateral or top-orientated 'windows' in the trawl body made from either T0 or T45 mesh, with some extending throughout (Ball et al. 2003; Bayse et al. 2016; Bonanomi et al. 2020). Generally, the utility of these windows has reflected not only the behaviour of key species but also their shape, with flatfishes better suited to escaping through T0 than T45 meshes (Milliken and DeAlteris 2004). Most designs have reduced unwanted sizes, although it is clear lateral-mesh openings need to be carefully considered in multi-species fisheries to avoid loss of targets (Bonanomi et al. 2020).

Zone 4 (extension and codend)

Based on the long-standing assumption that the codend is responsible for most of the selection in a trawl (Millar and Fryer 1999), the earliest modifications tested to improve fish-trawl size selectivity involved simply increasing the conventional T0 mesh (e.g. Walsh et al. 1992). Such changes are described in 14 papers (Table 2) and, because many fisheries initially had mesh sizes chosen by industry prior to being regulated (and were therefore as small as possible), in virtually all cases these changes led to increases in L_{50}s, often with reasonable SRs and therefore maintained target catches commiserate with expectations.

Some studies concurrently investigated changes in codend configurations other than increasing mesh size. For example, reducing the circumferences of codends and/or the lengths of extensions improved selectivity for various species for T0 mesh codends (described in 15 papers including very good studies by Wienbeck et al. 2011; Eryasar et al. 2014; Herrmann et al. 2015a). The codend material also had effects, whereby single and more flexible twine often improved selectivity (in nine papers and particularly those by Kynoch et al. 1999; Sala et al. 2007); however variable twine diameters were sometimes overlooked in some zone-4 studies assessing other factors (Lowry and Robertson 1996; O'Neill et al. 2016). Also, removing external rigging like strengthening bags and chafing gear, or even increasing their circumferences improved selectivity in seven papers including those by Tosunoğlu et al. (2003), Kynoch et al. (2004) and Demirci et al. (2019).

But the largest number of studies done to improve selectivity in fish trawls has involved simply replacing T0 with T45 mesh throughout codends (38 papers including very good experiments by Robertson and Stewart 1988; Millar and Walsh 1992; Halliday et al. 1999; He 2007; Lucchetti 2008; Özbilgin et al. 2012; Tokaç et al. 2014; Düzbastilar et al. 2017; Demirci and Akyurt 2017) (Table 2). Various configurations of T45 codends have been assessed in many fisheries, across many species assemblages and with a general trend of facilitating either maintained or improved L_{50}s across lower SRs for roundfish, including Atlantic horse mackerel (Campos et al. 2003), red mullet (Dereli and Aydin 2016), hake (Halliday and Cooper 2000), cod (Halliday et al. 1999; He 2007), haddock and saithe (Halliday et al. 1999), Dussumier's anchovy (*Thryssa dussumieri* Engraulidae Madhu et al. 2016; Joshy et al. 2018) and largehead hairtail (*Trichiurus lepturus*, Trichiuridae; Rajeswari et al. 2013). While codends made from T45 mesh can also have lower SRs than the same-sized T0 mesh for flatfish (e.g. American plaice; Millar and Walsh 1992; Walsh et al. 1992), generally they are less effective at improving their size selection (Wallace et al. 1996; Perez-Comas et al. 1998).

One recurring issue with T45 codends is their relatively lower netting flexibility and strength than T0 codends (Madsen 2007). These deficits have been addressed in some fisheries by simply turning meshes to 90°, effectively increasing and maintaining lateral-mesh openings which can produce similar selectivity across comparable mesh sizes as T45. Codends made entirely of T90 mesh first appeared in 1997 in the Baltic Sea (Moderhak 1997, 1999, 2000) and have subsequently been assessed in 13 papers (all in Europe except for Lomeli et al. 2017a) including detailed studies for cod, European plaice and red mullet by Wienbeck et al. (2011) and Kaykaç et al. (2018). We also located a single study examining hexagonal mesh, but the authors noted fewer benefits in terms of maintaining SR and increasing L_{50} than the same sized T45 mesh (Aydin and Tosunoglu 2010).

In addition to codends made entirely of alternative meshes, many studies assessed the effects and positioning of various windows made from larger T0 or T45 mesh, which have the advantage of only altering a small section of conventional codends and so maintaining many existing operational characteristics (Table 2). Generally, such windows allowed unwanted sizes or species to escape with few impacts on commercial catches and tended to function better the further aft they were positioned in the codend for several species, including haddock (Graham and Kynoch 2001; Graham et al. 2003; O'Neill et al. 2006) and cod (Herrmann et al. 2015b), but sometimes not for whiting (Graham et al. 2003). The use of guiding/stimulating devices in the codend to herd fish towards such windows where they can then be selected based on size further improved effectiveness in some cases (e.g. for cod; Fraser and Angus 2019), although LED lights seem to have little effect on the few assessed species, including hake and whiting (Cuende et al. 2020a, b).

As well as simple changes to lateral-mesh openings in the codend and/or extension, many studies have examined complex modifications including grids (with and without guiding panels and deflectors) to similarly exclude either (1) different sizes of the target species ('size-selective' grids); or (2) much larger organisms ('species-selective' grids). Both categories have been tested across many jurisdictions, but most work occurred with size-selective designs in the Barents and North seas in attempts at increasing or maintaining L_{50}s, while reducing SR for a few key species (Table 2).

Among the early size-selective grids was the 'sort-X' (Larsen and Isaksen 1993); a steel grid made in three sections with 55-mm bar spaces that was first tested in the North Sea with cod and haddock and then other fisheries (Sardá et al. 2004; Herrmann et al. 2013b; Gamaza et al. 2018). The sort-X improved selectivity for cod and haddock in several studies. Other authors tested variations of the sort-X concept with variations being the single steel, 'sort-V' (Kvamme and Isaksen 2004; Jørgensen et al. 2006; Sistiaga et al. 2008, 2010; Herrmann et al. 2013c), FRESWIND (Santos et al. 2016a) and the more commonly used plastic and fibreglass 'flexi-grids'

(Sistiaga et al. 2009, 2016a; Brinkhof et al. 2020) which, subject to determining appropriate bar spaces (Sistiaga et al. 2008; Herrmann et al. 2013c; Vogel et al. 2017) generally reduced SRs and so improved selectivities in the fishery(ies) examined, and with easier handling than the sort-X. However, SRs have remained sufficiently wide to evoke substantial loss of target sizes in fisheries seeking to reduce all undersized catches (Brinkhof et al. 2020). Further, at least some work has demonstrated similar selectivity being achieved though simpler modifications, like windows with greater/more consistent lateral-mesh openings; albeit with variable differences in the timings of escape (e.g. Grimaldo et al. 2008). In particular, Jørgensen et al. (2006) noted few differences for cod between the sort-V and simply increasing codend mesh size.

Following their widespread use and success in penaeid trawls (Broadhurst 2000), species-selective grids, including the Nordmøre-, super-shooter and other top- or bottom-opening, inclined grids have been tested in some fish trawls (Chosid et al. 2012; Lomeli and Wakefield 2013, 2016; Brčić et al. 2015), some with various types of lifting/guiding panels and/or funnels to direct fish (e.g. Halliday and Cooper 1999; Rose and Gauvin 2000; Grimaldo et al. 2015). Their consideration was mainly precipitated by a need to reduce bycatches of charismatic megafauna, including sea turtles (Vasapollo et al. 2019), elasmobranchs (Chosid et al. 2012; Brčić et al. 2015) and marine mammals (Wakefield et al. 2017). Providing bar spaces were sufficient, several designs have successfully maintained target catches (but see Brčić et al. 2015) while reducing megafauna by close to 100%.

There have also been several studies that have examined combinations of grids with T0/T45 mesh windows (Eigaard and Holst 2004; Graham et al. 2004a, b; Fonseca et al. 2005; Grimaldo et al. 2008, 2009; Herrmann et al. 2019). Most have proven to be quite successful at improving L50s at reduced or constant SRs.

A final suite of quite complex and expensive modifications to zone 4 involve mechanisms to release fish at certain depths or when catches reach a certain level using acoustic releases, weak-links or pre-set holes in the codend/extension (Grimaldo et al. 2014; Brinkhof et al. 2019). While they do have fishery-specific utility for ensuring quotas of target species are not exceeded, in terms of reducing unwanted bycatches more broadly, such modifications might not perform better than other, simpler approaches.

Other modifications

Sixteen papers simultaneously examined combinations of simple and complex modifications within more than one zone in the trawl. For some studies, the individual utility of some modifications could be deciphered and were included in the relevant zones discussed above, although some experimental designs precluded completely understanding which components were responsible for improving selectivity and/or efficiencies (e.g. Fiorentini et al. 1999; Madsen et al. 2006; Cartes et al. 2009; Manjarres-Martinez et al. 2015). Seven papers, including four assessing all zones in the trawl, were not partitioned above and are included here because they mostly comprised completely different trawls which were typically assessed during surveys (e.g. Cartes et al. 2009; Reid et al. 2012; Manjarres-Martinez et al. 2015). The exceptions were Sangster and Breen (1998) who compared single and twin rigs and showed that standardised (for swept area) catches of some species were greater in twin gear, and Dahm et al. (2002) who compared different sizes of trawls and showed no effect on standardized catches.

Discussion

The problem unresolved

The reviewed 203 papers describe some 28 broad categories of simple and complex technical modifications for improving size or species selectivity, and so reducing unwanted bycatches in fish trawls over the past three decades. However, despite these options, no fishery has completely resolved all bycatch problems while maintaining targeted catches at conventional levels. And nor is this likely to occur—because the generic design of trawls, the different behaviours, sizes and shapes of fish caught, combined with diverse, and ever-changing priorities regarding target species (and therefore bycatches) preclude absolute 100% selectivity in such gears (and, indeed, for most fishing gears—Kennelly and Broadhurst 2002).

The effect of the above issues is clearly evident in the many papers and, indeed, overarching bias in research efforts in this field towards relatively few species—particularly the 64 and 59 papers focussing on haddock and cod, respectively (with 15 in the most recent two years). Some justification for this historical focus can be attributed to variable minimum legal sizes among fisheries, such as 32 (Madsen and Staehr 2005), 35 (Moderhak 1999), 38 (Santos et al. 2016a), 44 (Sistiaga et al. 2015) and 47 cm TL (Sistiaga et al. 2008) for cod, and inconsistent relationships between L_{50} and SR affecting the consistency of scaled-up modifications (Wileman et al. 1996). But, as for other commonly assessed species (including whiting, hake, red mullet and Atlantic horse mackerel), most efforts appear to reflect either unresolved or new selectivity issues and/or, in some cases, technological solutions that were not easily transferable among fisheries.

Irrespective of the mechanisms leading to repetitive research on relatively few species, this outcome provides a positive corollary for maximizing future progress in this field (which may not extend to 100% resolution but could nevertheless substantially ameliorate bycatch problems). That is, by developing and documenting the broad ranges of (1) experimental approaches and (2) potential modifications to reduce bycatch in fish trawls, we suggest studies of other species, in fisheries in the same or other parts of the world, might be progressed with less unnecessary repetition, and so ensure maximum cost–benefit in designing, refining and implementing solutions.

Considerations regarding experimental approaches

All the reviewed literature used at least one of three broad categories of experimental methods (covers, alternate hauls or paired comparisons)—albeit with considerable variability among technical details and the use of ancillary equipment (cameras or trawl-monitoring equipment)—to quantitatively assess the efficacy of modifications. Nevertheless, irrespective of the approach, there were some consistent confounding issues that, in many cases may have compromised identifying successful solutions to bycatch problems.

One of the key limiting factors has been failure to incorporate sufficient spatio-temporal replication in experiments. Many studies have shown that, in addition to sometimes even subtle technical factors within a trawl, a plethora of other biological, environmental and operational factors variably affect selectivity (Wileman et al. 1996; Broadhurst et al. 2016). These include, but are not limited to, water temperature and/or fish condition (Özbilgin et al. 2007); sea state (Somerton et al. 2018); diel patterns (Ryer et al. 2010); towing speed (Sala et al. 2007; Somerton and Weinburg 2001); haul-back delay (Madsen et al. 2008); catch weight (O'Neill et al. 2008); or water depth (Sala et al. 2008). The number and variety of such issues and fishery-specific importance mean that it is difficult to envisage their variability being captured in studies involving just two to five hauls over a few days in a fishing season (e.g. Sardá et al. 2006; Aydin et al. 2008; Özdemir et al. 2012, 2014; Rajeswari et al. 2013). In fact, several authors have acknowledged such factors probably contributed to differences in estimated parameter vectors for the same modifications tested in subsequent experiments (e.g. Brinkhof et al. 2020). Only by incorporating appropriate spatio-temporal replication across the full range of fishing conditions can such factors be adequately addressed. We acknowledge that operational costs usually restrict the days at sea available for experiments, but even within such constraints, experiments can still optimize replication given levels of variance using well-established cost–benefit procedures (Kennelly et al. 1993). And because of the number and variety of studies already done, the required parameters for such analyses should be readily available for many fisheries.

In addition to problems of replication, we suggest that many studies did not adequately assess for confounding effects of the experimental procedure on the treatments of interest. In particular, some designs of covers could affect the geometry and efficiency of trawls (Madsen and Holst 2002), and certainly fine-mesh liners in codends would displace more water forwards, potentially affecting the passage of fish (Broadhurst et al. 1999, 2002). Such effects were rarely tested for, or their confounding effects ignored. As one example, Madsen et al. (2001) recommended the kite cover for codends and subsequently demonstrated few confounding effects on selectivity (Madsen and Holst 2002), but despite this, most studies used hooped covers (but see Grimaldo et al. 2009). It should be a fairly simple procedure to confirm that codend/escape exit covers or liners do not affect the performances of either the trawl or the modifications using alternate hauls within the same experiments. And considering that repeated experiments have been done using consistent trawl designs in many fisheries, testing for ancillary cover effects might only need to be published periodically.

Many studies have also identified other technical factors that can confound trawl-gear comparisons, such as variable codend lengths or circumferences (Reeves et al. 1992; Sala and Lucchetti 2011), twine diameters (Lowry and Robertson 1996) and/or netting materials (Tokaç et al. 2004; O'Neill et al. 2016). But consistency among these factors was not identified (or stated) in many of the reviewed papers. Further, there was a tendency to present and discuss nominal mesh sizes (i.e. from the manufacturer) which were not stated as being measured (e.g. Özbilgin et al. 2005; Sola and Maynou 2018; Santos et al. 2016b), but if this did occur, mean mesh sizes were always different (e.g. Perez-Comas et al. 1998; Sala and Lucchetti 2011; Özbilgin et al. 2015). Because manufactures' nominal mesh sizes are not replicable, following Wileman et al. (1996) and Ferro and Xu (1996), we reiterate that these should be quantified and presented as mean sizes with variances. Similarly, all other technical specifications known to affect the selectivity of trawls should be stated.

Another issue regarding experimental procedures concerns the ease of their interpretation by fishing industries (who need to use any modifications) and managers (who need to legislate them). Many analyses involved producing selectivity ogives which present the probability of fish escaping at a particular size, and are needed to illustrate the absolute selectivities of gears independent of the population fished (Millar and Fryer 1999). Nevertheless, this approach is not particularly intuitive for fishers or managers, and contrasts with attempts to reduce bycatches in other fisheries where bycatches are usually discussed in terms of percentage reductions in whole weights or numbers (rather than sizes) (Pérez Roda et al. 2019; Kennelly 2020).

While we do not propose that the existing analytical methods be avoided, we suggest that there may be some scope for complementary approaches that, in addition to providing estimates of L_{50} and SR, also indicate total bycatch reductions due to the modification(s). Certainly, there appears to be a regional pattern in this regard, with European studies focusing more on experimental approaches using covers and therefore mostly reporting analyses of catches at size (e.g. Larsen and Isaksen 1993; Sistiaga et al. 2010; Ceylan and Sahin 2019). In contrast, studies in North America and Australia (although fewer in number) have been more biased towards alternate-haul experiments that concomitantly presented estimates of bycatch reductions as standardised predicted mean weights and/or numbers of animals (e.g. Lauth et al. 1998; King et al. 2004; Hannah et al. 2005; Graham et al. 2009; Eayrs et al. 2020). An additional advantage of combining approaches is that more data about the assemblages of species would be used, which may reduce the need for researchers to report results from the same cruises in separate papers (e.g. Özvarol 2016a, b; Larsen et al. 2016, 2018b; Pol et al. 2016a, b). Although presenting variations among broad categories of catches will not change the hypotheses tested, it might promote better understanding by industries which, in turn would encourage their greater development, refinement and ownership of solutions and, eventually, implementation of successful designs (Kennelly and Broadhurst 2002).

Some rationalization and consistency in experimental approaches would also benefit the future synthesis of data, especially those involving meta-analyses. The latter are increasingly being used to examine various parameters/estimates obtained in experiments to derive generalisable patterns over diverse situations (including those involving gear selectivity; Fryer et al. 2016; Melli et al. 2020) and subsets of the 203 papers summarized here could provide starting points for such work. However, as we identified in this review, inconsistency among papers in the estimation of parameters, variable scientific rigour (in terms of experimental designs and replication) and the non-reporting of null results, could compromise the validity of such analyses. That is, as is the case for individual experiments, confidence in any generalities that may come from meta-analyses of papers will be entirely dependent on the quality of the data used in them.

Choosing effective modifications

In examining the various categories of modifications developed to reduce bycatch in fish trawls, this review has assessed the utility, applicability, advantages and disadvantages of each. This led to the development of a framework which could be followed in future work, particularly for hitherto un-examined fisheries (Table 3). Often, key prerequisites to getting technological solutions into practice throughout a fishery are

Table 3 A framework for assessing modifications in demersal fish trawls

Consideration	Zone(s)	Modifications to test in sequence	Advantages	Disadvantages
First:	4	Choose the correct mesh size and shape for the smallest target species	Simple changes usually improve selectivity	Modifications will not reduce drag or fuel usage
		Choose the narrowest possible codend circumference and twine diameter	This zone is usually common among fleets	Some modifications (e.g. square-mesh configurations) can alter through time
		To reduce catches of round fish, locate escape windows as close as possible to the catch and on the top of the codend	Changes can be flexible and easy-to-source	Fish escape may occur after substantial interactions with the gear leading to some mortality
		To increase fish entering escape exits, consider guiding panels/stimulants (e.g. LEDs for nocturnal fishing or deep water)	Trawl monitoring equipment is not required	
		To reduce catches of small fish in fisheries with very few target species, consider size-selective grids		
		To reduce catches of animals larger than the targeted species, consider species-selective grids		
Next:	1–3	Choose the largest possible diamond-mesh sizes throughout zone 3	Simple changes usually improve selectivity	These zones are often not common throughout fleets
		Choose the narrowest possible twine diameter	Changes can reduce drag and fuel usage	It can be difficult to distinguish the key factors improving selectivity
		Use a horizontal separator panel(s) to confirm species-specific behaviour in the trawl to inform the design of modifications	Changes can be flexible and easy-to-source	Trawl-monitoring equipment is usually required
		Depending on species distributions inside the trawl, assess windows with different mesh shapes in the wings, or top panels	Unwanted fish often escape the trawl entirely with low mortality	
		To increase fish contact with panels/windows, consider guiding panels/stimulants (e.g. LEDs)		
		Depending on species distributions inside the trawl, assess different types of ground gears		
		Optimise bridle and sweep lengths for target species		
		Optimise the spread ratio of the trawl		

that they not only reduce bycatches while maintaining target catches across most spatio-temporal scales, but are also simple and easy to understand and implement (Tucker et al. 1997). While we have no quantitative measure regarding the relative success and adoption of complex vs simple modifications, there was no clear trend towards either being more or less efficient, although simpler modifications were more common—especially in zone 4 of the trawl. Therefore, it seems appropriate for fledgling studies to first modify existing configurations within the codend to improve selection, simply because these are usually cheapest, within the (often-generational) experience of fishers, and codends are relatively homogenous within, and even between, fleets (Table 3).

More specifically, increasing lateral-mesh openings throughout codends via the use of larger T0 or similar sizes of T45 or perhaps T90 mesh (considering the operational issues with T45) to match the desired sizes and shapes of focus species would be a logical starting point, and especially for fusiform fish morphologically similar to the commonly assessed Atlantic horse mackerel, hake, haddock or red mullet (Halliday and Cooper 2000; Campos et al. 2003; Dereli and Aydin

2016). Alternatively, if there is industry resistance to alternative-mesh configurations, reducing codend circumference might be an even simpler option for T0 codends (Reeves et al. 1992; Galbraith et al. 1994; O'Neill et al. 2008; Graham et al. 2009), but with fewer benefits for T45 (Sala et al. 2016)—a similar result found for penaeid trawls (Broadhurst and Millar 2009). Narrower twine dimeters and/or avoiding double twine would similarly be appropriate options for all mesh configurations (Graham et al. 2009).

In some cases, instead of changes to the whole codend (that might affect strength or flexibility), installing relatively small windows in codends (mostly on the top or sides) made from meshes with larger lateral openings could have utility, although positioning is clearly important with locations closer to the catch most beneficial (e.g. Graham and Kynoch 2001; Graham et al. 2003) (Table 3). Such positioning was further discussed by Herrmann et al. (2015a, b) and reaffirms earlier research in penaeid trawls where displaced water was shown to assist fish to escape via proximal openings (Broadhurst et al. 1999, 2002). A consequence of these effects is that they imply confounding impacts of the use of codend liners and/or inappropriate cover designs (discussed above).

Grids are also clearly successful zone-4 options, although their choice needs to be very fishery-specific (Table 3). That is, size-selective grids, and especially the flex-grid and variants might warrant future extension and assessment in those fisheries with few species or where most bycatches are juveniles of the targets (e.g. Larsen and Isaksen 1993; Sardá et al. 2004; Eigaard et al. 2012; Herrmann et al. 2013b; Larsen et al. 2016, 2018b; O'Neill et al. 2008; Sistiaga et al. 2018). In addition, using guiding panels and deflectors to direct fish toward such grids can augment selectivity (e.g. Halliday and Cooper 1999; Kvamme and Isaksen 2004; Kvalsvik et al. 2006; Grimaldo et al. 2015). But in some cases, compared to size-selective grids, simpler modifications like increasing codend mesh size could be just as effective (Jørgensen et al. 2006; Grimaldo et al. 2008). In contrast, and as for penaeid trawls, there appear to be few simple options for excluding charismatic megafauna like turtles, seals and elasmobranchs other than species-selective grids, although subtle refinements (e.g. to bar shape, size and design) can be made to maintain target catches of fish (Wakefield et al. 2017; Vasapollo et al. 2019).

Concomitant with simple zone-4 modifications as a starting point for improving trawl selection are several promising options for the anterior sections of the trawl (Table 3). However, considering there are few examples in the literature where the relative utility of individual multiple-zone configurations could be deciphered, all anterior modifications need to be assessed in isolation and with carefully considered experimental controls. Simple options involve entire areas or windows with larger lateral-mesh openings (like those used in zone 4) and designed to partition species based on size (e.g. Milliken and DeAlteris 2004; Bayse et al. 2016; Santos et al. 2016b; Bonanomi et al. 2020). But most modifications in these trawl sections rely on species-specific behavioural responses. As a broad distinction, many roundfish rise up (but not all; e.g. cod), while flatfish remain low; a characteristic which can and has been used to separate species using modifications like horizontal panels (Engås et al. 1998; Ferro et al. 2007; He et al. 2008; Holst et al. 2009; Park et al. 2012) or topless trawls (e.g. Chosid et al. 2008; Krag et al. 2015; Eayrs et al. 2017).

Certainly, horizontal panels might be positioned in studies of unassessed trawls to provide initial information on the preferred orientations of the key species as a precursor to making simple changes to promote bycatch escape (He et al. 2008). Light emitting diodes might then also be tested to exploit any identified behavioural differences (Lomeli et al. 2018). For example, Southworth et al. (2020) used a T45 window with and without LEDs in the top body of a scallop trawl and showed that the non-illuminated window reduced catches of whiting and haddock in shallow water while illuminating the panel in deep water reduced haddock and flatfish catches.

Notwithstanding the potential complementary benefits on overall trawl selection associated with modifying the anterior sections, the reviewed studies indicated that considerable ancillary information concerning the behavioural subtleties of focus species in nets is needed, and incorporating often wide spatio-temporal variability in key environmental parameters (Wardle 1989). In addition to sufficient replication, this often requires quite specialized equipment including cameras and/or sonar (e.g. Krag et al. 2015; Cotter et al. 1997; Engås et al. 1998; Ferro et al. 2007). Furthermore, changes in the anterior section affect whole trawl geometries (i.e. spread ratios and headline height) which means trawl-monitoring equipment needs to be used and any effects incorporated into analyses (e.g. Lauth et al. 1998; Fiorentini et al. 1999; Milliken and DeAlteris 2004; Krag et al. 2015). Such implicit requirements of zone 1 to 3 modifications and their isolated testing may limit attempts at resolving bycatch issues in this part of the trawl in some fisheries, especially those in developing countries.

Nevertheless, advantages of modifying the anterior trawl include minimizing escape mortalities because, unlike the close confines of zone 4, fish are less likely to contact netting or other animals and so get injured or killed (Table 3). Further, because this area dictates most of the system drag, there is considerable potential to reduce operating costs through so-called 'low impact fuel efficient' designs (LIFE; Suuronen et al. 2012) which can, in turn, facilitate adoption throughout fleets due to concomitant fuel savings (McHugh et al. 2017).

Conclusions

This review demonstrated that most efforts towards reducing bycatch in fish trawls have involved relatively few species in the North Atlantic Ocean which, when combined with considerable collaboration among researchers, has precipitated significant similarity in the designs of modifications and ways to assess them. But despite a geographic bias in effort, within this region are diverse fisheries that range from nearly mono- to multi-specific targeting various fish sizes and shapes (round and flatfish) and with divergent behaviours. This means the reviewed studies encompass sufficient variety to provide excellent starting points for unassessed fisheries, especially with respect to simple modifications like T45/90 mesh throughout codends, or as posterior top-orientated windows.

The less-studied, non-European fisheries also offer unique perspectives, including variability in operations that could benefit existing modifications, and experimental approaches based more towards alternate haul and paired-gear comparisons that facilitate relative comparisons of absolute catches—which can be more easily understood by stakeholders. But no matter the region or basic approach, a major conclusion from this review is that maintaining a rigorous empirical framework to adequately test and quantify the efficacy of individual modifications, while conveying implications about catches and bycatches to stakeholders, is as important as the simplicity and reliability of the modifications themselves.

While we advocate zone-4 modifications as an excellent starting point for unassessed fisheries, wherever possible these should be complemented by a more holistic LIFE approach to resolving issues in trawl fisheries (Suuronen et al. 2012). Fishers are more likely to refine and adopt modifications that reduce bycatch if there are additional benefits such as minimising fuel usage via reductions in drag through simple modifications in zones 1 to 3. And of course, engaging industries in all such work should dramatically increase the eventual implementation of successful solutions.

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References

Alzorriz N, Arregi L, Herrmann B, Sistiaga M, Casey J, Poos JJ (2016) Questioning the effectiveness of technical measures implemented by the Basque bottom otter trawl fleet: Implications under the EU landing obligation. Fish Res 175:116–126. https://doi.org/10.1016/j.fishres.2015.11.023

Ateş C, Deval MC, Bök T, Tosunoğlu Z (2010) Selectivity of diamond (PA) and square (PE) mesh codends for commercially important fish species in the Antalya Bay, eastern Mediterranean. J Appl Ichthyol 26:465–471. https://doi.org/10.1111/j.1439-0426.2010.01462.x

Aydin C, Sensurat T, Özdemir Y, Tosunoğlu Z (2014) Effect of the number of meshes in the protective bag circumference on size selectivity of demersal trawl codends. J Appl Ichthyol 30:454–462. https://doi.org/10.1111/jai.12413

Aydin C, Tokaç A, Ulaş A, Maktay B, Şensurat T (2011) Selectivity of 40 mm square and 50 mm diamond mesh codends for five species in the eastern Mediterranean demersal trawl fishery. Afr J Biotechnol 10:5037–5047

Aydin C, Tosunoglu Z (2010) Selectivity of diamond, square and hexagonal mesh codends for Atlantic horse mackerel *Trachurus trachurus*, European hake *Merluccius merluccius*, and greater forkbeard *Phycis blennoides* in the eastern Mediterranean. J Appl Ichthyol 26:71–77. https://doi.org/10.1111/j.1439-0426.2009.01376.x

Aydin C, Tosunoğlu Z, Tokaç A (2008) Sorting grid trials to improve size selectivity of red mullet (*Mullus barbatus*) and annular sea bream (*Diplodus annularis*) in Turkish bottom trawl fishery. J Appl Ichthyol 24:306–310. https://doi.org/10.1111/j.1439-0426.2007.01052.x

Bahamon N, Sardá F, Suuronen P (2006) Improvement of trawl selectivity in the NW Mediterranean demersal fishery by using a 40 mm square mesh codend. Fish Res 81:15–25. https://doi.org/10.1016/j.fishres.2006.05.020

Bahamon N, Sardá F, Suuronen P (2007) Selectivity of flexible size-sorting grid in Mediterranean multispecies trawl fishery. Fish Sci 73:1231–1240. https://doi.org/10.1111/j.1444-2906.2007.01460.x

Ball B, Linnane A, Munday B, Davies R, McDonnell J (2003) The rollerball net: A new approach to environmentally friendly ottertrawl design. Arch Fish Mar Res 50:193–203

Bayse SM, Rillahan CB, Jones NF, Balzano V, He P (2016) Evaluating a large-mesh belly window to reduce bycatch in silver hake (*Merluccius bilinearis*) trawls. Fish Res 174:1–9. https://doi.org/10.1016/j.fishres.2015.08.022

Beutel D, Skrobe L, Castro K, Ruhle P, Ruhle P, O'Grady J, Knight J (2008) Bycatch reduction in the Northeast USA directed haddock bottom trawl fishery. Fish Res 94:190–198. https://doi.org/10.1016/j.fishres.2008.08.008

Bonanomi S et al (2020) Effect of a lateral square-mesh panel on the catch pattern and catch efficiency in a Mediterranean bottom trawl fishery. Mediterr Mar Sci 21:105–115. https://doi.org/10.12681/mms.21955

Brčić J, Herrmann B, De Carlo F, Sala A (2015) Selective characteristics of a shark-excluding grid device in a Mediterranean trawl. Fish Res 172:352–360. https://doi.org/10.1016/j.fishres.2015.07.035

Brcic J, Herrmann B, Sala A (2016) Can a square-mesh panel inserted in front of the codend improve the exploitation pattern in Mediterranean bottom trawl fisheries? Fish Res 183:13–18. https://doi.org/10.1016/j.fishres.2016.05.007

Brčić J, Herrmann B, Sala A (2018a) Can a square-mesh panel inserted in front of the cod end improve size and species selectivity in Mediterranean trawl fisheries? Can J Fish Aquat Sci 75:704–713. https://doi.org/10.1139/cjfas-2017-0123

Brčić J, Herrmann B, Sala A (2018b) Predictive models for codend size selectivity for four commercially important species in the Mediterranean bottom trawl fishery in spring and summer: Effects of codend type and catch size. PLoS ONE. https://doi.org/10.1371/journal.pone.0206044

Brewer D, Eayrs S, Mounsey R, Wang YG (1996) Assessment of an environmentally friendly, semi-pelagic fish trawl. Fish Res 26:225–237. https://doi.org/10.1016/0165-7836(95)00433-5

Brinkhof J, Herrmann B, Larsen RB, Veiga-Malta T (2019) Effect of a quality-improving cod end on size selectivity and catch patterns of cod in bottom trawl fishery. Can J Fish Aquat Sci 76:2110–2120. https://doi.org/10.1139/cjfas-2018-0402

Brinkhof J, Larsen RB, Herrmann B, Grimaldo E (2017) Improving catch efficiency by changing ground gear design: Case study of Northeast Atlantic cod (*Gadus morhua*) in the Barents Sea bottom trawl fishery. Fish Res 186:269–282. https://doi.org/10.1016/j.fishres.2016.10.008

Brinkhof J, Larsen RB, Herrmann B, Sistiaga M (2020) Size selectivity and catch efficiency of bottom trawl with a double sorting grid and diamond mesh codend in the North-east Atlantic gadoid fishery. Fish Res. https://doi.org/10.1016/j.fishres.2020.105647

Broadhurst MK (2000) Modifications to reduce bycatch in prawn trawls: a review and framework for development. Rev Fish Biol Fisher 10:27–60. https://doi.org/10.1023/A:1008936820089

Broadhurst MK, Kennelly SJ (1995) Effects of an increase in mesh size on the catches of fish trawls off New South Wales, Australia. Mar Freshw Res 46:745–750. https://doi.org/10.1071/Mf9950745

Broadhurst MK, Kennelly SJ, Eayrs S (1999) Flow-related effects in prawn-trawl codends: potential for increasing the escape of unwanted fish through square-mesh panels. Fish Bull 97:1–8

Broadhurst MK, Kennelly SJ, Gray CA (2002) Optimal positioning and design of behavioural-type by-catch reduction devices involving square-mesh panels in penaeid prawn-trawl codends. Mar Freshw Res 53:813–823

Broadhurst MK, Millar RB (2009) Square-mesh codend circumference and selectivity. ICES J Mar Sci 66:566–572. https://doi.org/10.1093/icesjms/fsp001

Broadhurst MK, Sterling DJ, Millar RB (2016) Confounding effects of knot orientation in penaeid trawls. Fish Res 179:124–130. https://doi.org/10.1016/j.fishres.2016.02.020

Broadhurst MK, Suuronen P, Hulme A (2006) Estimating collateral mortality from towed fishing gear. Fish Fish 7:180–218. https://doi.org/10.1111/j.1467-2979.2006.00213.x

Bullough LW, Napier IR, Laurenson CH, Riley D, Fryer RJ, Ferro RST, Kynoch RJ (2007) A year-long trial of a square mesh panel in a commercial demersal trawl. Fish Res 83:105–112. https://doi.org/10.1016/j.fishres.2006.09.008

Campbell R, Harcus T, Weirman D, Fryer RJ, Kynoch RJ, O'Neill FG (2010) The reduction of cod discards by inserting 300 mm diamond mesh netting in the forward sections of a trawl gear. Fish Res 102:221–226. https://doi.org/10.1016/j.fishres.2009.12.001

Campos A, Fonseca P (2003) Selectivity of diamond and square mesh cod ends for horse mackerel (*Trachurus trachurus*), European hake (*Merluccius merluccius*) and axillary seabream (*Pagellus acarne*) in the shallow groundfish assemblage off the south-west coast of Portugal. Sci Mar 67:249–260. https://doi.org/10.3989/scimar.2003.67n2249

Campos A, Fonseca P, Henriques V (2003) Size selectivity for four fish species of the deep groundfish assemblage off the Portuguese southwest coast: evidence of mesh size, mesh configuration and cod end catch effects. Fish Res 63:213–233. https://doi.org/10.1016/S0165-7836(03)00060-2

Cartes JE, Maynou F, Lloris D, de Sola LG, Garcia M (2009) Influence of trawl type on the composition and diversity of deep benthopelagic fish and decapod assemblages off the Catalan coasts (western Mediterranean). Sci Mar 73:725–737. https://doi.org/10.3989/scimar.2009.73n4725

Ceylan Y, Sahin C (2019) Selectivity of different alternative cod ends and radial square mesh escape panels (RSEP). Turk J

Fish Aquat Sci 19:451–461. https://doi.org/10.4194/1303-2712-v19_6_01
Cheng ZH, Einarsson HA, Bayse S, Herrmann B, Winger P (2019) Comparing size selectivity of traditional and knotless diamond-mesh codends in the Iceland redfish (*Sebastes* spp.) fishery. Fish Res 216:138–144. https://doi.org/10.1016/j.fishres.2019.04.009
Chosid D, Pol M, Szymanski M, Ribas L, Moth-Poulsen T (2008) Diel variation within the species selective "topless" trawl net. J Oce Tech 3:31–58
Chosid DM, Pol M, Szymanski M, Mirarchi F, Mirarchi A (2012) Development and observations of a spiny dogfish *Squalus acanthias* reduction device in a raised footrope silver hake *Merluccius bilinearis* trawl. Fish Res 114:66–75. https://doi.org/10.1016/j.fishres.2011.03.007
Coll M, Bahamon N, Sardá F, Palomera I, Tudela S, Suuronen P (2008) Improved trawl selectivity: effects on the ecosystem in the South Catalan Sea (NW Mediterranean). Mar Ecol Prog Ser 355:131–147. https://doi.org/10.3354/meps07183
Cotter AJR, Boon TW, Brown CG (1997) Statistical aspects of trials of a separator trawl using a twin rig trawler. Fish Res 29:25–32. https://doi.org/10.1016/S0165-7836(96)00521-8
Cuende E, Arregi L, Herrmann B, Sistiaga M, Onandia I (2020a) Stimulating release of undersized fish through a square mesh panel in the Basque otter trawl fishery. Fish Res. https://doi.org/10.1016/j.fishres.2019.105431
Cuende E, Arregi L, Herrmann B, Sistiaga M, Basterretxea M (2020b) Release efficiency and selectivity of four different square mesh panel configurations in the Basque mixed bottom trawl fishery. Sci Mar 84:39–47 doi:https://doi.org/10.3989/scimar.04975.17A
Dahm E (1998) Measurements of codend selectivity for North Sea saithe by the covered codend and divided trawl methods. Arch Fish Mar Res 46:43–59
Dahm E (2000) Changes in the length compositions of some fish species as a consequence of alterations in the groundgear of the GOV-trawl. Fish Res 49:39–50. https://doi.org/10.1016/S0165-7836(00)00192-2
Dahm E, Wienbeck H, West CW, Valdemarsen JW, O'Neill FG (2002) On the influence of towing speed and gear size on the selective properties of bottom trawls. Fish Res 55:103–119. https://doi.org/10.1016/S0165-7836(01)00301-0
Demirci S, Akyurt İ (2017) Size selectivity of square and diamond mesh trawl codend for fish with different body shapes. Ind J Geo-Mar Sci 46:774–779
Demirci S, Demirci A, Simsek E (2019) Negative effect of protective bag on trawl codend selectivity Indian. Ind J Geo-Mar Sci 48:499–503
Demirci S, Dogru Z, Simsek E (2017) Effect of shortening the length of codend on brushtooth lizardfish caught in square mesh codend of otter trawl in Eastern Mediterranean. Ind J Fish 64:29–34. https://doi.org/10.21077/ijf.2017.64.3.71048-05
Dereli H, Aydin C (2016) Selectivity of commercial and alternative codends for four species in the Eastern Mediterranean demersal trawl fishery. Turk J Fish Aquat Sci 16:971–992. https://doi.org/10.4194/1303-2712-v16_4_25
Digre H, Hansen UJ, Erikson U (2010) Effect of trawling with traditional and "T90" trawl codends on fish size and on different quality parameters of cod *Gadus morhua* and haddock *Melanogrammus aeglefinus*. Fish Sci 76:549–559. https://doi.org/10.1007/s12562-010-0254-2
Düzbastilar FO et al. (2017) Seasonal variation in mortality of red mullet (*Mullus barbatus*) escaping from codends of three different sizes in the Aegean Sea. Sci Mar 81:339–349 doi:https://doi.org/10.3989/scimar.04600.19A
Eayrs S, Pol M, Caporossi ST, Bouchard C (2017) Avoidance of Atlantic cod (*Gadus morhua*) with a topless trawl in the New England groundfish fishery. Fish Res 185:145–152. https://doi.org/10.1016/j.fishres.2016.09.014
Eayrs S, Pol M, Knight J, Ford J (2020) Development and testing of an ultra-low-opening trawl to improve utilization of quota of Atlantic cod (Gadus morhua) in the groundfish fishery of New England. Fish Bull 118:171–183. https://doi.org/10.7755/Fb.118.2.6
Eigaard OR, Herrmann B, Nielsen JR (2012) Influence of grid orientation and time of day on grid sorting in a small-meshed trawl fishery for Norway pout (*Trisopterus esmarkii*). Aquat Living Resour 25:15–26. https://doi.org/10.1051/alr/2011152
Eigaard OR, Holst R (2004) The effective selectivity of a composite gear for industrial fishing: a sorting grid in combination with a square mesh window. Fish Res 68:99–112. https://doi.org/10.1016/j.fishres.2004.02.002
Engås A, Godø OR (1989) Escape of fish under the fishing line of a Norwegian sampling trawl and its influence on survey results. J du Cons 45:269–276
Engås A, Godø OR (1989) The effect of different sweep lengths on the length composition of bottom-sampling trawl catches. ICES J Mar Sci 45:263–268. https://doi.org/10.1093/icesjms/45.3.263
Engås A, Jorgensen T, West CW (1998) A species-selective trawl for demersal gadoid fisheries. ICES J Mar Sci 55:835–845. https://doi.org/10.1006/jmsc.1998.0352
Eryasar AR, Özbilgin H (2015) Implications for catch composition and revenue in changing from diamond to square mesh codends in the northeastern Mediterranean. J Appl Ichthyol 31:282–289. https://doi.org/10.1111/jai.12643
Eryasar AR, Özbilgin H, Gokce G, Özbilgin YD, Saygu I, Bozaoglu AS, Kalecik E (2014) The effect of codend circumference on selectivity of hand-woven slack knotted codend in the north eastern Mediterranean demersal trawl fishery. Turk J Fish Aquat Sci 14:463–470. https://doi.org/10.4194/1303-2712-v14_2_17
FAO (2011) International guidelines on bycatch management and reduction of discards. Food and Agriculture Organisation of the United Nations. FAO, Rome, p 73
Fryer RJ (1991) A model of between-haul variation in selectivity. ICES J Mar Sci 48:281–290. https://doi.org/10.1093/icesjms/48.3.281
Feekings J, Lewy P, Madsen N (2013) The effect of regulation changes and influential factors on Atlantic cod discards in the Baltic Sea demersal trawl fishery. Can J Fish Aquat Sci 70:534–542. https://doi.org/10.1139/cjfas-2012-0273
Ferro RST, Xu L (1996) An investigation of three methods of mesh size measurement. Fish Res 25:171–190. https://doi.org/10.1016/0165-7836(95)00403-3
Ferro RST, Jones EG, Kynoch RJ, Fryer RJ, Buckett BE (2007) Separating species using a horizontal panel in the Scottish

North Sea whitefish trawl fishery. ICES J Mar Sci 64:1543–1550. https://doi.org/10.1093/icesjms/fsm099
Fiorentini L, Dremiere PY, Leonori I, Sala A, Palumbo V (1999) Efficiency of the bottom trawl used for the Mediterranean international trawl survey (MEDITS). Aquat Living Resour 12:187–205. https://doi.org/10.1016/S0990-7440(00)88470-3
Fonseca P, Campos A, Mendes B, Larsen RB (2005) Potential use of a Nordmore grid for by-catch reduction in a Portuguese bottom-trawl multispecies fishery. Fish Res 73:49–66. https://doi.org/10.1016/j.fishres.2005.01.005
Fraser S, Angus CH (2019) Trial of a new escape panel concept to reduce cod catches in a mixed demersal fishery. Fish Res 213:212–218. https://doi.org/10.1016/j.fishres.2019.01.026
Fryer RJ, O'Neill FG, Edridge A (2016) A meta-analysis of haddock size-selection data. Fish Fish 17: 358–374.Galbraith RD, Fryer RJ, Maitland KMS (1994) Demersal pair trawl cod-end selectivity models. Fish Res 20:13–27. https://doi.org/10.1016/0165-7836(94)90003-5
Galbraith RD, Fryer RJ, Maitland KMS (1994) Demersal pair trawl cod-end selectivity models. Fish Res 20(1):13–27
Gamaza M, Fonseca P, Campos A, Erzini K, Sobrino I (2018) One device does not fit all: Limited results of using a Sort-X grid in the multi-species trawl fishery in the Gulf of Cadiz. Fish Manag Ecol 25:409–416. https://doi.org/10.1111/fme.12310
Gilman E, Pérez Roda MA, Huntington T, Kennelly SJ, Suuronen P, Chaloupka M, Medley PAH (2020) Benchmarking global fisheries discards. Nat Sci Rep 10:14017. https://doi.org/10.1038/s41598-020-71021-x
Glass CW, Wardle CS (1995) Studies on the use of visual-stimuli to control fish escape from codends. 2. The effect of a black tunnel on the reaction behavior of fish in otter trawl codends. Fish Res 23:165–174. https://doi.org/10.1016/0165-7836(94)00331-P
Graham KJ, Broadhurst MK, Millar RB (2009) Effects of codend circumference and twine diameter on selection in south-eastern Australian fish trawls. Fish Res 95:341–349. https://doi.org/10.1016/j.fishres.2008.10.001
Graham N (2006) Trawling: Historic development, current status and future challenges. Mar Technol Soc J 40:20–24. https://doi.org/10.4031/002533206787353231
Graham N, Kynoch RJ (2001) Square mesh panels in demersal trawls: some data on haddock selectivity in relation to mesh size and position. Fish Res 49:207–218. https://doi.org/10.1016/S0165-7836(00)00211-3
Graham N, Kynoch RJ, Fryer RJ (2003) Square mesh panels in demersal trawls: further data relating haddock and whiting selectivity to panel position. Fish Res 62:361–375. https://doi.org/10.1016/S0165-7836(02)00279-5
Graham N, O'Neill FG, Fryer RJ, Galbraith RD, Myklebust A (2004) Selectivity of a 120 mm diamond cod-end and the effect of inserting a rigid grid or a square mesh panel. Fish Res 67:151–161. https://doi.org/10.1016/j.fishres.2003.09.037
Graham N, Jones EG, Reid DG (2004) Review of technological advances for the study of fish behaviour in relation to demersal fishing trawls. Ices J Mar Sci 61:1036–1043. https://doi.org/10.1016/j.icesjms.2004.06.006
Grimaldo E, Larsen RB, Holst R (2007) Exit windows as an alternative selective system for the Barents Sea demersal fishery for cod and haddock. Fish Res 85:295–305. https://doi.org/10.1016/j.fishres.2007.03.005
Grimaldo E, Larsen RB, Sistiaga M, Madsen N, Breen M (2009) Selectivity and escape percentages during three phases of the towing process for codends fitted with different selection systems. Fish Res 95:198–205. https://doi.org/10.1016/j.fishres.2008.08.019
Grimaldo E, Sistiaga M, Herrmann B, Gjøsund SH, Jørgensen T (2015) Effect of the lifting panel on selectivity of a compulsory grid section (Sort-V) used by the demersal trawler fleet in the Barents Sea cod fishery. Fish Res 170:158–165. https://doi.org/10.1016/j.fishres.2015.05.028
Grimaldo E, Sistiaga M, Larsen RB (2008) Evaluation of codends with sorting grids, exit windows, and diamond meshes: size selection and fish behaviour. Fish Res 91:271–280. https://doi.org/10.1016/j.fishres.2007.12.003
Grimaldo E, Sistiaga M, Larsen RB (2014) Development of catch control devices in the Barents Sea cod fishery. Fish Res 155:122–126. https://doi.org/10.1016/j.fishres.2014.02.035
Guyonnet B, Grall J, Vincent B (2008) Modified otter trawl legs to reduce damage and mortality of benthic organisms in North East Atlantic fisheries (Bay of Biscay). J Mar Sys 72:2–16. https://doi.org/10.1016/j.jmarsys.2007.05.017
Halliday RG, Cooper CG (1999) Evaluation of separator grates for reduction of bycatch in the silver hake (*Merluccius bilinearis*) otter trawl fishery off Nova Scotia, Canada. Fish Res 40:237–249. https://doi.org/10.1016/S0165-7836(98)00229-X
Halliday RG, Cooper CG (2000) Size selection of silver hake (*Merluccius bilinearis*) by otter trawls with square and diamond mesh codends of 55–60 mm mesh size. Fish Res 49:77–84. https://doi.org/10.1016/S0165-7836(00)00188-0
Halliday RG, Cooper CG, Fanning P, Hickey WM, Gagnon P (1999) Size selection of Atlantic cod, haddock and pollock (saithe) by otter trawls with square and diamond mesh codends of 130–155 mm mesh size. Fish Res 44:197–197. https://doi.org/10.1016/S0165-7836(99)00088-0
Hannah RW, Parker SJ, Buell TV (2005) Evaluation of a selective flatfish trawl and diel variation in rockfish catchability as bycatch reduction tools in the deepwater complex fishery off the US West Coast. N Am J Fish Manage 25:581–593. https://doi.org/10.1577/m04-126.1
He PG (2007) Selectivity of large mesh trawl codends in the Gulf of Maine—I. Comparison of square and diamond mesh. Fish Res 83:44–59. https://doi.org/10.1016/j.fishres.2006.08.019
He PG, Smith T, Bouchard C (2008) Fish behaviour and species separation for the Gulf of Maine multispecies trawls. J Ocean Tech 3(2):56–71
Herrmann B, Sistiaga M, Grimaldo E, Larsen RB, Olsen L, Brinkhof J, Tatone I (2019) Size selectivity and length-dependent escape behaviour of haddock in a sorting device combining a grid and a square mesh panel. Can J Fish Aquat Sci 76:1350–1361. https://doi.org/10.1139/cjfas-2017-0461
Herrmann B, Sistiaga M, Larsen RB, Nielsen KN (2013) Size selectivity of redfish (*Sebastes* spp.) in the Northeast

Atlantic using grid-based selection systems for trawls. Aquat Living Resour 26:109–120. https://doi.org/10.1051/alr/2013051
Herrmann B, Sistiaga M, Larsen RB, Nielsen KN, Grimaldo E (2013) Understanding sorting grid and codend size selectivity of Greenland halibut (*Reinhardtius hippoglossoides*). Fish Res 146:59–73. https://doi.org/10.1016/j.fishres.2013.04.004
Herrmann B, Wienbeck H, Karlsen JD, Stepputtis D, Dahm E, Moderhak W (2015) Understanding the release efficiency of Atlantic cod (*Gadus morhua*) from trawls with a square mesh panel: effects of panel area, panel position, and stimulation of escape response. ICES J Mar Sci 72:686–696. https://doi.org/10.1093/icesjms/fsu124
Herrmann B, Wienbeck H, Moderhak W, Stepputtis D, Krag LA (2013) The influence of twine thickness, twine number and netting orientation on codend selectivity. Fish Res 145:22–36. https://doi.org/10.1016/j.fishres.2013.03.002
Herrmann B, Wienbeck H, Stepputtis D, Krag LA, Feekings J, Moderhak W (2015) Size selection in codends made of thin-twined Dyneema netting compared to standard codends: a case study with cod, plaice and flounder. Fish Res 167:82–91. https://doi.org/10.1016/j.fishres.2015.01.014
Holst R, Ferro RST, Krag LA, Kynoch RJ, Madsen N (2009) Quantification of species selectivity by using separating devices at different locations in two whitefish demersal trawls. Can J Fish Aquat Sci 66:2052–2061. https://doi.org/10.1139/F09-145
Holst R, Revill A (2009) A simple statistical method for catch comparison studies. Fish Res 95:254–259. https://doi.org/10.1016/j.fishres.2008.09.027
Hunt DE, Maynard DL, Gaston TF (2014) Tailoring codend mesh size to improve the size selectivity of undifferentiated trawl species. Fish Man Ecol 21:503–508. https://doi.org/10.1111/fme.12099
İlkyaz AT, Şensurat T, Dereli H, Aydin C (2017) Codends selectivity for bogue (*Boops boops* L., 1758) in the Eastern Mediterranean demersal trawl fishery. Turk J Fish Aquat Sci 17:673–680. https://doi.org/10.4194/1303-2712-v17_4_03
Joksimovic A, Regner S, Sacchi J (2009) The effects of trawl codend mesh size selectivity on the length composition of catches of pandora, *Pagellus erythrinus* L. 1758 in the shelf area of the Montenegrin coast (South Adriatic). Acta Adriat 50:151–157
Jørgensen T, Ingólfsson OA, Graham N, Isaksen B (2006) Size selection of cod by rigid grids—is anything gained compared to diamond mesh codends only? Fish Res 79:337–348. https://doi.org/10.1016/j.fishres.2006.01.017
Joshy CG, Balakrishna N, Madhu VR (2018) Local polynomial regression estimation of trawl size selectivity parameters using genetic algorithm. Ind J Fish 65:25–32. https://doi.org/10.21077/ijf.2018.65.3.76544-03
Kaykaç H (2010) Size selectivity of commercial (300 MC) and larger square mesh top panel (LSMTPC) trawl codends for blue whiting (*Micromesistius poutassou* Risso, 1826) in the Aegean Sea. Afr J Biotechnol 9:9037–9041
Kaykaç MH, Zengin M, Tosunoğlu Z (2018) Can shifting codend mesh shape and mesh size increase the size selectivity of red mullet (*Mullus barbatus*) in the Black Sea? Turk J Fish Aquat Sci 18:859–870. https://doi.org/10.4194/1303-2712-v18_7_04
Kennelly SJ, Graham KJ, Montgomery SS, Andrew NL, Brett PA (1993) Variance and cost-benefit analyses to determine optimal duration of tows and levels of replication for sampling relative abundances of species using demersal trawling. Fish Res 16:51–67
Kennelly SJ (1995) The issue of bycatch in Australia's demersal trawl fisheries. Rev Fish Biol Fish 5:213–234
Kennelly SJ (2020) Bycatch beknown: methodology for jurisdictional reporting of fisheries discards—using Australia as a case study. Fish Fish 21:1046–1066. https://doi.org/10.1111/faf.12494
Kennelly SJ, Broadhurst MK (2002) By-catch begone: changes in the philosophy of fishing technology. Fish Fish 3:340–355. https://doi.org/10.1046/j.1467-2979.2002.00090.x
King SE, Hannah RW, Parker SJ, Matteson KM, Berkeley SA (2004) Protecting rockfish through gear design: development of a selective flatfish trawl for the US west coast bottom trawl fishery. Can J Fish Aquat Sci 61:487–496. https://doi.org/10.1139/F03-153
Kopp D, Morandeau F, Mouchet M, Vogel C, Mehault S (2018) What can be expected of a T90 extension piece to improve selectivity in bottom trawl multispecific fisheries in the Bay of Biscay? Fish Sci 84:597–604. https://doi.org/10.1007/s12562-018-1203-8
Krag LA, Herrmann B, Karlsen JD, Mieske B (2015) Species selectivity in different sized topless trawl designs: does size matter? Fish Res 172:243–249. https://doi.org/10.1016/j.fishres.2015.07.010
Krag LA, Holst R, Madsen N (2009) The vertical separation of fish in the aft end of a demersal trawl. ICES J Mar Sci 66:772–777. https://doi.org/10.1093/icesjms/fsp034
Krag LA, Holst R, Madsen N, Hansen K, Frandsen RP (2010) Selective haddock (*Melanogrammus aeglefinus*) trawling: avoiding cod (*Gadus morhua*) bycatch. Fish Res 101:20–26. https://doi.org/10.1016/j.fishres.2009.09.001
Kunjipalu KK, Meenakumari B, Mathai TJ, Boopendranath MR, Manoharadoss RS (2001) Effect of mesh size on selectivity of square mesh codends. Fish Tech 38:1–7
Kunjipalu KK, Varghese MD, Nair AKV (1994) Studies on square mesh codend in trawls—I studies with 30 mm mesh size. Fish Tech 31:112–117
Kvalsvik K, Huse I, Misund OA, Gamst K (2006) Grid selection in the North Sea industrial trawl fishery for Norway pout: efficient size selection reduces bycatch. Fish Res 77:248–263. https://doi.org/10.1016/j.fishres.2005.10.002
Kvamme C, Isaksen B (2004) Total selectivity of a commercial cod trawl with and without a grid mounted: grid and codend selectivity of north-east Artic cod. Fish Res 68:305–318. https://doi.org/10.1016/j.fishres.2003.11.011
Kynoch RJ, Ferro RST, Zuur G (1999) The effect on juvenile haddock by-catch of changing cod-end twine thickness in EU trawl fisheries. Mar Tech Soc J 33:61–72. https://doi.org/10.4031/Mtsj.33.2.10
Kynoch RJ, Fryer RJ, Neat FC (2015) A simple technical measure to reduce bycatch and discard of skates and sharks in mixed-species bottom-trawl fisheries. ICES J Mar Sci 72:1861–1868. https://doi.org/10.1093/icesjms/fsv037

Kynoch RJ, O'Dea MC, O'Neill E (2004) The effect of strengthening bags on cod-end selectivity of a Scottish demersal trawl. Fish Res 68:249–257. https://doi.org/10.1016/j.fishres.2003.12.003

Kynoch RJ, O'Neill FG, Fryer RJ (2011) Test of 300 and 600 mm netting in the forward sections of a Scottish whitefish trawl. Fish Res 108:277–282. https://doi.org/10.1016/j.fishres.2010.12.019

Larsen RB, Isaksen B (1993) Size selectivity of rigid sorting grids in bottom trawls for Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*). ICES Mar Sci Symp 196:178–182

Larsen RB, Herrmann B, Brinkhof J, Grimaldo E, Sistiaga M, Tatone I (2018) Catch efficiency of groundgears in a bottom trawl fishery: a case study of the Barents Sea haddock. Mar Coast Fish 10:493–507. https://doi.org/10.1002/mcf2.10048

Larsen RB, Herrmann B, Sistiaga M, Grimaldo E, Tatone I, Brinkhof J (2018) Size selection of cod (*Gadus morhua*) and haddock (*Melanograrnrnus aeglefinus*) in the Northeast Atlantic bottom trawl fishery with a newly developed double steel grid system. Fish Res 201:120–130. https://doi.org/10.1016/j.fishres.2018.01.021

Larsen RB, Herrmann B, Sistiaga M, Grimaldo E, Tatone I, Onandia I (2016) Size selection of redfish (*Sebastes* spp.) in a double grid system: estimating escapement through individual grids and comparison to former grid trials. Fish Res 183:385–395. https://doi.org/10.1016/j.fishres.2016.07.013

Lauth RR, Syrjala SE, McEntire SW (1998) Effects of gear modifications on the trawl performance and catching efficiency of the west coast upper continental slope groundfish survey trawl. Mar Fish Rev 60:1–26

Liberati A, Altman DG, Tetzlaff J, Mulrow C, Gøtzsche PC, Ioannidis JPA, Clarke M, Devereaux PJ, Kleijnen J, Moher D (2009) The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. J Clin Epid 62:e1ee34. https://doi.org/10.1016/j.jclinepi.2009.06.006

Lök A, Tokaç A, Tosunoğlu Z, Metin C, Ferro RST (1997) The effects of different cod-end design on bottom trawl selectivity in Turkish fisheries of the Aegean Sea. Fish Res 32:149–156. https://doi.org/10.1016/S0165-7836(97)00048-9

Lomeli MJM, Hamel OS, Wakefield WW, Erickson DL (2017) Improving catch utilization in the US west coast groundfish bottom trawl fishery: an evaluation of T90-mesh and diamond-mesh cod ends. Mar Coast Fish 9:149–160. https://doi.org/10.1080/19425120.2016.1274697

Lomeli MJM, Wakefield WW (2012) Efforts to reduce Chinook salmon (*Oncorhynchus tshawytscha*) and rockfish (*Sebastes* spp.) bycatch in the U.S. west coast Pacific hake (*Merluccius productus*) fishery. Fish Res 119:128–132. https://doi.org/10.1016/j.fishres.2011.11.003

Lomeli MJM, Wakefield WW (2013) A flexible sorting grid to reduce Pacific halibut (*Hippoglossus stenolepis*) bycatch in the US west coast groundfish bottom trawl fishery. Fish Res 143:102–108. https://doi.org/10.1016/j.fishres.2013.01.017

Lomeli MJM, Wakefield WW (2016) Evaluation of a sorting grid bycatch reduction device for the selective flatfish bottom trawl in the US West Coast fishery. Fish Res 183:294–303. https://doi.org/10.1016/j.fishres.2016.06.011

Lomeli MJM, Wakefield WW, Herrmann B (2017) Testing of two selective flatfish sorting-grid bycatch reduction devices in the US west coast groundfish bottom trawl fishery. Mar Coast Fish 9:597–611. https://doi.org/10.1080/19425120.2017.1388888

Lomeli MJM, Wakefield WW, Herrmann B (2018) Illuminating the headrope of a selective flatfish trawl: effect on catches of groundfishes, including Pacific halibut. Mar Coast Fish 10:118–131. https://doi.org/10.1002/mcf2.10003

Lomeli MJM, Wakefield WW, Herrmann B (2019) Evaluating off-bottom sweeps of a US West Coast groundfish bottom trawl: effects on catch efficiency and seafloor interactions. Fish Res 213:204–211. https://doi.org/10.1016/j.fishres.2019.01.016

Lowry N, Robertson JHB (1996) The effect of twine thickness on cod-end selectivity of trawls for haddock in the North Sea. Fish Res 26:353–363. https://doi.org/10.1016/0165-7836(95)00418-1

Lucchetti A (2008) Comparison of diamond- and square-mesh codends in the hake (*Merluccius merluccius* L. 1758) trawl fishery of the Adriatic Sea (central Mediterranean). Sci Mar 72:451–460

Lucchetti A, Punzo E, Virgili M (2016) Flexible turtle excluder device (TED): an effective tool for Mediterranean coastal multispecies bottom trawl fisheries. Aquat Living Resour. https://doi.org/10.1051/alr/2016016

Maartens L, Gamst KA, Schneider PM (2002) Size selection and release of juvenile monkfish *Lophius vomerinus* using rigid sorting grids. Fish Res 57:75–88. https://doi.org/10.1016/S0165-7836(01)00338-1

Madhu VR (2010) A review of trawl selectivity studies carried out along Indian coast. Fish Tech 55:1–18

Madhu VR, Raphael L, Meenakumari B (2015) Influence of codend mesh size on bycatch composition of two trawls operated off Veraval, Gujarat, India. Fish Tech 52:228–236

Madhu VR, Remesan MP, Meenakumari B (2016) Trawl selectivity estimates of *Thryssa dussumieri* (Valenciennes, 1848) in square and diamond mesh codends. Fish Tech 53:105–109

Madsen N (2007) Selectivity of fishing gears used in the Baltic Sea cod fishery. Rev Fish Biol Fish 17:517–544. https://doi.org/10.1007/s11160-007-9053-y

Madsen N, Holst R (2002) Assessment of the cover effect in trawl codend selectivity experiments. Fish Res 56:289–301. https://doi.org/10.1016/S0165-7836(01)00330-7

Madsen N, Staehr KJ (2005) Selectivity experiments to estimate the effect of escape windows in the Skagerak roundfish fishery. Fish Res 71:241–245. https://doi.org/10.1016/j.fishres.2004.08.019

Madsen N, Moth-Poulsen T, Lowry N (1998) Selectivity experiments with window codends fished in the Baltic Sea cod (*Gadus morhua*) fishery. Fish Res 36:1–14. https://doi.org/10.1016/S0165-7836(98)00085-X

Madsen N, Hansen KE, Moth-Poulsen T (2001) The kite cover: a new concept for covered codend selectivity studies. Fish Res 49:219–226. https://doi.org/10.1016/S0165-7836(00)00210-1

Madsen N, Holst R, Foldager L (2002) Escape windows to improve the size selectivity in the Baltic cod trawl fishery. Fish Res 57:223–235. https://doi.org/10.1016/S0165-7836(01)00355-1

Madsen N, Tschernij V, Hansen K, Larsson PO (2006) Development and testing of a species-selective flatfish ottertrawl to reduce cod bycatches. Fish Res 78:298–308. https://doi.org/10.1016/j.fishres.2006.01.002

Madsen N, Skeide R, Breen M, Krag LA, Huse I, Soldal AV (2008) Selectivity in a trawl codend during haul-back operation—an overlooked phenomenon. Fish Res 91:168–174. https://doi.org/10.1016/j.fishres.2007.11.016

Manjarres-Martinez LM, Gutierrez-Estrada JC, Hernando JA (2015) Effects of mesh size and towing speed on the multispecies catch rates of historical swept area surveys. Fish Res 164:143–152. https://doi.org/10.1016/j.fishres.2014.11.006

McHugh MJ, Broadhurst MK, Sterling DJ (2017) Choosing anterior-gear modifications to reduce the global environmental impacts of penaeid trawls. Rev Fish Biol Fisher 27:111–134. https://doi.org/10.1007/s11160-016-9459-5

Melli V, Herrmann B, Karlsen JD, Feekings JP, Krag LA (2020) Predicting optimal combinations of by-catch reduction devices in trawl gears: a meta-analytical approach. Fish Fish 21:252–268. https://doi.org/10.1111/faf.12428

Metin C et al (2005) Effect of square mesh escape window on codend selectivity for three fish species in the Aegean Sea. Turk J Vet Ani Sci 29:461–468

Millar RB (1992) Estimating the size-selectivity of fishing gear by conditioning on the total catch. J Am Stat Assoc 87:962–968. https://doi.org/10.2307/2290632

Millar RB, Fryer RJ (1999) Estimating the size-selection curves of towed gears, traps, nets and hooks. Rev Fish Biol Fisher 9:89–116. https://doi.org/10.1023/A:1008838220001

Millar RB, Walsh SJ (1992) Analysis of trawl selectivity studies with an application to trouser trawls. Fish Res 13:205–220. https://doi.org/10.1016/0165-7836(92)90077-7

Milliken HO, DeAlteris JT (2004) Evaluation of a large-mesh panel to reduce the flatfish bycatch in the small-mesh bottom trawls used in the New England silver hake fishery. N Am J Fish Man 24:20–32. https://doi.org/10.1577/M02-063

Moderhak W (1997) Determination of selectivity of cod codends made of netting turned through 90o. Bull Sea Fish Inst 1:3–14

Moderhak W (1999) Investigation of the selectivity of cod codends with meshes turned through 90o. Bull Sea Fish Inst 1:39–53

Moderhak W (2000) Selectivity tests of polyamide and polyethylene codends made of netting with meshes turned 90. Bull Sea Fish Inst 1(149):17–26

Mouchet M, Poirson M, Morandeau F, Vogel C, Mehault S, Kopp D (2019) Using a trait-based approach to understand the efficiency of a selective device in a multispecific fishery. Sci Rep UK. https://doi.org/10.1038/s41598-019-47117-4

O'Neill FG, Graham N, Kynoch RJ, Ferro RST, Kunzlik PA, Fryer RJ (2008) The effect of varying cod-end circumference, inserting a "flexi-grid" or inserting a Bacoma type panel on the selectivity of North Sea haddock and saithe. Fish Res 94:175–183. https://doi.org/10.1016/j.fishres.2008.06.007

O'Neill FG, Kynoch RJ, Blackadder L, Fryer RJ, Eryasar AR, Notti E, Sala A (2016) The influence of twine tenacity, thickness and bending stiffness on codend selectivity. Fish Res 176:94–99. https://doi.org/10.1016/j.fishres.2015.12.012

O'Neill FG, Kynoch RJ, Fryer RJ (2006) Square mesh panels in North Sea demersal trawls: separate estimates of panel and cod-end selectivity. Fish Res 78:333–341. https://doi.org/10.1016/j.fishres.2005.12.012

O'Neill FG, Summerbell K (2019) The influence of continuous lines of light on the height at which fish enter demersal trawls. Fish Res 215:131–142. https://doi.org/10.1016/j.fishres.2019.03.010

Ordines F, Massuti E, Guijarro B, Mas R (2006) Diamond vs. square mesh codend in a multi-species trawl fishery of the western Mediterranean: effects on catch composition, yield, size selectivity and discards. Aquat Living Resour 19:329–338. https://doi.org/10.1051/alr:2007003

Özbilgin H, Eryaşar AR, Gökce G, Özbilgin YD, Bozaoğlu AS, Kalecik E, Herrmann B (2015) Size selectivity of hand and machine woven codends and short term commercial loss in the Northeastern Mediterranean. Fish Res 164:73–85. https://doi.org/10.1016/j.fishres.2014.10.022

Özbilgin H, Tokaç A, Kaykaç H (2012) Selectivity of commercial compared to larger mesh and square mesh trawl codends for four fish species in the Aegean Sea. J Appl Ichthyol 28:51–59. https://doi.org/10.1111/j.1439-0426.2011.01916.x

Özbilgin H, Tosunoğlu Z (2003) Comparison of the selectivities of double and single codends. Fish Res 63:143–147. https://doi.org/10.1016/S0165-7836(03)00005-5

Özbilgin H, Tosunoğlu Z, Aydin C, Kaykaç H, Tokaç A (2005) Selectivity of standard, narrow and square mesh panel trawl codends for hake (*Merluccius merluccius*) and poor cod (*Trisopterus minutus capelanus*). Turk J Vet Anim Sci 29:967–973

Özbilgin H, Tosunoğlu Z, Tokaç A, Metin G (2007) Seasonal variation in the trawl codend selectivity of picarel (*Spicare smaris*). ICES J Mar Sci 64:1569–1572. https://doi.org/10.1093/icesjms/fsm115

Özdemir S, Erdem Y, Erdem E (2012) The determination of size selection of whiting (*merlangius merlangus euxinus*) by square mesh panel and diamond mesh codends of demersal trawl in the southern part of Black Sea. Turk J Fish Aquat Sci 12:407–410. https://doi.org/10.4194/1303-2712-v12_1_00

Özdemir S, Erdem Y, Erdem E, Özdemir ZB (2014) Effects of square mesh panels position of bottom trawls on by-catch bluefish *Pomatomus saltatrix* (Linnaeus, 1776) selectivity in the Southern Coast of the Black Sea, Turkey. Cah De Biol Mar 55:315–321

Özvarol Y (2016) Size selectivity of sorting grid for common pandora (*Pagellus erythrinus* (Linnaeus, 1758)) in the Gulf of Antalya, Eastern Mediterranean. Sci Pap-Ser D-Anim Sci 59:336–341

Özvarol Y (2016) Size selectivity of sorting grid for eight fish species in the Gulf of Antalya, northeastern Mediterranean Sea. Iran J Ichthy 3:294–303

Park CD, Lee K, Kim SH, Fujimori Y (2012) Performance of a conical jellyfish exclusion device installed in a trawl net. Fish Sci 78:23–32. https://doi.org/10.1007/s12562-011-0416-x

Perez-Comas JA, Erickson DL, Pikitch EK (1998) Cod-end mesh size selection for rockfish and flatfish of the US West Coast. Fish Res 34:247–268. https://doi.org/10.1016/S0165-7836(97)00102-1

Pérez Roda MA, Gilman E, Huntington T, Kennelly SJ, Suuronen P, Chaloupka M, Medley P (2019) A third assessment of global marine fisheries discards. FAO Fisheries and Aquaculture Technical Paper No. 633, FAO, Rome, 78pp

Petrakis G, Stergiou KI (1997) Size selectivity of diamond and square mesh codends for four commercial Mediterranean fish species. ICES J Mar Sci 54:13–23. https://doi.org/10.1006/jmsc.1996.0172

Pol MV, Herrmann B, Rillahan C, He PG (2016) Impact of codend mesh sizes on selectivity and retention of Acadian redfish *Sebastes fasciatus* in the Gulf of Maine trawl fishery. Fish Res 184:54–63. https://doi.org/10.1016/j.fishres.2016.06.013

Pol MV, Herrmann B, Rillahan C, He PG (2016) Selectivity and retention of pollock *Pollachius virens* in a Gulf of Maine trawl fishery. Fish Res 184:47–53. https://doi.org/10.1016/j.fishres.2015.07.029

Pol M, Carr HA (2000) Overview of gear developments and trends in the New England commercial fishing industry. Northeast Nat 7:329–336

Prakash RR, Rajeshwari G, Sreedhar U (2008) Size selectivity of 40 mm square mesh codend with respect to yellow-striped goatfish, *Upeneus vittatus* (forsskal, 1775) and orangefin ponyfish, *Leiognathus bindus* (Valenciennes, 1835). Fish Tech 45:29–34

Prakash RR, Rajeshwari G, Sreedhar U, Kumar MS (2013) Size selectivity of square mesh codends for *Saurida tumbil* (Bloch 1795) and *Nibea maculata* (Bloch & Schneider, 1801) in Bay of Bengal. Fish Tech 50:285–288

Rajeswari G, Prakash RR, Sreedhar U, Kumar MS (2013) Size selectivity of diamond and square mesh codends for largehead hairtail *Trichiurus lepturus* Linnaeus, 1758. Ind J Fish 60:13–16

Ramm DC, Mounsey RP, Xiao YS, Poole SE (1993) Use of a semipelagic trawl in a tropical demersal trawl fishery. Fish Res 15:301–313. https://doi.org/10.1016/0165-7836(93)90081-H

Reeves SA, Armstrong DW, Fryer RJ, Coull KA (1992) The effects of mesh size, cod-end extension length and cod-end diameter on the selectivity of Scottish trawls and seines. ICES J Mar Sci 49:279–288. https://doi.org/10.1093/icesjms/49.3.279

Reid DG, Kynoch RJ, Penny I, Summerbell K, Edridge A, O'Neill FG (2012) A comparison of the GOV survey trawl with a commercial whitefish trawl. Fish Res 121:136–143. https://doi.org/10.1016/j.fishres.2012.01.021

Robertson JHB, Stewart PAM (1988) A comparison of size selection of haddock and whiting by square and diamond mesh codends. J du Cons 44:148–161

Rose CS (1999) Initial tests of a flexible grate for size selection of trawl caught fish. Mar Technol Soc J 33:57–60. https://doi.org/10.4031/Mtsj.33.2.9

Rose CS, Gauvin JR (2000) Effectiveness of a rigid grate for excluding Pacific halibut *Hippoglossus stenolepis*, from ground fish trawl catches. Mar Fish Rev 62:6

Rose CS, Gauvin JR, Hammond CF (2010) Effective herding of flatfish by cables with minimal seafloor contact. Fish Bull 108:136–144

Rose CS, Nunnallee EP (1998) A study of changes in groundfish trawl catching efficiency due to differences in operating width, and measures to reduce width variation. Fish Res 36:139–147. https://doi.org/10.1016/S0165-7836(98)00099-X

Ryer CH, Rose CS, Iseri PJ (2010) Flatfish herding behavior in response to trawl sweeps: a comparison of diel responses to conventional sweeps and elevated sweeps. Fish Bull 108:145–154

Sainsbury KJ (1984) Optimal mesh size for tropical multi-species trawl fisheries. J du Cons 41:129–139

Sala A, Herrmann B, De Carlo F, Lucchetti A, Brčić J (2016) Effect of codend circumference on the size selection of square-mesh codends in trawl fisheries. PLoS ONE. https://doi.org/10.1371/journal.pone.0160354

Sala A, Lucchetti A (2011) Effect of mesh size and codend circumference on selectivity in the Mediterranean demersal trawl fisheries. Fish Res 110:252–258. https://doi.org/10.1016/j.fishres.2011.04.012

Sala A, Lucchetti A, Buglioni G (2007) The influence of twine thickness on the size selectivity of polyamide codends in a Mediterranean bottom trawl. Fish Res 83:192–203. https://doi.org/10.1016/j.fishres.2006.09.013

Sala A, Lucchetti A, Piccinetti C, Ferretti M (2008) Size selection by diamond- and square-mesh codends in multi-species Mediterranean demersal trawl fisheries. Fish Res 93:8–21. https://doi.org/10.1016/j.fishres.2008.02.003

Sangster GI, Breen M (1998) Gear performance and catch comparison trials between a single trawl and a twin rigged gear. Fish Res 36:15–26. https://doi.org/10.1016/S0165-7836(98)00086-1

Santos J, Herrmann B, Mieske B, Stepputtis D, Krumme U, Nilsson H (2016) Reducing flatfish bycatch in roundfish fisheries. Fish Res 184:64–73. https://doi.org/10.1016/j.fishres.2015.08.025

Santos J, Herrmann B, Otero P, Fernandez J, Perez N (2016) Square mesh panels in demersal trawls: does lateral positioning enhance fish contact probability? Aquat Living Resour 29:10. https://doi.org/10.1051/alr/2016025

Sardá F, Bahamon N, Molí B, Sardá-Palomera F (2006) The use of a square mesh codend and sorting grids to reduce catches of young fish and improve sustainability in a multispecies bottom trawl fishery in the Mediterranean. Sci Mar 70:347–353. https://doi.org/10.3989/scimar.2006.70n3347

Sardá F, Bahamon N, Sardá-Palomera F, Moli B (2005) Commercial testing of a sorting grid to reduce catches of juvenile hake (*Merluccius merluccius*) in the western Mediterranean demersal trawl fishery. Aquat Living Resour 18:87–91. https://doi.org/10.1051/alr:2005010

Sardá F, Moli B, Palomera I (2004) Preservation of juvenile hake (*Merluccius merluccius*, L.) in the western Mediterranean demersal trawl fishery by using sorting grids. Sci Mar 68:435–444. https://doi.org/10.3989/scimar.2004.68n3435

Sistiaga M, Brinkhof J, Herrmann B, Grimaldo E, Langard L, Lilleng D (2016) Size selective performance of two flexible sorting grid designs in the Northeast Arctic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) fishery. Fish Res 183:340–351. https://doi.org/10.1016/j.fishres.2016.06.022

Sistiaga M, Grimaldo E, Larsen RB (2008) Size selectivity patterns in the North-east Arctic cod and haddock fishery with sorting grids of 55, 60, 70 and 80 mm. Fish Res 93:195–203. https://doi.org/10.1016/j.fishres.2008.04.014

Sistiaga M, Herrmann B, Grimaldo E, Larsen RB (2010) Assessment of dual selection in grid based selectivity systems. Fish Res 105:187–199. https://doi.org/10.1016/j.fishres.2010.05.006

Sistiaga M, Herrmann B, Grimaldo E, Larsen RB, Olsen L, Brinkhof J, Tatone I (2018) Combination of a sorting grid and a square mesh panel to optimize size selection in the North-East Arctic cod (*Gadus morhua*) and redfish (*Sebastes* spp.) trawl fisheries. ICES J Mar Sci 75:1105–1116. https://doi.org/10.1093/icesjms/fsx231

Sistiaga M, Herrmann B, Grimaldo E, Larsen RB, Tatone I (2015) Effect of lifting the sweeps on bottom trawling catch efficiency: a study based on the Northeast Arctic cod (*Gadus morhua*) trawl fishery. Fish Res 167:164–173. https://doi.org/10.1016/j.fishres.2015.01.015

Sistiaga M, Herrmann B, Grimaldo E, Larsen RB, Tatone I (2016) The effect of sweep bottom contact on the catch efficiency of haddock (*Melanogrammus aeglefinus*). Fish Res 179:302–307. https://doi.org/10.1016/j.fishres.2016.03.016

Sistiaga M, Herrmann B, Larsen RB (2009) Investigation of the paired-gear method in selectivity studies. Fish Res 97:196–205. https://doi.org/10.1016/j.fishres.2009.02.002

Sola I, Maynou F (2018) Assessment of the relative catch performance of hake, red mullet and striped red mullet in a modified trawl extension with T90 netting. Sci Mar 82:19–26. https://doi.org/10.3989/scimar.04711.04A

Somerton DA (2004) Do Pacific cod (*Gadus macrocephalus*) and walleye pollock (*Theregra chalcogramma*) lack a herding response to the doors, bridles, and mudclouds of survey trawls? ICES J Mar Sci 61:1186–1189. https://doi.org/10.1016/j.icesjms.2004.06.003

Somerton DA, Munro P (2001) Bridle efficiency of a survey trawl for flatfish. Fish Bull NOAA 99:641–652

Somerton DA, Weinberg KL (2001) The effect of speed through the water on footrope contact of a survey trawl. Fish Res 53:17–24. https://doi.org/10.1016/S0165-7836(00)00272-1

Somerton D, Weinberg K, Munro P, Rugolo L, Wilderbuer T (2018) The effects of wave-induced vessel motion on the geometry of a bottom survey trawl and the herding of yellowfin sole (*Limanda aspera*). Fish Bull 116:21–33. https://doi.org/10.7755/Fb.116.1.3

Southworth LK, Ratcliffe FC, Bloor ISM, Emmerson J, Watson D, Beard D, Kaiser MJ (2020) Artificial light improves escapement of fish from a trawl net. J Mar Biologic Assoc United Kingdom 100(2):267–275

Stergiou KI (1999) Effects of changes in the size and shape of codend on catch of Aegean Sea fishes. ICES J Mar Sci 56:96–102. https://doi.org/10.1006/jmsc.1998.0421

Stergiou KI, Politou CY, Christou ED, Petrakis G (1997) Selectivity experiments in the NE Mediterranean: the effect of trawl codend mesh size on species diversity and discards. ICES J Mar Sci 54:774–786. https://doi.org/10.1006/jmsc.1997.0231

Suuronen P, Sarda F (2007) The role of technical measures in European fisheries management and how to make them work better. Ices J Mar Sci 64:751–756. https://doi.org/10.1093/icesjms/fsm049

Suuronen P, Chopin F, Glass C, Løkkeborg S, Matsushita Y, Queirolo D, Rihan D (2012) Low impact and fuel efficient fishing—looking beyond the horizon. Fish Res 119–120:135–146. https://doi.org/10.1016/j.fishres.2011.12.009

Thomsen B (1993) Selective flatfish trawling. ICES Mar Sci Symp 196:161–164

Tokaç A, Herrmann B, Aydin C, Özbilgin H, Kaykaç H, Ünlüler A, Gökçe G (2014) Predictive models and comparison of the selectivity of standard (TO) and turned mesh (T90) codends for three species in the Eastern Mediterranean. Fish Res 150:76–88. https://doi.org/10.1016/j.fishres.2013.10.015

Tokaç A, Herrmann B, Gökçe G, Krag LA, Nezhad DS (2018) The influence of mesh size and shape on the size selection of European hake (*Merluccius merluccius*) in demersal trawl codends: an investigation based on fish morphology and simulation of mesh geometry. Sci Mar 82:147–157. https://doi.org/10.3989/scimar.04764.18A

Tokaç A, Lök A, Tosunoğlu Z, Metin C, Ferro RST (1998) Codend selectivities of a modified bottom trawl for three fish species in the Aegean Sea. Fish Res 39:17–31. https://doi.org/10.1016/S0165-7836(98)00172-6

Tokaç A, Özbilgin H, Kaykaç H (2010) Selectivity of conventional and alternative codend design for five fish species in the Aegean Sea. J Appl Ichthyol 26:403–409. https://doi.org/10.1111/j.1439-0426.2009.01379.x

Tokaç A, Özbilgin H, Tosunoğlu Z (2004) Effect of PA and PE material on codend selectivity in Turkish bottom trawl. Fish Res 67:317–327. https://doi.org/10.1016/j.fishres.2003.10.001

Tosunoğlu Z, Aydin C, Özaydin O (2008) Selectivity of a 50-mm diamond mesh knotless polyethylene codend for commercially important fish species in the Aegean Sea. J Appl Ichthyol 24:311–315. https://doi.org/10.1111/j.1439-0426.2008.01067.x

Tosunoğlu Z, Özbilgin H, Tokaç A (2003) Effects of the protective bags on the codend selectivity in Turkish bottom-trawl fishery. Arch Fish Mar Res 50:239–252

Tucker AD, Robins JB, McPhee DP (1997) Adopting turtle excluder devices in Australia and the United States: what are the differences in technology transfer, promotion, and acceptance? Coast Manage 25:405–421. https://doi.org/10.1080/08920759709362332

Uhlmann SS, Broadhurst MK (2015) Mitigating unaccounted fishing mortality from gillnets and traps. Fish Fish 16:183–229. https://doi.org/10.1111/faf.12049

Uhlmann SS, Ulrich C, Kennelly SJ (2019) The European Landing Obligation—reducing discards in complex, multi-species and multi-jurisdictional fisheries. Springer, Berlin, p 431

Vasapollo C, Virgili M, Petetta A, Bargione G, Sala A, Lucchetti A (2019) Bommon trawl catch comparison in the Mediterranean Sea: flexible turtle excluder device (TRED) vs traditional gear. PLoS ONE. https://doi.org/10.1371/journal.pone.0216023

Valdemarsen JW, Suuronen P (eds) (2003) Modifying fishing gear to achieve ecosystem objectives. Responsible Fisheries in the Marine Ecosystem. FAO, Rome

Veiga-Malta T, Feekings J, Herrmann B, Krag LA (2019) Industry-led fishing gear development: can it facilitate the process? Ocean Coast Man 177:148–155. https://doi.org/10.1016/j.ocecoaman.2019.05.009

Vogel C, Kopp D, Morandeau F, Morfin M, Mehault S (2017) Improving gear selectivity of whiting (*Merlangius merlangus*) on board French demersal trawlers in the English Channel and North Sea. Fish Res 193:207–216. https://doi.org/10.1016/j.fishres.2017.04.013

Wakefield CB et al (2017) Performance of bycatch reduction devices varies for chondrichthyan, reptile, and cetacean mitigation in demersal fish trawls: assimilating subsurface interactions and unaccounted mortality. ICES J Mar Sci 74:343–358. https://doi.org/10.1093/icesjms/fsw143

Wallace JR, Pikitch EK, Erickson DL (1996) Can changing cod end mesh size and mesh shape affect the nearshore trawl fishery off the west coast of the united states? N Am J Fish Man 16:530–539. https://doi.org/10.1577/1548-8675(1996)016%3c0530:Cccems%3e2.3.Co;2

Walsh SJ, Millar RB, Cooper CG, Hickey WM (1992) Codend selection in American plaice—diamond versus square mesh. Fish Res 13:235–254. https://doi.org/10.1016/0165-7836(92)90079-9

Wardle CS (1989) Understanding fish behaviour can lead to more selective fishing gears. In: Campbell CM (ed) Proceedings of the world symposium on fishing gear and fishing vessels. St Johns, pp 12–18

Wenger AS et al (2017) A critical analysis of the direct effects of dredging on fish. Fish Fish 18:967–985. https://doi.org/10.1111/faf.12218

Wienbeck H, Herrmann B, Feekings JP, Stepputtis D, Moderhak W (2014) A comparative analysis of legislated and modified Baltic Sea trawl codends for simultaneously improving the size selection of cod (*Gadus morhua*) and plaice (*Pleuronectes platessa*). Fish Res 150:28–37. https://doi.org/10.1016/j.fishres.2013.10.007

Wienbeck H, Herrmann B, Moderhak W, Stepputtis D (2011) Effect of netting direction and number of meshes around on size selection in the codend for Baltic cod (*Gadus morhua*). Fish Res 109:80–88. https://doi.org/10.1016/j.fishres.2011.01.019

Wileman DA, Ferro RST, Fonteyne R, Millar R (1996) Manual of methods of measuring the selectivity of towed fishing gears. ICES Cooperative Research Report No. 215. ICES, Copenhagen, Denmark

Zengin M, Akpinar İÖ, Özbilgin H, Kaykaç MH, Tosunoğlu Z (2019) Comparison of selectivity of the trawl codends for whiting (*Merlangius merlangus euxinus*) in the Black Sea. Su Urun Derg 36:301–311. https://doi.org/10.12714/egejfas.2019.36.3.11

Zuur G, Fryer RJ, Ferro RST, Tokai T (2001) Modelling the size selectivities of a trawl codend and an associated square mesh panel. ICES J Mar Sci 58:657–671. https://doi.org/10.1006/jmsc.2001.1049