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MITIGATION TECHNIQUES TO REDUCE BENTHIC IMPACTS OF TRAWLING

MIT2019-02 A Review for the Department of Conservation by Terra Moana Limited

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ABOUT TERRA MOANA

Terra Moana Ltd and Associates (TML) bring a highly experienced team with expertise in natural resource management and collaboration. We focus on primary industries, especially fisheries and oceans. Our areas of expertise include research, policy, business, analysis, management, valuation, facilitation, regenesis, extensive global networks, cultural intelligence, and business development.

Terra Moana's mission is grounded in natural capital "know how" and recognition of the need to regenerate human and natural systems. This is predicated on a respect for, and understanding of, the multiple factors that must be considered to enable wise stewardship of natural resources and the communities reliant upon them. We can support teams, executives, divisions and individuals to do the right thing.

TML seeks to bring tailored, best practice evidence, assessment and valuation to these areas to enable sound decision-making support for businesses and governments. Using careful design and sensitive engagement principles we work with both those who seek economic development and those who may be affected by it.

Executive Summary

This review has been prepared in response to the New Zealand Department of Conservation's request to review techniques to mitigate the benthic impacts of bottom trawling. The deliverables associated with this request were to:

1. Provide a technical report detailing methods used to mitigate the benthic impacts of bottom trawling and results found, including recommendations on mitigation techniques used to reduce benthic impacts of trawling.
2. Provision of all data collected in electronic format.

This review satisfies the first deliverable. Remedial efforts to eliminate or mitigate the benthic impacts of a bottom trawl are described, and their potential application in New Zealand trawl fisheries is discussed, including relative impact on seabed contact, fisher profitability, and handling and operation of the trawl. This information is based on a review of literature, both published and otherwise, as well as primary author knowledge and experience. Several recommendations are also described and which are designed to guide next-steps towards reducing seabed contact by trawl gear in New Zealand. These recommendations are;

- Sharing this review with the New Zealand trawl industry and seeking their feedback and ideas for eliminating or mitigating impact through gear modification.
- Conducting an audit of trawl gear used in New Zealand, to identify and quantify variation in trawl gear, allow estimation of potential reduction in swept area through gear modification, and help prioritise efforts to modify trawl gear to reduce benthic impact.
- Interviewing fishers, seeking information about their concerns associated with benthic impact by trawl gear, asking how they have or would like to reduce this impact, and understanding their needs in the context of reducing this impact.
- Taking deliberate steps to forge close relationships with industry bodies, fishing companies, and individuals and searching for 'win-win' outcomes for the fishing industry and benthic habitat.
- Considering mechanisms to fast-track the adoption of remedial trawl gear, including industry testing of this gear at low-cost or free of charge, and the use of low-cost loans linked to the purchase of this gear.
- Considering how improved operational efficiency can reduce the footprint and other environmental impacts of trawling, by contributing to the development of a holisitic, strategic, amd long-term plan to facilitate modernisation of the trawl fleet.

- Further extending this approach, consideration should also be given to a collaboration with seafood sector leaders to establish agreed principles associated with protecting benthic habitats, protecting of livelihoods in the catching sector and supply chain, and respecting Treaty of Waitangi obligations. It also includes agreeing to actions to reduce benthic impacts, and considering the potential might for regenerating marine ecosystems and underpinning quota rights if such a collaborative, respectful and principled approach were taken.

The second deliverable has been satisfied by sharing all electronic references with the Department of Conservation, with the exception of book chapters and a small number of papers that were unavailable for download.

This review identified and describes numerous worldwide efforts by fishing technologists, fishers, and others to reduce benthic impact by trawl gear. Most of these efforts have focussed on eliminating seabed contact by lifting trawl components into the water column, including the use of semi-pelagic otter boards, elevated sweeps and bridles, and ground gear removal to 'fly' trawl gear over the seabed. Other efforts have attempted to minimise or 'lighten' seabed contact. These efforts are laudable, although their efficacy is questionable given an inability to control the extent of bottom contact and a poor understanding if habitat recovery times are reduced.

Every attempt has been made to be as exhaustive as possible in this review, although some literature was not included if it was duplicative, did not provide new insights, or lacked detail. Selected efforts by researchers and others to reduce seabed contact through gear modification are summarised in the Appendices. Appendix A presents examples of efforts to rig, modify, or use low-impact otter boards, Appendix B presents examples of efforts to elevate the sweeps and lower bridles clear of the seabed, and Appendix C presents efforts to mitigate contact through ground gear modification or replacement. Each example is described using a standardised reporting template that also includes notes and comments by the primary (first) author.

Finally, while this review focuses on technical gear mitigation, we consider that a more comprehensive assessment of a suite of options, including spatial management and trawl industry collaboration would provide a more complete understanding of the full range of mitigation options and their implications. Given that spatial measures are a form of mitigation we point to where this could be developed in subsequent reviews. Similarly a review of the interactions between trawl gear and protected species, and relevant mitigations has not been undertaken. Considering the wider suite of options and related issues in depth would make sensible subsequent companion reviews.

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1 Introduction

Bottom trawling is one of the most widely used commercial fishing gears in the world. Bottom trawling occurs in all but the highest latitudes, from shallow lakes and rivers to offshore waters, sometimes in depths more than 2,500 m (Valdemarsen *et al.*, 2007). Landings from bottom trawl fisheries include finfish, crustaceans, and molluscs, using vessels ranging from small human-powered craft to industrial trawlers measuring over 100 m. Bottom trawling is responsible for approximately 25% of global capture fisheries production (Watson *et al.*, 2006; Collie *et al.*, 2017; Larsen *et al.*, 2019), and large volumes of seafood can be landed cheaply over a relatively short time period. Bottom trawling contributes to global food security, is also a key economic driver, a major source of employment, and vital to the cultural identity of many coastal communities worldwide.

Trawling can, however, have substantial deleterious impacts on the seabed and sensitive benthic habitats. Direct impacts of trawling include scraping (displacement), ploughing, and compression of seabed sediments, sediment resuspension, scattering, removal, destruction, or mortality of benthic biota, and indirect effects such as post-fishing damage or mortality of benthic organisms and long-term change in habitat complexity and community structure (Jones, 1992; Collie *et al.*, 1997; Linnane, *et al.*, 2000; Kaiser *et al.*, 2003; Winger *et al.*, 2010; O'Neill *et al.*, 2013; Clark *et al.*, 2016; O'Neill & Ivanovic, 2016; Collie *et al.*, 2017). Some of these impacts are observable for many years prior to recovery (Jones, 1992), while many others are permanent.

In simple terms, a bottom trawl consists of two netting wings attached to a cone-shaped net (Figure 1.). A bag of netting called a codend retains the catch and is attached to the tapered end of the cone. The vertical opening of the trawl is maintained by multiple floats attached to the headline. The horizontal opening of the trawl is maintained using otter boards (sometimes called trawl boards or doors). Otter boards also help keep the trawl net on the seabed (or in midwater if intended), and they help herd and guide fish into the path of the approaching trawl net. Long wires called sweeps and bridles extend between the otter boards and the wingends of the net; they also help herd fish toward the net. Heavy ground gear, usually comprising a combination of steel wire rope, chain, and rubber discs or bobbins, ensures the trawl mouth remains close to the seabed. It also helps the trawl net pass over seabed obstacles and prevents the escape of fish underneath the net.

By its very nature, the catching efficiency of bottom trawling relies upon close and persistent contact with the seabed. Bottom trawling occurs on various types of substrate, such as mud, sand, and gravel,

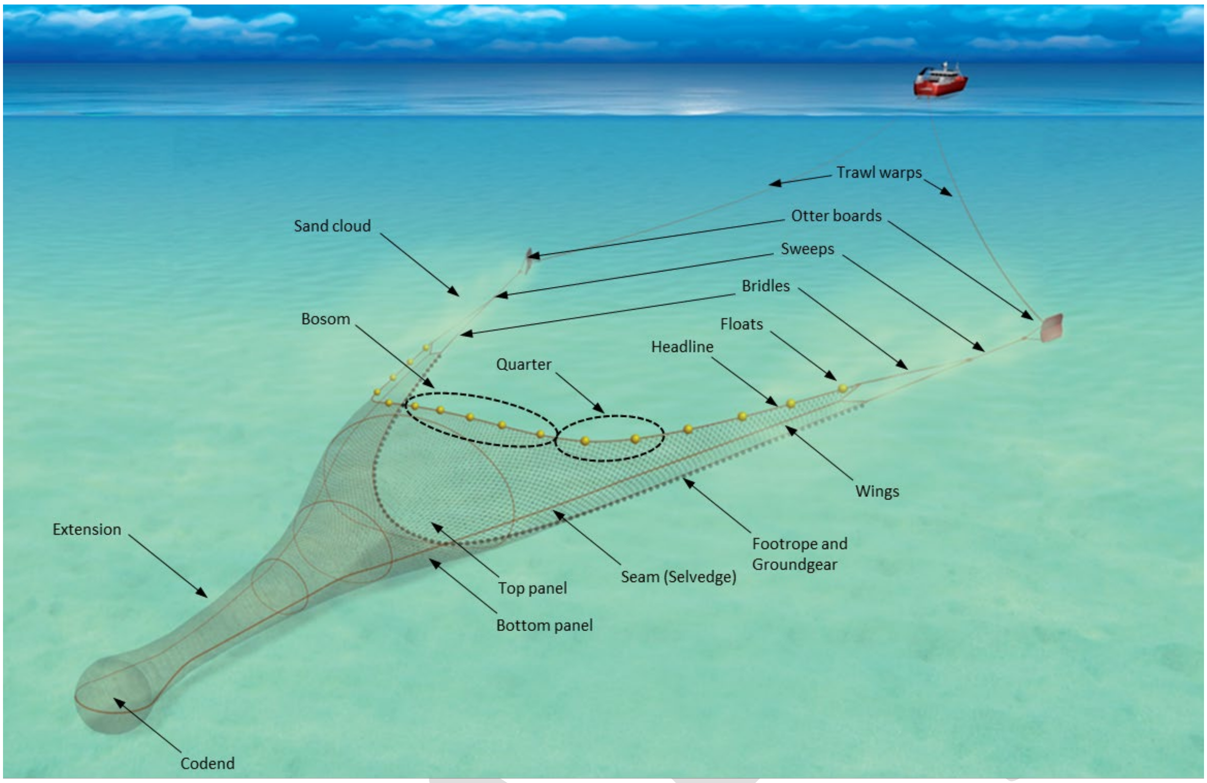

Figure 1. Bottom trawl with key sections and components labelled. Image courtesy of Seafish Asset Bank.

and is usually restricted to smooth substrates to avoid snagging the seabed (hooking up) and damage to the trawl gear. As a guide, trawl nets fitted with chain ground gear or small-diameter rubber discs or bobbins signify that fishing usually occurs on smooth substrates, while nets fitted with large rubber discs or bobbins may signify use where rocks or rock ledges may be encountered. Therefore, there is a limit to areas where bottom trawling activity can take place, as the rugosity of coral reefs and other areas makes it impossible to use a bottom trawl without significant damage, destruction, or loss of the trawl gear. This is a significant disincentive to not fish these areas, particularly when the cost of lost fishing time and gear loss may be many thousands of dollars.

Concerns over the impacts of bottom trawling date back to at least the 14th century (Engelhard, 2008). These concerns grew in the late 19th century with the rise of mechanised trawlers able to tow larger and heavier trawl nets, stay at sea longer and refrigerate the catch, travel to distant fishing grounds, and fish in deeper waters. The advent of electronic navigation aids and underwater acoustic technology in the mid-20th century enabled trawlers to operate closer to known reefs and other hazardous areas while avoiding gear damage or loss. It also enabled them to return to productive fishing grounds repeatedly, and quickly move to other grounds when catch rates decreased. An excellent history of these developments and their impact on fishing power and fish stocks is provided in Murawski (2005) and Engelhard (2008).

Whilst concerns over the impact of bottom trawling have a long history, it is only in recent decades that dedicated and persistent attempts have been made to eliminate or mitigate this impact (Buhl-Mortensen *et al*., 2016). These efforts have included the introduction of marine protected areas that eliminate or regulate trawling activity by space, time and/or gear-type. It has also included efforts by fishing technologists, other researchers, and commercial fishers to mitigate these impacts through gear modification, often with the goal of reducing the swept area (footprint) of the trawl. In some cases, these modifications have resulted in significant impact reductions (see chapter 6. Options to reduce seabed impact by bottom trawl gear and Appendices for details).

This review summarises efforts to achieve a reduction in swept area and seabed contact. It also describes various types of bottom trawl gear used around the world, identifies and describes trawl components responsible for seabed contact, and evaluates their potential application in New Zealand trawl fisheries, including relative impact on seabed contact and the fishing operation.

2 An Overview of Trawling and Swept Area in New Zealand

New Zealand is widely acknowledged as a global leader in sustainable fisheries development (McCormack, 2017). It is specifically renowned for being the first country in the world to introduce a wide-ranging quota management system (QMS) to manage and cap fishery landings at sustainable levels (Day, 2004; Bodwitch, 2017). The QMS was introduced in the early 1980s, but was not without incident. In 1988, Māori challenged the legitimacy of the QMS in the New Zealand High Court against the Treaty of Waitangi expectations laid down in 1840. The outcome of this challenge was the creation of the Māori Fisheries Settlement in 1992 that saw Māori allocated 10% of all quota issued pre-settlement and 20% of all quota issued post-settlement, whilst ceding their current and future commercial fishing rights (Boast, 1999; Toki, 2010; Bodwitch, 2017). It is estimated that Māori now own almost 50% of all fishing quota and their inclusion along with a strong spiritual and cultural affinity and commitment to kaitiakitanga (stewardship) for the marine realm is shaping much of the current agenda to improve fisheries management.

The QMS is complemented by a comprehensive and globally respected suite of other key fishery regulations including the establishment of Benthic Protected Areas (BPAs) where trawling is banned, marine reserves, restrictions on fishing gear, minimum landing size limits, and protection of marine mammals and seabirds. Regulations also include a comprehensive monitoring and compliance program based on electronic and observer monitoring of vessel location and fishing activity, as well as vessel and landings record keeping. Collectively, these efforts have contributed to six New Zealand fisheries being certified by the Marine Stewardship Council (MSC) (WWF, 2020), the recognised gold standard in fisheries sustainability. Approximately 50% of fishery landings in the country are now sourced from certified fisheries (Seafood New Zealand, n.d), and New Zealand fisheries have twice (2009 & 2010) been ranked as the most sustainable in the world (McCormack, 2017). Currently, 84% of assessed commercial fish stocks are not considered overfished and 95% of assessed landings were made up of stocks that were not overfished (Fisheries New Zealand, 2019).

Continuing this tradition of innovation and leadership in sustainable development, a world-first approach to fish harvesting and handling has been developed by Precision Seafood Harvesting. This $43.3 million research and development partnership between government, research, and industry has developed a significantly different approach to bulk-harvest fishing known as the Tiaki modular harvesting system, and includes a radically modified trawl codend and specialised onboard handling procedures designed to keep the fish unharmed and alive (Tiaki, 2020). These procedures have been proven to significantly improve catch quality and ensure that any unwanted fish can be released alive (Wilson *et al*., 2019). PSH is being used on the new Sealord vessel, FV Tokatu, and the RMD Māori family company owned vessel, the FV Santy Maria, which supplies Moana New Zealand. There is also growing international interest in adopting PSH technology. (Note: Moana New Zealand is the marketing name for Aotearoa Fisheries Limited (legal name) which arose from the Treaty of Waitangi Fisheries Settlement and which owns 50% of Sealord, the deepwater fishing company). A similar innovation is the Better Fishing Cage, a stainless-steel cage designed by a local fisher that replaces a traditional codend and allows the escape of undersized fish prior to hauling of the trawl (Bates, 2018).

Commercial landing volumes in New Zealand fisheries are dominated by trawl-caught species such as hoki (*Macruronus novazelandiae*), jack mackerel (*Trachurus* spp.), orange roughy (*Hoplostethus atlanticus*), oreo (*Allocyttus niger* and *Pseudocyttus maculatus*), snapper (*Pagrus auratus*), and gurnard (*Chelidonichthys kumu*). These species are caught by both bottom and midwater trawls (middle-water trawls), although the latter are commonly used in contact with the seabed. There are approximately 1200 registered fishing vessels in New Zealand, landing around 430 000 t each year; trawl vessels represent about half of the registered fleet by number, and around 93% of New Zealand trawlers measure less than 24 m in length (FAO, 2014)

Fleet reviews conducted by Terra Moana Ltd and Craig Group Solutions between 2011-2016 noted that both fishermen and the fleet are aging nationally and there has not been (commensurate to other business) investment in new vessels and new technology. Although the Rawlinson Family (FV Santy Maria) in partnership with Moana New Zealand and Sealord (Tokatu) have invested in building modern trawlers.

Hoki fishing contributes around 80% of the total swept area in waters between 400-800 m (Black & Tilney, 2015). Alfredo-style trawl nets are often used by the domestic fishing fleet in these waters, characterised by low headline height (3-5 m), short ground gear (20-30 m), small mesh netting (100-300 mm), and small rubber bobbins (300-450 mm diameter) (O'Boyle *et al*., 2018). Sweep and bridle length may reach 220 m and 30 m respectively. Midwater trawl nets are sometimes also used, often with ground gear in contact with the seabed. Bottom trawling in these waters also targets relatively dense aggregations of orange roughy, oreo, cardinal fish (*Epigonus telescopus*) and alfonsino (*Beryx splendens*) (Morrison *et al*., 2014), often on seamounts using acoustic technology to detect and target fish species (Ministry of Fisheries, 2008). Almost 80% of seamounts located between 500-1000 m in New Zealand waters have been fished using bottom trawls (Morrison *et al*., 2014).

High aspect ratio otter boards are commonly used when fishing seamounts and may weigh 2 000 kg or more with a surface area up to 8 m^2. They are also designed and rigged to operate clear of the seabed or with minimal contact. Otter board spread may be as wide as 150 m. Sweeps and bridles are relatively short, often around half the length used to target hoki. The combined use of high aspect ratio otter boards and short sweeps and bridles improves trawl manoeuvrability, allowing the net to be ‘flown’ clear of the seabed prior to encountering the aggregated fish, therefore reduceing the likelihood of hook ups and gear damage. The trawl net is also different, being designed with reduced ground gear length and net size, sometimes with larger diameter twine to improve abrasion resistance. An indepth review of deep-water trawl fishing gear and fishing effort in New Zealand waters is provided by the Ministry of Fisheries (2008), while the extent of bottom contact by domestic trawling is described in Baird & Wood (2018) and the effects of trawling on soft sediments is reviewed in Tuck *et al*. (2017).

While BPAs and other closures to marine areas prevent trawl fishing in approximately 30% of New Zealand’s Exclusive Economic Zone (EEZ) (Seafood New Zealand, n.d.; Black & Tilney, 2015; O'Boyle *et al*., 2018), around 24% of seabed available to trawling (>1 600 m) was fished at least once since 1990, representing a total area swept of around 335 000 km^2 (Ministry for the Environment & Stats NZ, 2019). Approximately 75% of the area swept by bottom trawls is located <400 m and 25% located between 400-600 m. Almost half of the seabed in the shallow-water range was trawled at least once between 1990-2011 (Ministry for the Environment, 2016). Notably, approximately 90% of the EEZ has never been bottom trawled, in part because most of the EEZ is deeper than 1250 m where there is little bottom trawling (Ministry for Primary Industries, 2016).

New Zealand bottom trawl fisheries have operated for several decades and the most serious damage to seabed habitats is likely to have already occurred (MPI, 2018), presumably during the early days of bottom trawl activity within each fishery. However, pressure to minimise trawl impacts is increasing and there remains a need to mitigate habitat impacts to the greatest extent practicable given the critical role of benthic habitats in marine ecosystem health and resilience. For example, in the most recent MSC recertification of hoki, hake, and ling trawl fisheries (O'Boyle *et al*., 2018), concern was expressed at the potential to expand and operate in new areas if the distribution of target stocks change in the future. Implicit in this concern was that these fisheries could adversely impact undisturbed deep-water benthic habitats that are not currently subject to fishing pressure. Whilst these concerns had a negative impact on assessment of the fisheries, recertification was nonetheless gratned. Similar concerns over the impact of trawling have been expressed in recent media articles (e.g. Vance, 2018; LegaSea, 2019; Mitchell, 2019; Scoop, 2020), some which expressed distrust over the behaviour and motives of the fishing industry, suggesting the social licence of fishers involved in bottom trawling is being questioned by some stakeholder groups.

To date, responses to this pressure in New Zealand appear to have been scant and limited largely to ad hoc attempts to address the issues. Some fishers have endeavoured to improve trawl manoeuvrability and minimise seabed contact, for example, while targeting orange rought on sea-mounts. Minimal scientific research appears to have been dedicated to systematically developing, testing, and evaluating the performance of trawl gear modified to reduce seabed contact, with the exception of semi-pelagic otter board testing by Jones (2015). This resarch demonstrated the viability of these otter boards in the inshore trawl fishery, although anecdotal evidence suggests that the outcomes were not embraced by the fishing industry.

The New Zealand Government has sought to use marine spatial planning and oceans policy to address marine health overall although there is not yet systematic benthic habitat protection. However, the Minister of Conservation recently noted that whilst BPAs protect around 30% of New Zealand's EEZ, New Zealand will not meet the 2020 United Nations (UN) Sustainable Development Goals for 10% marine protection (Anon, 2020). This recognises New Zealand's current BPAs do not meet the IUCN Other Effective Area-Based Conservation (OECM) (Day, *et al*., 2019) criteria given:

- OECMs are not protected areas.
- Industrial activities (such as commercial fisheries and mining) should not occur in OECMs.
- Sustainably managed commercial fisheries should be reported under Target 6.
- Management of OECMs should be consistent with ecosystem and precautionary approaches
- OECMs are expected to achieve the conservation of nature as a while (i.e. not a single habitat or species).

To align and integrate key initiatives to advance New Zealand's environmental and economic security, it is critical to consider the following:

- The Hauraki Gulf SeaChange and South East Regional Planning processes;
- Under the recent Motiti Decision[1], Regional Councils are seeking to fulfill their Resource Management Act responsibilities to marine ecosystems out to 12 nautical miles;

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[1] The Court of Appeal ruled regional councils control fishing to protect biodiversity, using the Resource Management Act. November 2019.

- The Natural Resource Sector agency collaboration in the Marine Geospatial Information Systems (GIS) project (led by LINZ) to catalogue marine databases nationally and the MetService's Moana Project together with NIWA are collaborating to create and populate the New Zealand Ocean Data Network, which is gearing up to have the capability to make these databases visible in GIS format;
- Furthermore, through Terra Moana's work as sustainability advisers to Moana New Zealand we are aware of the need to better understand the critical habitats in relation to fish harvesting.

3 Classification of trawl gear

The International Standard Statistical Classification of Fishing Gear (ISSCFG) classifies trawl gears based on key operational characteristics including location in the water column, number of trawl nets towed simultaneously, and the number of trawlers towing a trawl net (Table 1.).

Table 1. International classification of trawl gear. Source: FAO (2013).

Trawl category	Abbreviation	Gear code
Beam trawl	TBB	03.11
Single boat otter trawl	OTB	03.12
Twin bottom trawl	OTB	03.13
Multiple bottom trawl	OTP	03.14
Bottom pair trawl	PTB	03.15
Bottom trawl (NEI)	TB	03.19
Single boat midwater trawls	OTM	03.21
Midwater pair trawls	PTM	03.22
Midwater trawls (NEI)	TM	03.29
Semi-pelagic trawl	TSP	03.3
Trawls (NEI)	TX	03.9

NEI not enough information

3.1 Beam trawls (03.11)

Beam trawls are arguably the simplest trawl gear (Figure 2). Depending on the fishery one or more beam trawls may be towed simultaneously. The horizontal opening of each net is provided by attachment of the wingends to the steel shoes at the end of a rigid, horizontal beam. The vertical opening of the net is provided by attachment of the headline to the top of the shoes, and in some instances, attachment of the headline to the rigid beam. Headline flotation is therfore often unnecessary, and sweeps and bridles are not usually used. Ground gear may consist of a single chain, chain mat, or rubber bobbins and discs depending on the fishery. The area of seabed swept by a beam trawl is the product of beam width and distance trawled.

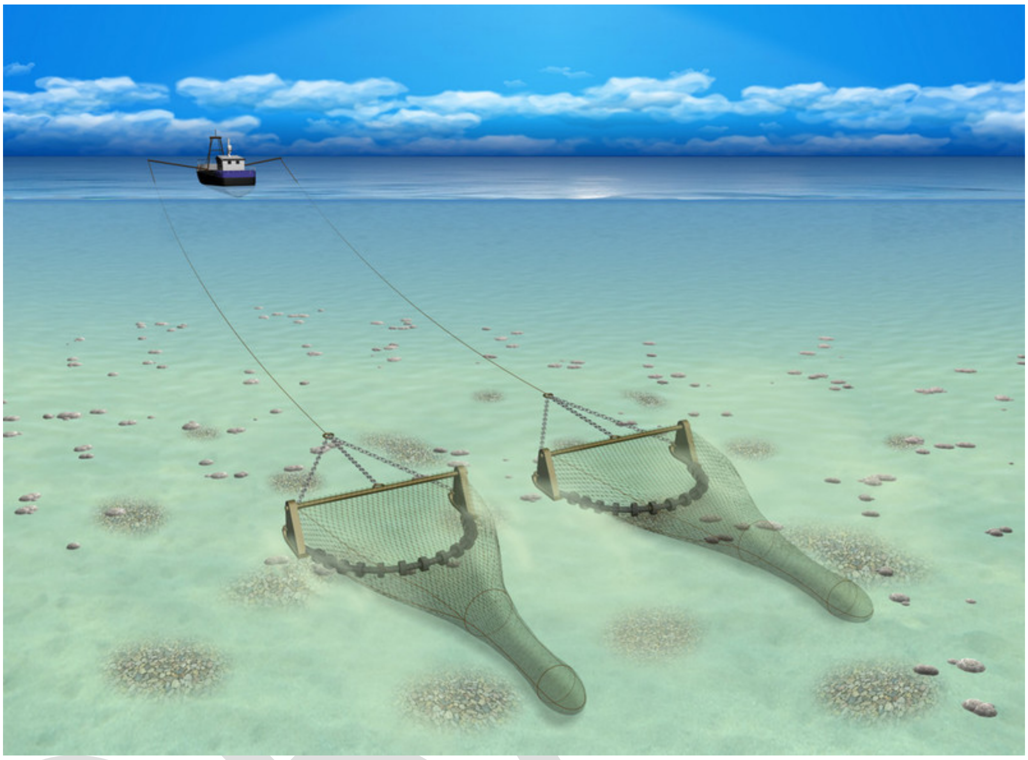

Figure 2. A beam trawl. The shoes are located at each end of the rigid beam. Image courtesy of Seafish Asset Bank

3.2 Single boat otter trawl (03.12)

This category represents the vast majority of bottom trawling activity worldwide (Larsen *et al*., 2019). It is characterised by a single net towed by a single boat (Figure 3), the use of otter boards to spread the net horizontally, and sweeps and bridles to herd fish into the approaching net. Ground gear may consist of rubber bobbins and discs, or chain. The area of seabed swept by this trawl is the product of otter board spread and distance trawled.

3.3 Twin bottom trawl (03.13)

As the name implies, this category is characterised by two nets that are connected and towed side by side (Figure 4). A pair of otter boards are used to spread the nets, attached to the outer wings of each

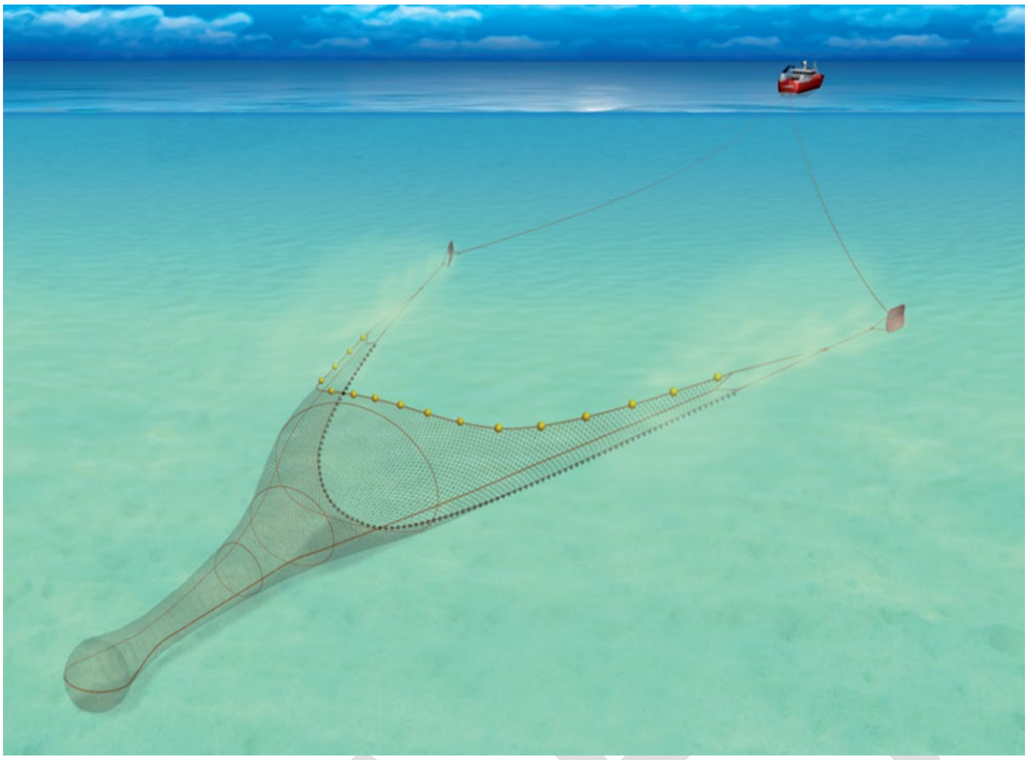

Figure 3. Single bottom trawl. Image courtesy of Seafish Asset Bank.

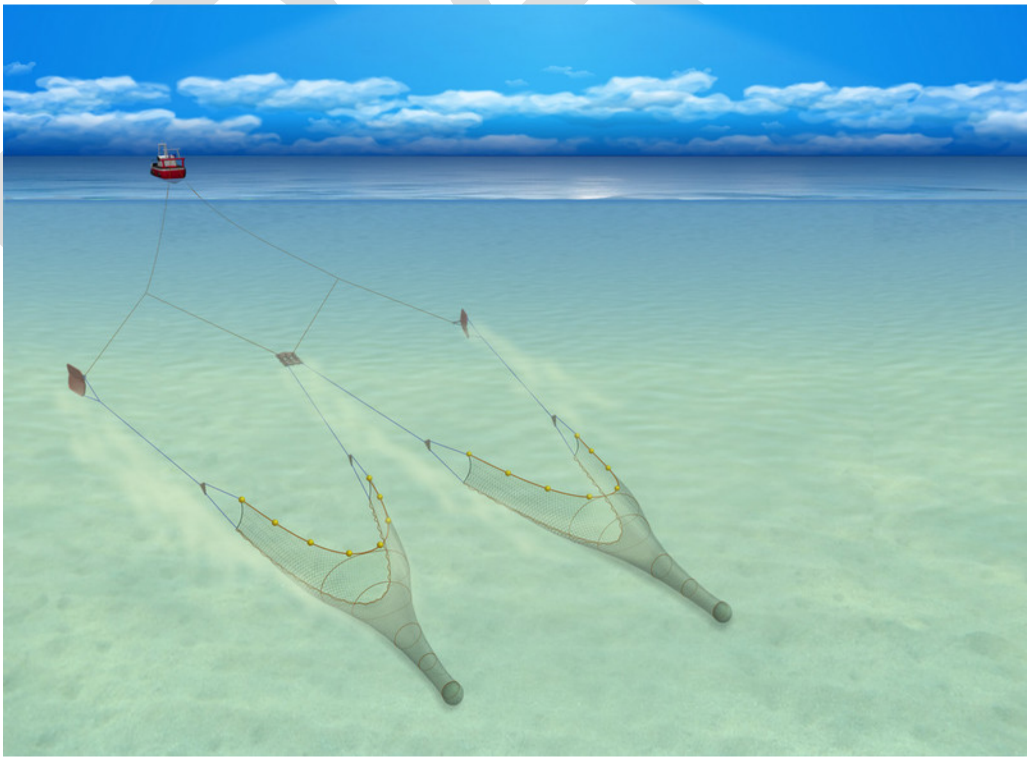

Figure 4. Twin bottom trawl. Image courtesy of Seafish Asset Bank.

net. The inner wings are connected to a single sledge, sled, or clump weight. Ground gear may consist of rubber bobbins and discs, or chain. A similar system includes towing two nets side by side each with their own pair of otter boards (Figure 5). This system is sometimes called double rig and is commonly used in tropical prawn trawl fisheries. The area of seabed swept by this trawl system is the product of otter board spread and distance trawled.

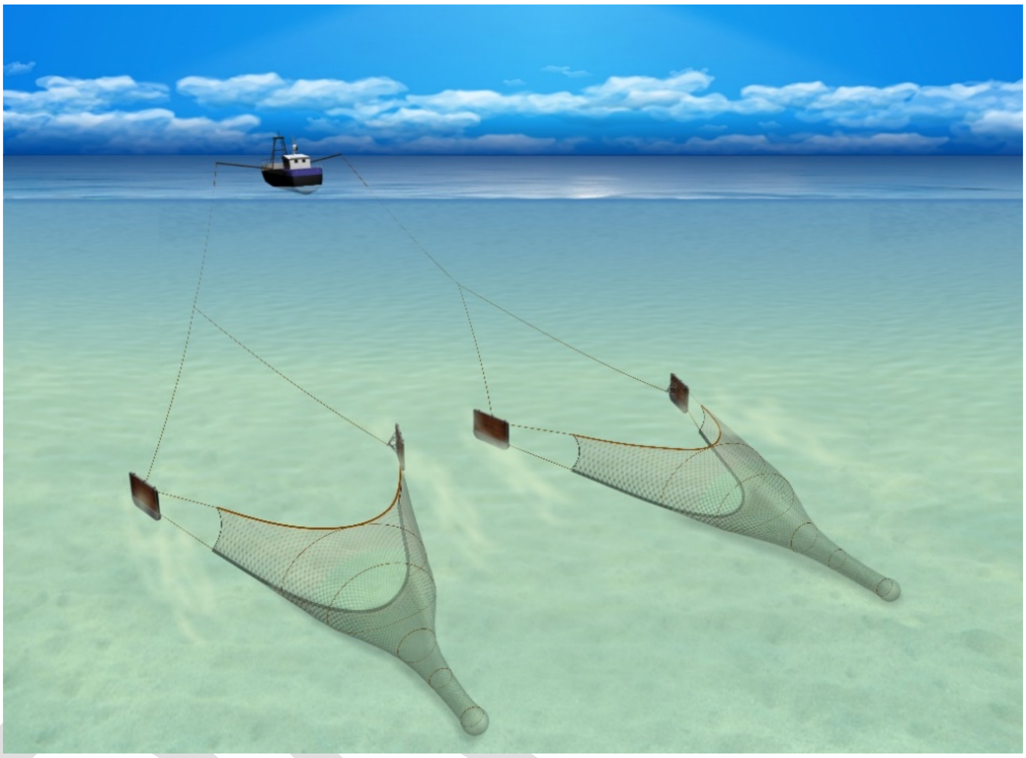

Figure 5. Alternative twin bottom trawl. Image courtesy of Seafish Asset Bank.

3.4 Multiple bottom trawl (03.14)

In some fisheries, particularly those that target prawns, three, four, or more nets may be towed simultaneously side by side. A three-net system, commonly known as triple rig, is characterised by three connected nets spread horizontally by two otter boards (Figure 6). A single sledge, sled, or clump weight is used to connect the nets. A four-net system, commonly known as quad-rig, is characterised by four connected nets spread horizontally by two otter boards, and the nets are connected together using a sledge, sled, or clump weight (Figure 7). Ground gear may consist of rubber bobbins and discs, or chain. An alternative quad rig system is two twin trawl systems towed side by side, with each system towed from an outrigger or boom. This arrangement is commonly used in tropical prawn trawl

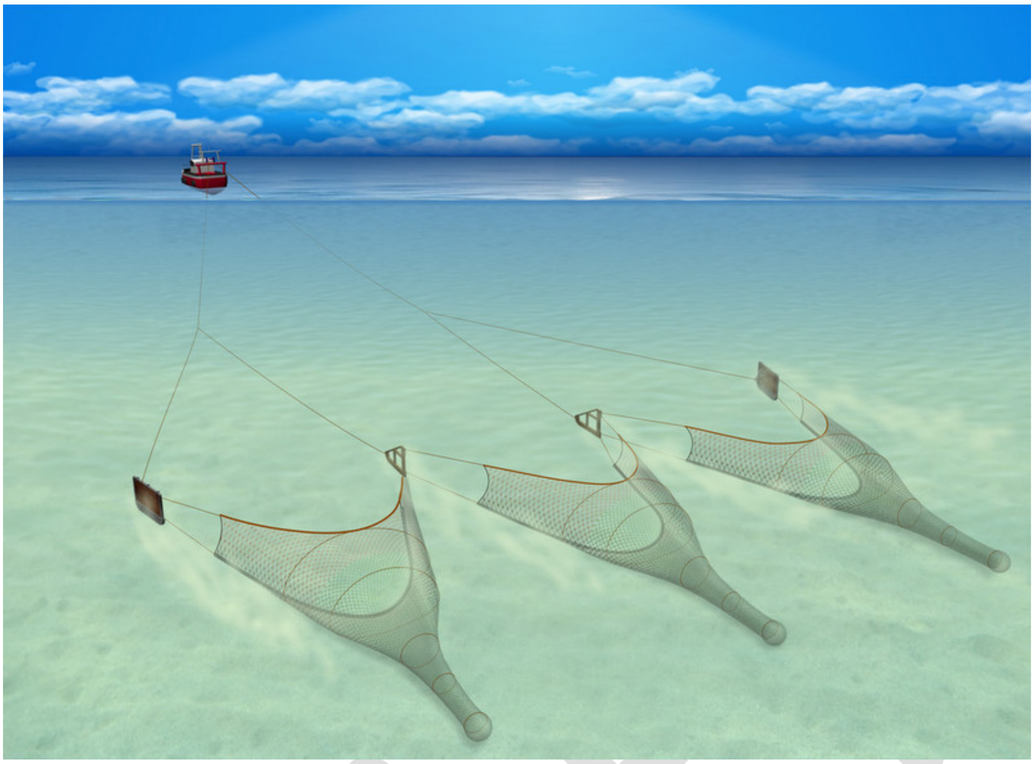

Figure 6. A triple trawl system. Image courtesy of Seafish Asset Bank.

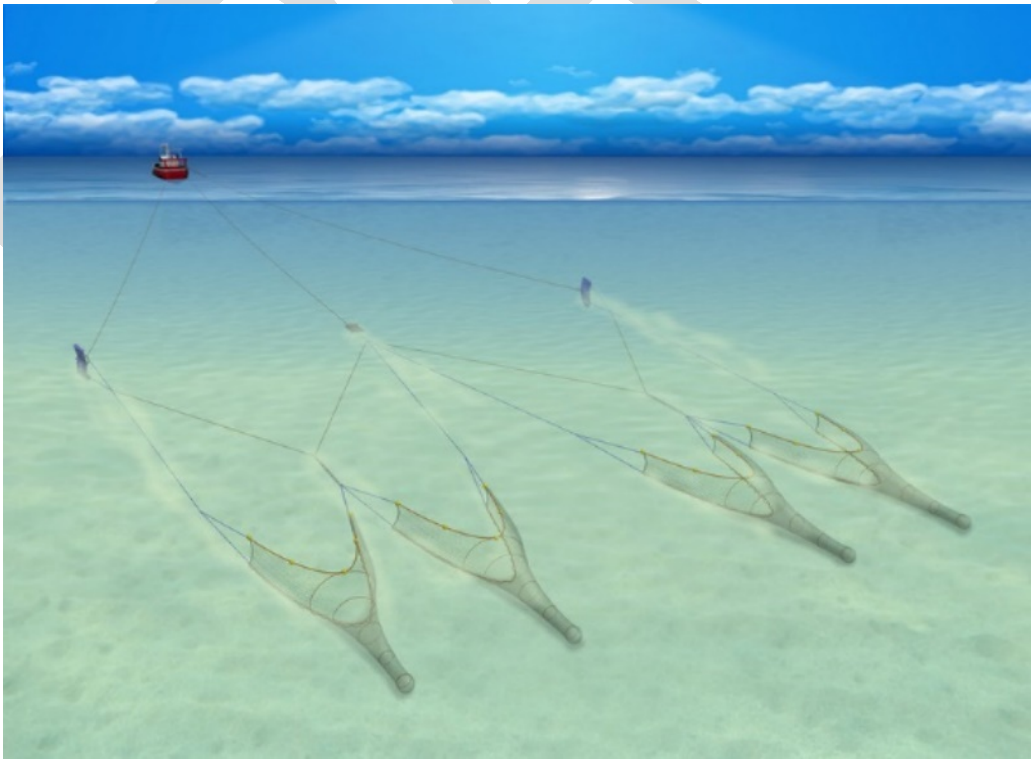

Figure 7. A quad trawl system. Image courtesy of Seafish Asset Bank.

fisheries. The area of seabed swept by this trawl system is the product of otter board spread and distance trawled.

3.5 Bottom pair trawl (03.15)

This trawl category involves the use of two boats towing a single net (Figure 8). Otter boards are not used because the horizontal opening of the net is the result of the horizontal separation between the two boats. To optimise bottom contact, heavy weights are usually attached to the leading ends of the sweeps. Ground gear may consist of rubber bobbins and discs, or chain. The area of seabed swept by this trawl is the product of the spread between the two weights (or first point of sweep contact) and distance trawled. These trawls are usually substantially larger than single-boat trawls, not only because two boats are used, but because the absence of otter boards frees up engine power that can be used to tow a larger net. The area of seabed swept by this trawl system is the product of the horizontal distance between the first point of sweep contact with the seabed and distance trawled.

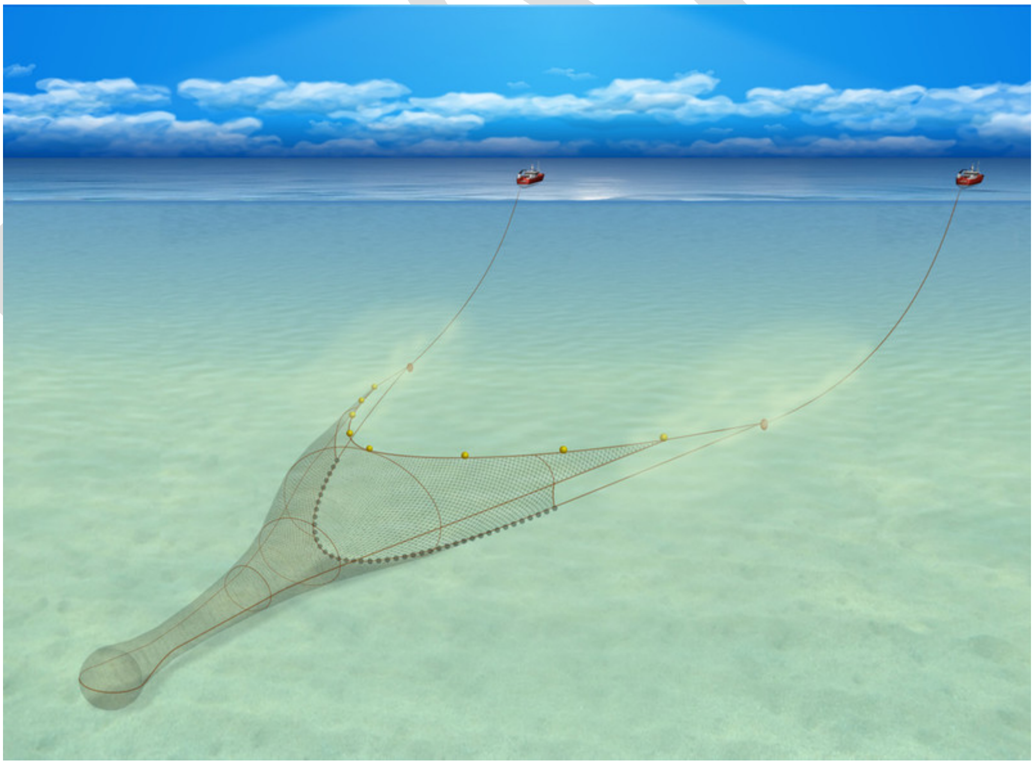

Figure 8. Bottom pair trawl. Image courtesy of Seafish Asset Bank.

3.6 Single boat midwater trawls (03.21)

Midwater trawl nets are often significantly larger than bottom trawl nets because they are typically designed to target pelagic species in the water column (Figure 9). Mesh sizes are also larger, sometimes reaching tens of meters in the wingends, to minimise drag and permit operation at high speed. Two clump weights are usually attached at each lower wingend and chain or other weights may be added to the footrope. The otter boards open the net horizontally while the clump and/or other weights help pull the net down to open the net vertically. The lower bridle is usually longer than the upper bridle. Headline flotation helps separate the trawl as it is deployed; flotation is usually inadequate to open the trawl vertically. These nets are not typically designed to be operated in contact with the seabed, although in some fisheries the clump weights and footrope are deliberately operated in contact with the seabed. Ground gear, if used, may consist of rubber bobbins and discs, or chain along some or the entire length of the footline, sometimes with other weights attached at intervals. The area swept is the product of the distance between the otter boards and the distance trawled, although if used in contact with the seabed, the area swept is the product of the distance between the clump weights and the distance trawled.

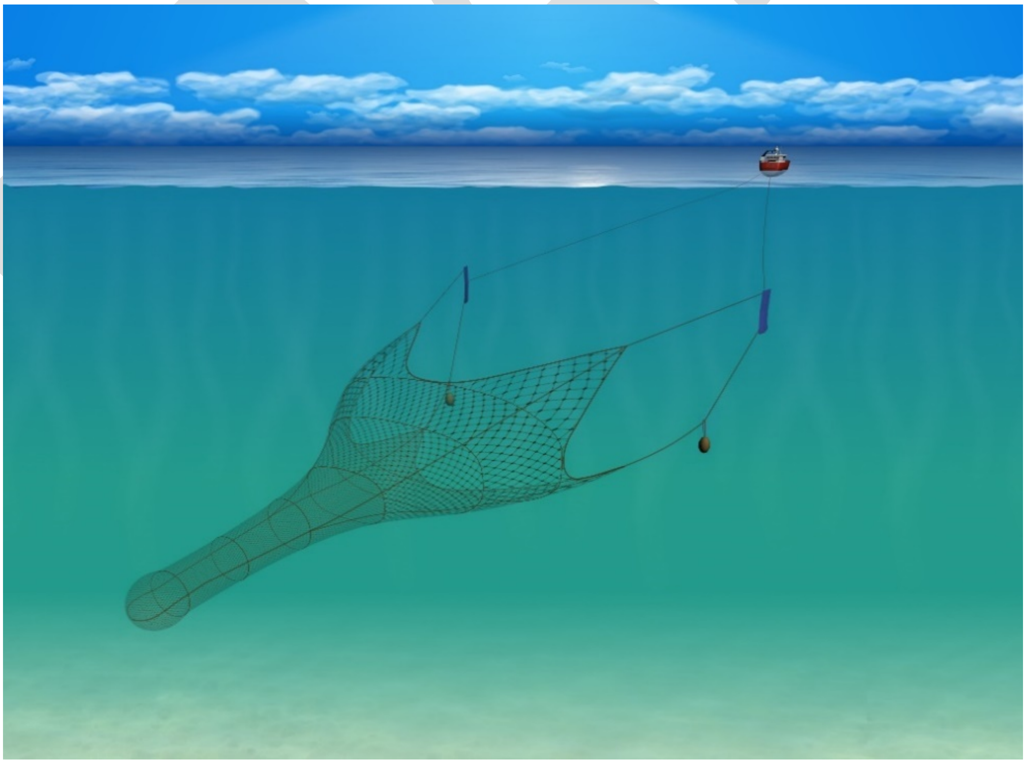

Figure 9. Single boat midwater trawl. Image courtesy of Seafish Asset Bank.

3.7 Midwater pair trawls (03.22)

These are some of the largest trawl nets ever constructed. Otter boards are not used and the horizontal opening of the trawl is a result of the horizontal distance between two trawlers (Figure 10). Heavy weights are attached to the lower wingends of the trawl and/or along the footrope, and the lower bridle is usually longer than the upper bridle. The weights help pull the net downwards and open the trawl vertically. Headline flotation, if used, helps separate the trawl as it is deployed. These trawls are also not usually designed for bottom contact, although in some fisheries they are operated close to, or in contact with, the seabed. Ground gear may consist of chain along some, or the entire length, of the footline, or other weights attached at intervals.

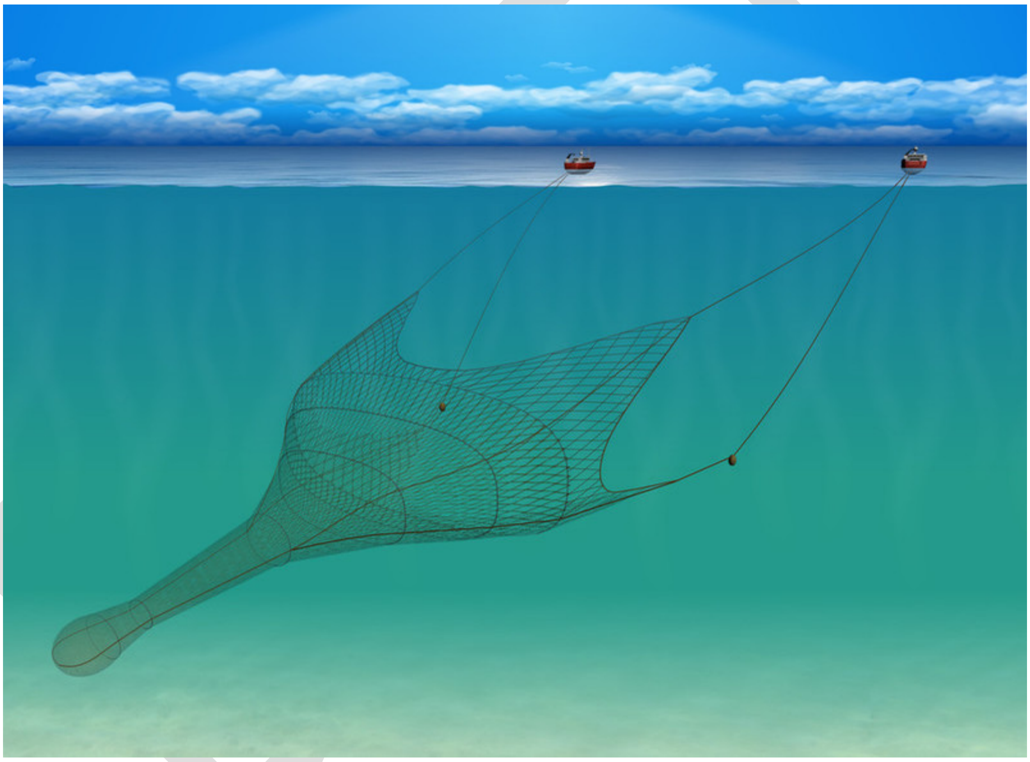

Figure 10. Midwater pair trawl. Image courtesy of Seafish Asset Bank.

3.8 Semi-pelagic trawls (03.3)

This system typically comprises an ordinary bottom trawl net with the otter boards and some or all of the sweeps lifted clear of the seabed (Figure 11). An alternative in some fisheries is a trawl system with otter boards in contact with the seabed but not the trawl net (Larsen *et al*., 2019). Ground gear may consist of rubber bobbins and discs, or chain. The area of seabed contacted by this trawl system is the product of the distance between the sweeps at first point of seabed contact and the distance trawled.

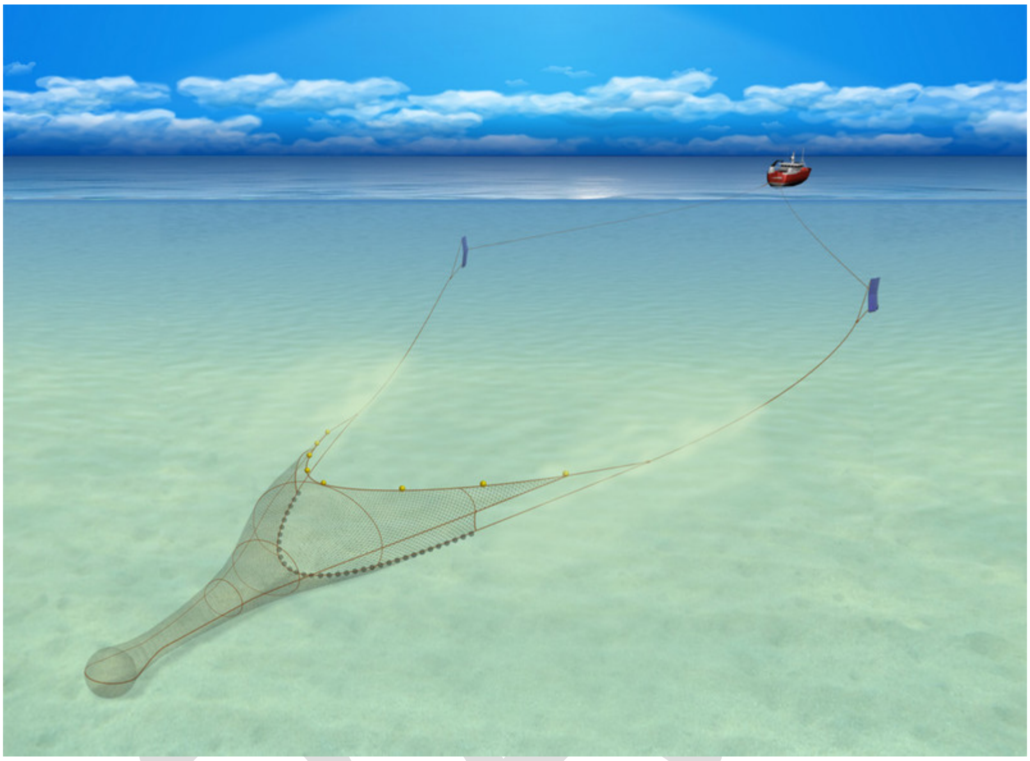

Figure 11. Semi-pelagic trawl. Image courtesy of Seafish Asset Bank.

4 Trawl components in contact with the seabed

The components of a trawl system that contact the seabed are the otter boards, sweeps and lower bridles, and the ground rope (Figure 1.), plus any sledges, sleds, or clump weights used to connect multiple trawl nets. The tapered net does not usually contact the seabed although the codend may do so intermittently when filled with catch or debris.

4.1 Otter boards - design and operation

The function of the otter boards includes spreading the trawl net horizontally, keeping the entire trawl system in close contact with the seabed, and herding fish towards the approaching trawl net. For most bottom-trawl systems the otter boards are the first point of seabed contact, and the distance between them is colloquially referred to as trawl spread. This distance is important in calculating the area of seabed contacted by the trawl because in addition to the otter boards themselves, the sweeps, lower bridles, and the ground rope are also in seabed contact (Figure 12); note that for simplicity the ground

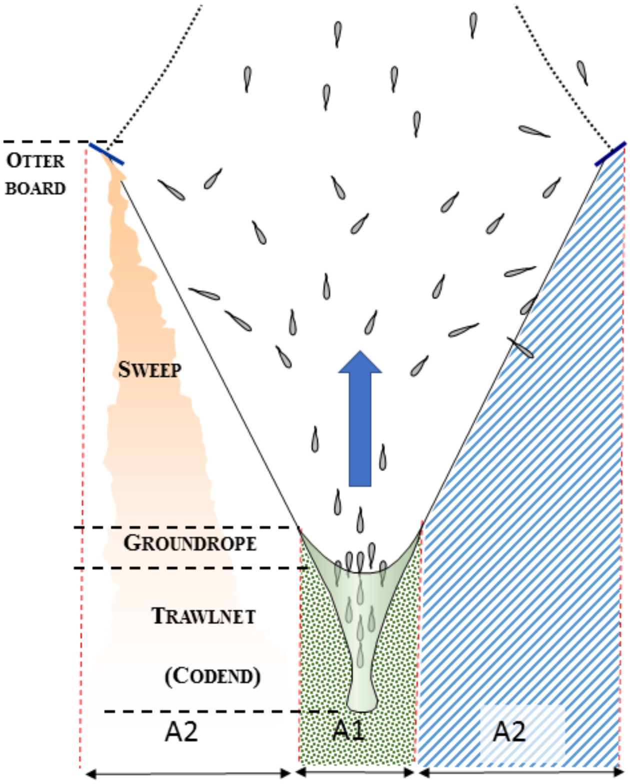

Figure 12. Schematic indicating swept width of a single-boat bottom trawl system. This includes the width of the trawl net between wingends (A1) and width covered by the sweep and otter boards (A2). A sediment plume produced by the otter board on the left is also indicated – and which would clearly occur on both sides. Image courtesy of Seafish Asset Bank.

rope is often assumed to be in seabed contact along its entire length, irrespective of ground rope type. A range of otter board designs are used in trawl fisheries worldwide (Figure 13). The rectangular flat otter board was the earliest otter board design, and although they have largely been superseded by more efficient designs they are still commonly used, particularly in fisheries in developing countries. This is because purchase and maintenance costs are low and they are easy to rig and operate. The evolution of otter board design includes the use of oval-shaped otter boards with one or more cambered foils, and more recently, the use of high aspect ratio, multi-foil otter boards.

Rectangular flat otter board

Rectangular vee otter board

Oval cambered otter board

Multi-foiled oval otter board

Cambered vee otter board

Round multi-foiled otter board

Rectangular multi-foiled otter board

High aspect ratio, multi-foiled otter board

Figure 13. Commonly used otter boards for bottom trawling. Image courtesy of Seafish Asset Bank.

Rectangular flat otter boards are not hydrodynamically efficient. Hydrodynamic efficiency is a measure of the lift to drag ratio of the otter board, where lift is the horizontal spreading force generated by the otter board as it is towed through the water and the drag force is the penalty attempting to oppose the motion of the otter board. In these otter boards the lift to drag ratio is close to 1:1.

In contrast, the lift to drag ratio of a high aspect ratio, multi-foiled otter board may be 2:1 or higher. In effect this means that smaller multi-foiled otter boards can be used to produce the same spreading force[2] as a less efficient otter board, with an attendant reduction in drag and associated improvement in fuel efficiency. These otter boards may also be more manoeuvrable and more easily handled onboard.

Another benefit of improved hydrodynamic efficiency is to reduce the otter board angle of attack. This is the angle of the otter board relative to the direction of tow, and which is needed to generate the required spreading force and maintain the spread of the trawl. Inefficient otter boards, such as the rectangular flat otter board, are commonly operated at an angle of 30 degrees or more, primarily to ensure their stability during deployment and retrieval, while more efficient designs can be operated at 20 degrees or less, reducing the area of seabed contact.

4.2 Sweeps and bridles - design and function

The primary function of the sweeps and bridles is to herd fish towards the approaching trawl net. They are also used to connect the otter boards to the trawl net and to a limited extent help to keep the trawl net close to the seabed. The lower bridle extends between the sweep and the juncture where the footrope and groundrope are attached, while the upper bridle extends between the sweep and the headline. Both are usually similar in length, although in some instances an offset in the upper bridle may be used to alter headline height or seabed contact. Sometimes a third or middle bridle is used, attached to a side panel in the trawl net. This bridle may be short compared to the upper and lower bridle, thus taking relatively more strain and allowing headline height and bottom contact to be increased.

Sweeps and bridles are usually constructed from steel wire rope, although alternatives include the use of combination rope, natural or synthetic rope, or even chain (Plate 1). Combination rope is

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[2] Note that spreading force does not necessarily equate to the distance (spread) between otter boards. Spread is the outcome of all forces acting on the otter board, some which hinder the ability of otter boards to increase spread. See SEAFISH, IFREMER, & DIFTA (1993) or FAO (1974) for details.

constructed with a steel wire core covered by twisted strands of wire wrapped in synthetic fibre such as polypropylene. The material, size (diameter), and breaking strain of the sweeps and bridles is based on the expected amount of tension (drag) generated by the trawl during the fishing operation and abrasion from contact with the seabed (Larsen *et al*., 2019). In some fisheries the sweep and/or lower bridle may be covered in a protective plastic hose or tightly fitting small rubber discs measuring around 100 mm in diameter.

The length of sweeps and bridles varies based on target species, seabed type, and net design. Where the seabed is flat and characterised by sand or soft mud, sweeps may measure 200 m or more. The bridles may measure at least 25 m although if too long their weight may reduce headline height. Where the seabed is characterised by rocks, crevasses, or other obstacles the sweeps may be as short as 50 m or less, to increase trawl manoeuvrability and reduce the risk of becoming fouled on the seabed.

Plate 1. Common sweep and bridle materials in bottom trawling. a) Steel wire rope, b) combination rope, c) natural rope, and d) chain. Adapted from Larsen *et al*., 2019.

4.3 Ground gear - design and function

Ground gear is designed explicitly to contact the seabed, protect trawl netting from damage, and help to keep the trawl net close to the seabed. Their design varies significantly, from simple lengths of rope with weights attached to lengths of wire rope threaded through rubber discs of varying size.

Ground gear terminology can be confusing. In the United States of America this part of the trawl is called the sweep, and the sweeps are called ground cables. A ground gear is also sometimes called a footrope or footline, and these terms can also to refer to the rope that is attached to trawl netting in the bottom panel (Figure 14).

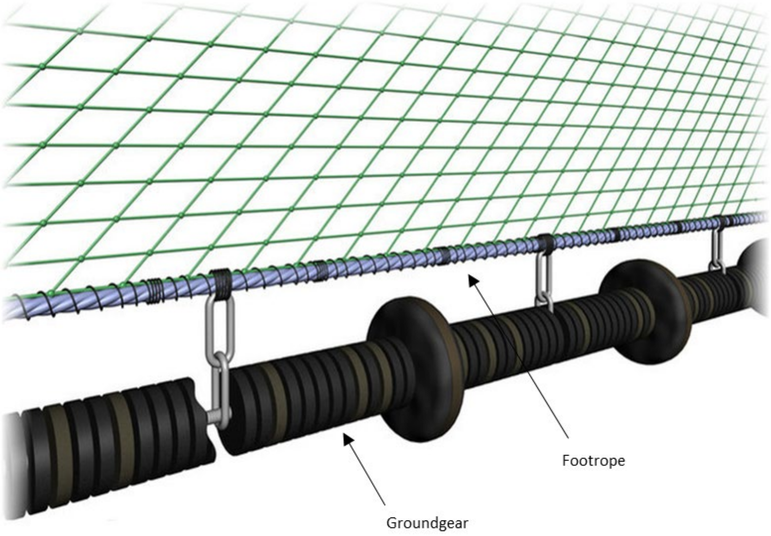

Figure 14. A typical ground gear arrangement in a fish-trawl fishery. Image courtesy of Seafish Asset Bank.

On very smooth substrates such as sand, mud, or gravel, the Ground gear may simply be comprised of chain wrapped around the footrope or attached (scalloped) to the footrope at equal intervals (Figure 15). These designs are commonly used in prawn- and fish-trawl fisheries in developing

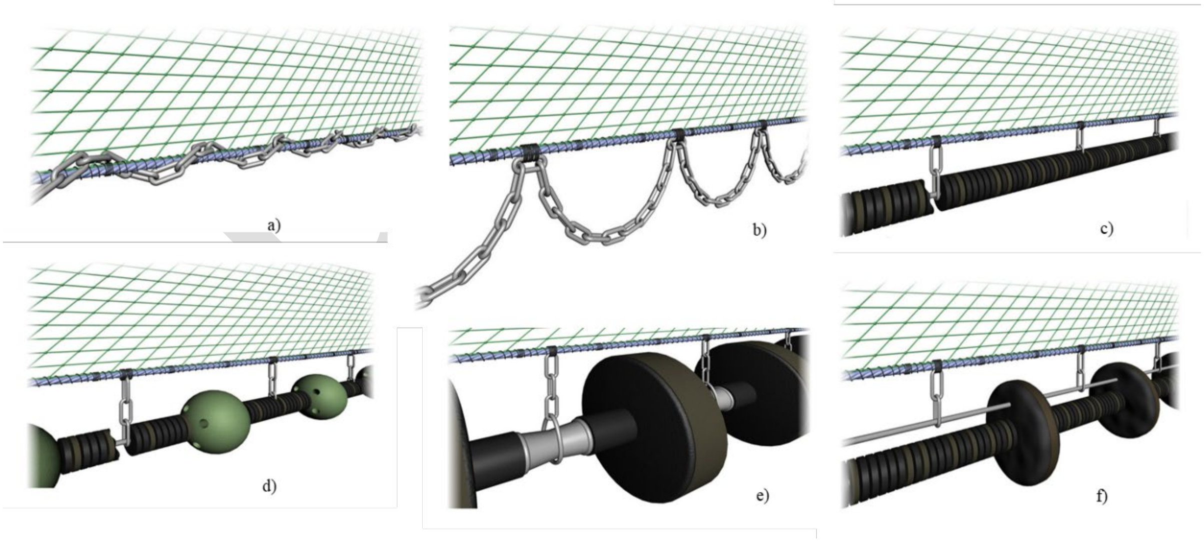

Figure 15. Some common ground gear designs: a) chain-wrapped footrope, b) scalloped chain footrope, c) cookie ground gear, d) spherical bobbin ground gear, e) large bobbin ground gear, f) rockhopper ground gear. Image courtesy of Seafish Asset Bank.

countries to keep costs low. In other fisheries a simple groundrope consisting of numerous rubber discs threaded onto a wire rope may be used, measuring around 100 mm or 150 mm in diameter. This is particularly common if flat fish are the target species and the seabed is expected to be devoid of rocks, rubble, or other obstacles that may damage the net. The discs are sometimes made from car or truck tyres, and after being threaded onto the wire they are tightly compressed together. Sometimes, this is referred to as a ‘cookie’ groundrope.

On substrates that are less smooth, or where rocks and rubble may be encountered, the ground gear may include larger rubber discs, sometimes called bobbins. The diameter of these discs may be largest at the trawl mouth, sometimes measuring 600 mm or more, and they may be smaller towards the wingends. Between each disc, smaller rubber ‘cookie’ discs are used. In the center of the groundrope the large rubber discs may rotate as the trawl gear is towed over the seabed. This helps reduce seabed impact, although along the wings they are unable to rotate and are simply dragged over the seabed. In other fisheries, the ground gear may be fitted with spherical bobbins or rockhoppers to facilitate passage over obstacles. Rockhopper ground gear does not rotate; this gear is designed with a wire rope threaded through the large rubber discs, which helps ‘spring’ the ground gear over obstacles.

Dan lenos are a part of the ground gear that serves as an attachment point for the footrope and lower bridle (Figure 16). They are either triangular or bobbin-shaped and constructed from steel or heavy rubber (bumper bobbins) to protect the attachment point from impact and seabed damage. They are designed to be in contact with the seabed.

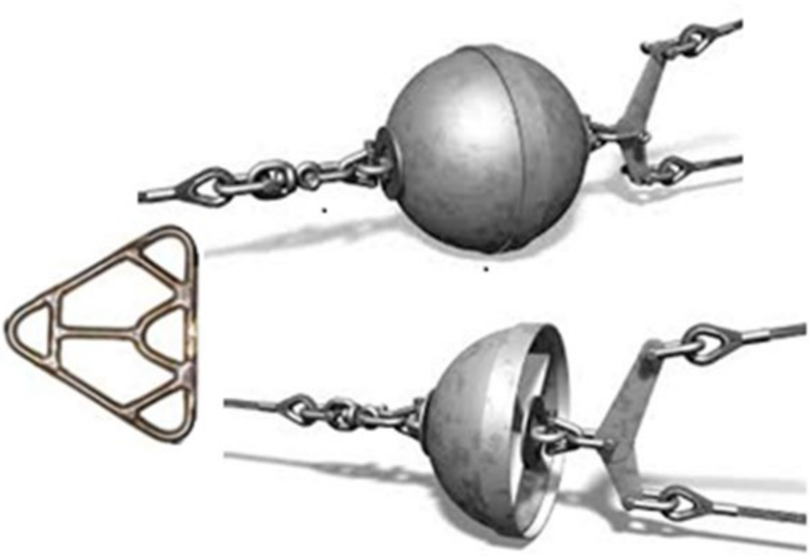

Figure 16. Triangular and bobbin-shaped dan lenos. Source: Larsen *et al*., 2019.

4.4 Codends

Codends may contact the seabed intermittently when filled with catch or debris. Little is known about the interplay between codend design and rigging, catch (volume and type), towing speed, and seabed contact. There is limited underwater video showing codends intermittently contacting the seabed but there are also videos of codends not contacting the seabed. Unless prevented by regulation, fishers may use an additional panel of netting to protect the underside of the codend and prevent chafing and damage to the codend, although in some instances the entire codend is protected, particularly when catch depredation by marine mammals and elasmobranchs is a concern. In other fisheries, long lengths of frayed rope are attached to the codend to protect it from abrasion, particularly on the underside of the codend. The additional netting or rope is usually positively buoyant, although it is likely insufficient to lift the codend and prevent it from contacting the seabed.

5 Description of habitat impact by bottom trawl gear

Bottom trawling has both direct and indirect effects on the seabed and benthic biota (flora and fauna). The direct effects of bottom trawling include scraping (displacement), ploughing, and compression of sediments, sediment resuspension, and physical damage (scattering, removal, mortality, or destruction) to benthic biota, while indirect effects include post-fishing damage or mortality of benthic organisms and long-term change in habitat complexity and community structure (Jones, 1992; Collie *et al.*, 1997; Linnane, *et al*., 2000; Kaiser *et al.*, 2003; Winger *et al*., 2010; O'Neill *et al*., 2013; Clark *et al*., 2016; Collie *et al.*, 2017; O'Neill & Ivanovic, 2016). An estimated 13.7 million km^2 (~50%) of the continental shelf globally has been affected by bottom trawling, with much of this area being trawled multiple times each year (Oberle *et al*., 2016).

5.1 Scraping and ploughing

Scraping and ploughing of the seabed by a bottom trawl is caused by otter boards, sweeps, lower bridles, ground gear, and in some circumstances, intermittent contact by the codend. Factors that influence the penetration depth or extent of this impact include gear design, rigging, and weight, towing speed, and seabed characteristics. Otter boards can plough deep furrows in the sediment that may be up to 30 cm deep and 20 cm wide (Jones, 1992; Linnane *et al*., 2000; Humborstad *et al*., 2004) and last for five years or longer (Jones, 1992). They are considered to have the greater impact on seabed sediments than other trawl components (Kaiser *et al*., 2003), although otter board furrows in sandy sediments may be less than 5 cm deep and can be quickly filled in by natural perturbation (Krost *et al*., 1990). Otter boards also produce a sediment berm on either side of each furrow, sometimes measuring up to 10 cm high (Humborstad *et al*., 2004). The footprint or swept width of this impact is usually less than 10% of the swept width of the ground gear (Ball *et al*., 2002) and may be 5% or less of the total swept width of the entire trawl system.

Sweeps and lower bridles generally skim over the seabed, lightly scraping surface sediments, although smoothing of sand ripples can occur particularly if trawling frequency is high. Sweeps and lower bridles fitted with rubber discs to increase seabed contact are likely to have relatively greater impact on sediments due to increased weight. Chain ground gear typically skims or lightly scrapes surface sediments, and has similar impacts compared to sweeps and lower bridles. Dan lenos and bobbins are responsible for both scraping and ploughing of sediments, particularly along the wings of the net where they do not rotate because their axes are not perpendicular to the towing direction (He &

Winger, 2010). The depth of furrows in the sediment caused by ground gear is likely less than that for otter boards (Humborstad *et al*., 2004). Compression of sediments occurs when trawl components contact the seabed (O'Neill & Ivanovic, 2016), particularly the bottom of furrows caused by ploughing of heavy otter boards and ground gear. Codend contact may be light and intermittent and thus responsible for scraping some sediments, and although poorly studied, this impact is considered relatively minor compared to that by other gear components.

5.2 Sediment resuspension

Sediment resuspension is a function of sediment grain size, degree of compaction, currents, and other sources of turbulence (Jones, 1992; Kaiser *et al*., 2003), and is usually inevitable if any part of the bottom trawl is in contact with the seabed. Otter boards are a major contributor to sediment resuspension, which occurs as a result of water turbulence (eddies) behind the otter boards as they are towed on or near the seabed. The resulting sediment plume is desirable in bottom trawl fishing because it expands and forms a barrier that facilitates the herding of fish towards the approaching net mouth (Jones, 1992; Wardle, 1993; Winger *et al*., 2010). However, resuspension of sediments can also result in the release of nutrients or contaminants held in the sediment, vertical redistribution of sediment layers or exposure of anoxic layers, increased oxygen demand, smothering of benthic organisms compromising feeding, respiration, and reproductive capability, and survival rates (Jones, 1992; Kaiser *et al*., 2003). In shallow water, suspended sediments may settle within hours or days depending on grain size and water movement, while in deep water it may remain suspended for 6 months or longer.

5.3 Benthic imact

All components of a bottom trawl in contact with the seabed contribute to the scattering, removal, injury, or mortality of benthic organisms. Some of these organisms suffer immediate mortality due to crush or impact injuries from contact with trawl components. Others survive initial impact but eventually suffer compromised growth or reproductive capacity as they recover from injury. Loss of habitat also contributes to high rates of predation due to exposure and compromised ability to escape or hide, or mortality due to an inability to recover from their injuries. Some benthic organisms such as molluscs, crustaceans, echinoderms may also be retained in the codend and then discarded overboard as the catch is processed. These may survive catch and release, and in some instances ultimately colonise new areas of seabed. Most, however, usually do not survive, succumbing to wound or crush injuries by other species in the codend or onboard, scale loss, barotrauma, oxygen deprivation, or consumption by predators as they return to the seabed (Suuronen & Erickson, 2010). Large-scale and intense removal of some species, such as those that naturally graze on or modify benthic biota, may also result in habitat modification over time (Kaiser *et al*., 2003) and disturbed population and ecology.

In some instances bottom trawling modifies habitats to an extent that species diversity and catch composition are changed, sometimes severely comromising once-productive fishing grounds (Jones, 1992). Examples include the removal of emergent, structurally complex habitats that provide food or shelter to target or prey species, such as coral reefs, sponge gardens, and seagrass beds. These habitats are usually more sensitive and adversely affected by trawl gear than sand or other unconsolidated seabed habitats, particularly if seldom disturbed by natural perturbation (Kaiser *et al*., 2003; Winger *et al*., 2010). In some instances the abundance of polychaete worms, echinoderms, and other benthic scavengers increases, and in others commercial species are replaced with other species that may or may not have commercial value. The recovery of these habitats may take many years or decades, or may not occur due to the scale of change or other factors.

6 Options to reduce seabed impact by bottom trawl gear

There are multiple options available to manage the impact of bottom trawling on the seabed and sensitive habitats. The National Research Council (2002) and Carr & Milliken (1998) identified four options to manage bottom trawl impacts: reduce fishing effort, establish closed areas, the use of alternative fishing gear, or the modification of existing fishing gear. McConnaughey *et al.* (2020) extended the number of options to nine, grouped into four classes: technical measures, spatial controls, impact quotas, and effort control (Table 2). All of the nine options should result in a reduction in habitat impact, to a greater or lesser extent, and improve the relative benthic status (RBS)[3] of the area of concern. Some may result in concentrating fishing effort (intensity) to specific locations or its displacement and subsequent increased impact in other locations. Some may also have significant negative socio-economic impacts on fishers and coastal communities.

There is a significant body of research that has investigated options to modify or adapt existing trawl gear to eliminate or mitigate seabed contact and habitat impact. Many of these options are designed to reduce the swept area or footprint of the trawl by elevating trawl components clear of the seabed to eliminate seabed contact. These options are discussed in detail in the next section. Key to the adoption and use of these options by fishers is that they have minimal impact on the target catch, are economically profitable, and the capital cost of conversion is quickly recovered through improved access (including security of access) to the fishery, reduced operating costs such as fuel, and/or increased catch value. If the catching efficiency of the gear is reduced as a result of modification, an unintended consequence of this option may be increased fishing effort to offset reduced catch and compromised reduction in habitat impact. This is one of the challenges the Tiaki, PSH programme has had to navigate given that increased trawl selectivity results in increased bottom contact time. This weighting of different sustainability criteria is an example of the need for coherent national policy. If PSH can reduce the mortality of target populations through increased selectivity, catchability will increase and therefore swept area and benthic impact will decrease.

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[3] RBS is defined by McConnaughey *et al.* (2020) as the current benthic biomass as proportion of the unimpacted benthic biomass.

Table 2. Options to reduce habitat impact. Adapted from McConnaughey *et al*. (2020).

Class	Option	Objective
Technical measures	Modify or adapt existing bottom trawl gear	Reduce seabed impacts and maintain or increase catchability of targets species
Spatial controls	Prohibition by gear type	Eliminate high-impact gears in a defined region
	Freeze trawl footprint	Confine impacts to previously disturbed areas
	Nearshore restrictions and zoning	Reduce trawling in shallow, sensitive habitats and minimise gear conflicts
	Prohibition by habitat type	Protect selected sensitive areas
	Multipurpose habitat management	Protect essential, representative and vulnerable habitats
Impact quotas	Invertebrate bycatch quotas	Reduce bycatch of benthic invertebrates
	Habitat impact quotas	Habitat conservation to protect benthic biota
Effort control	Removal of fishing effort	Reduce impacts by reducing fishing activity

Spatial controls serve to eliminate high-impact gear or restrict the use of this gear to specific locations. The use of low-impact fishing gear as a replacement, for example non-mobile (static) gear such as hooks and lines or pots, can be a viable option in some circumstances to minimise or mitigate seabed impact. However, as catch rates using this gear are usually reduced by several orders of magnitude, this option can have significant economic implications on fishers, even after accounting for possible improvements in catch quality and reduction in fuel consumption. The capital cost associated with the purchase of new fishing gear may preclude this as a viable option, particularly if accompanied by a need for substantial boat modification. There is also increased risk of gear conflict in areas that remain open to trawling and fishers may increase fishing effort to offset reduced catch rates, thereby eroding the gains associated with replacement of the high-impact gear.

Impact quotas serve to reduce habitat impact by placing a cap on the capture of benthic invertebrates or on access to sensitive biota. Benthic invertebrate quota can incentivise fishers to avoid fishing grounds where high numbers of these animals may be caught by the fishing gear, although this option is challenged by a need to establish sustainable quota levels, to fairly allocate this quota to fishers, and to ensure that appropriate monitoring, control, and surveillance (MCS) systems are in place and utilised. Such quotas may also impose significant financial hardship on fishers, particularly if they are insufficient in scale to allow them to fully utilise their quota of commercial fish.

Fishing effort control is usually applied to limit fishing mortality on fish stocks but it can also serve to reduce the frequency and extent of trawling impacts on the seabed. The success of this option is heavily dependent on the resilience of the benthic habitat to trawling and its ability to recover from trawl impact. Success may also be challenged by fishers introducing new technology or gear modification to offset any deleterious impact of effort control on catch rates, particularly if the impact of the new technology or modification is poorly understood or unregulated by management authorities. Notably, the application of a QMS, such as that used in New Zealand, can similarly reduce trawling impacts on the seabed. Such systems are designed to cap landings, but an inevitable consequence is fleet rationalisation and associated reduction in trawl footprint, particularly if accompanied by a suite of spatial and temporal fishing limitations and vessel and gear size restrictions.

7 Mitigating seabed contact and habitat impact through modification of bottom trawls

This section describes options to modify a bottom trawl to eliminate or mitigate seabed contact and subsequent habitat impact. These attempts are grouped into one of three categories, otter board modification, sweep and bridle modification, and ground gear modification. They are based on knowledge of trawl gear operation and supported by relevant scientific and grey literature. Summaries of key relevant literature describing modification of trawl gear to mitigate seabed contact are provided in Appendix A – Otter board modification, Appendix B – Sweep and bridle modification, and Appendix C – Ground gear modification.

7.1 Otter board modification

A range of options are available to modify otter board design or performance to mitigate seabed contact. These include;

- Reduced warp to depth ratio
- Increased towing speed
- Adjust otter board heel and tilt
- Lighter otter board materials
- Reduced angle of attack
- Semi-pelagic otter boards
- Controllable otter boards

7.1.1 Warp to depth ratio

This ratio describes the length of towing wire (warp) used to tow a bottom trawl in a given depth of water. It influences how closely the otter board and other trawl components contact the seabed and catching efficiency; without bottom contact the herding ability of the trawl is compromised and fish can escape underneath trawl components. As a general rule, higher warp to depth ratios are used in shallow water, e.g. 5:1 in 30 m of water and 1.5:1 in 1000 m of water. These ratios may differ between fishers because towing speed, tide and currents, and the design, weight, and rigging of trawl components can influence how closely the trawl contacts the seabed. Some fishers prefer to rig their trawl to fish 'hard' in contact with the seabed, and this might include using a higher warp to depth ratio to ensure close and persistent contact with the seabed[4]. Fishers may also choose to reduce warp to depth ratio where close contact with the seabed may result in net damage or the trawl becoming fouled or hooked up.

7.1.2 Towing speed

Towing speed can significantly influence the contact of a bottom trawl on the seabed. Towing speed is typically selected by fishers based on their knowledge of swimming performance of the target species. In fisheries where the target species cannot be herded into the path of the approaching trawl, for example prawn or scampi fisheries, this speed is generally around 1.0 to 2.1 m s^{-1}. In these fisheries catch rates are proportional to otter board spread and the distance trawled per unit time, hence persistent, close bottom contact is essential. In fisheries that target fish, squid, or other strong swimming species that can be herded, towing speed may range between 1.0 to 2.6 m s^{-1}, sometimes higher (Valdemarsen *et al*., 2007).

If towing speed is too slow, otter board stability may be compromised and they may fall over, perhaps becoming bogged and difficult to dislodge from the seabed. However, if towing speed is too fast, the otter boards may lose bottom contact resulting in loss of the sediment plume. The otter boards may also lift the anterior section of the sweeps clear of the seabed, resulting in reduced catching efficiency and fish loss from the trawl. Excessive towing speed can also result in the entire sweep, the lower bridles, and the ground gear losing bottom contact, either intermittently or otherwise, providing fish an opportunity to escape underneath. This occurs because drag forces acting on trawl components are attempting to retard the forward movement of the trawl, and they increase to an extent that results in lifting the trawl clear of the seabed.

7.1.3 Otter board heel and tilt

Fishers sometimes adjust the heel and tilt of an otter board (Figure 17) with otter board stability and catching efficiency in mind, although these adjustments can also be made to mitigate seabed contact. Both are influenced by the amount of trawl warp that is used, towing speed, and otter board rigging (FAO, 1974; SEAFISH *et al*., 1993). Outward heel ensures that hydrodynamic forces[5] acting on the otter

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[4] These fishers are reducing the declination angle ($\propto$) between the warps and the seabed. This in effect reduces the upward lift force (F_U) generated by the warps as they are towed through the water and increases the downward force of the otter board on the seabed (F_D). This relationship can be expressed by, $F_D = W - F_U = W - T.\sin(\propto)$, where W = otter board weight in water and T = warp tension.

[5] Hydrodynamic forces are produced as a result of towing an otter board through the water. They include an outward spreading force (lift), which is needed to open the trawl net horizontally, and a drag force. The

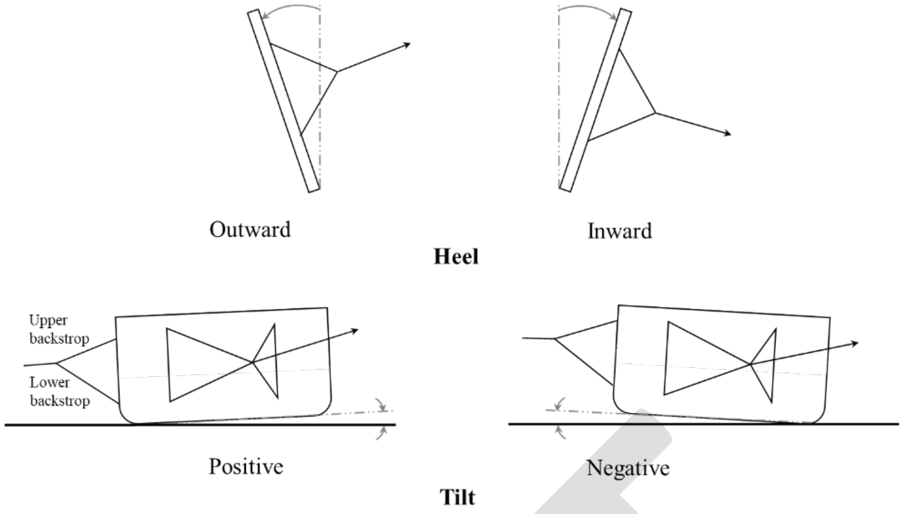

Figure 17. Otter board heel and tilt. Source: FAO, 1974.

board have a downward component that helps keep the otter board in contact with the seabed. Conversely, inward heel may result in less contact because the hydrodynamic forces are attempting to lift the otter board clear of the seabed. Inward heel is often caused by excessive warp length or excessive upper backstrop length relative to the lower backstrop chain. Moving lower the point where the warp is connected to the otter board or increasing towing speed are options to help overcome inward heel.

Otter board tilt (or pitch) can be negative or positive. Negative tilt results in the leading edge of the otter board digging in or "snubbing" on the seabed. This can be overcome by reducing warp length, raising the towing point on the otter board, increasing otter board weight, or reducing towing speed. Adjustment to backstrop chains may have limited or nil impact on tilt depending on otter board design (SEAFISH *et al*., 1993). Slight positive tilt is usually desirable as this facilitates the otter boards passing over obstacles on the seabed and may result in less seabed contact.

7.1.4 Lighter otter board materials

All things held equal, the use of a lighter otter board translates to lighter seabed contact and less scraping and ploughing of sediments. Reducing otter board weight can be achieved by removing any

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magnitude of these forces depends on towing speed, otter board size, weight, and shape (design), heel and tilt, and angle of attack.

weights attached to the shoe of the otter board or by using lighter construction materials.

Fishers commonly add weights to the shoe of the otter board to facilitate rapid sinking of the trawl, improve otter board stability in the water column and on the seabed, and ensure they closely tend the seabed. These weights may weigh 50-100 kg per otter board. While they can easily be removed to reduce seabed contact, a reduction or removal of these weights may compromise catching efficiency. It may also provide little or no appreciable reduction in seabed contact, given an inability to control the influence of environmental variables on the magnitude and extent of this contact. Fishers can also attempt to recover bottom contact by increasing warp to depth ratio, reducing towing speed, adding weight to the ground gear, or adjusting ground gear rigging, for example by shortening the upper bridle to release tension in the ground gear and improve bottom contact.

Otter boards are typically constructed from steel and may each weigh several hundred kilograms on small, low-powered trawlers and several thousand kilograms each on larger, high-powered trawlers. In water, otter boards lose around 13% of their in-air weight because they are subject to an upward buoyancy force, and additional weight saving can be achieved by replacing steel with lighter steel alloys (NET Systems, n.d.), polyethylene (Sterling & Eayrs, 2010), or heavy duty polyurethane (McHugh *et al.*, 2015). Another solution has been to insert high density foam inside a steel shell, which reduces otter board weight in water by up to 83% compared to their weight in air (NET Systems, n.d.)(Plate 2). While these otter boards are designed for midwater (pelagic) operations, the manufacturers suggest their operation in seabed contact is a feasible option.

7.1.5 Angle of attack

Angle of attack can be defined as the angle of the otter board to the forward direction as it is towed through the water (Figure 18). This angle is the result of all forces acting on the otter board, including hydrodynamic forces, seabed friction, and ploughing. At higher angles the width of the otter board's footprint on the seabed is increased, all things held equal. The profile area of the otter boards is also increased, resulting in higher fuel consumption[6]. In many bottom trawl fisheries, fishers have gravitated towards using more hydrodynamically efficient[7] otter board designs, either to spread larger nets or reduce fuel consumption. These otter boards include high-aspect ratio, multi-foil designs that

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[6] Fuel consumption is the penalty associated with overcoming the drag forces acting on the trawl. Drag is proportional to the profile area of the otter boards, the square of towing speed (velocity), and otter board shape.

[7] A measure of the lift to drag ratio produced by an otter board at a given angle of attack.

are operated at an angle of attack of 20-30°, where the lift to drag ratio close to maximum[8]. Less efficient otter boards, such as rectangular flat or vee otter boards, are usually operated at angles in excess of 30°. At 20° the otter board footprint is equivalent to just over 1/3rd of otter board length, and approximately half of otter board length when operated at 30° (Plate 3).

Plate 2. Lightweight otter boards by NET Systems. Source. NET Systems (n.d.).

Other than using more efficient designs, it is generally not possible for fishers to deliberately reduce the angle of attack to reduce seabed contact without compromising otter board stability and

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[8] Excellent reviews of otter board theory and the impact of angle of attack on their orientation and performance is provided in FAO, 1974; Patterson & Watts, 1985; and SEAFISH *et al.*, 1993).

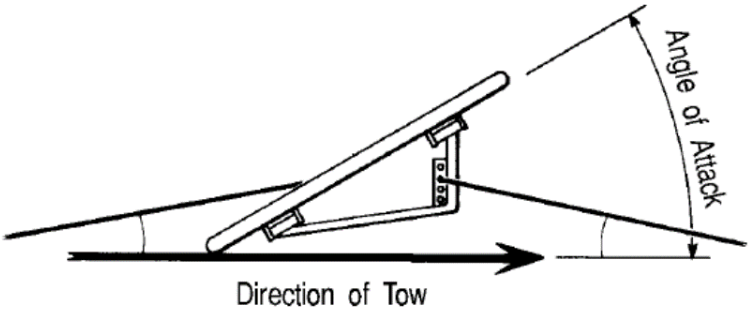

Figure 18. Otter board angle of attack. Source: SEAFISH *et al*., 1993.

Plate 3. The effect of angle of attack on the swept width (footprint) of otter boards. The flat rectangular otter board on the left is operating at an angle of attack in excess of 30^o and the 'batwing' otter board on the left is operating at around 20^o. Source. Sterling and Eayrs, 2010.

performance. One notable exception is the batwing otter board (Figure 19), designed with a flexible foil restricted to an angle of attack of around 20^o (Sterling & Eayrs, 2010; McHugh *et al*., 2015) The foil is hinged to a steel framework that is aligned to the towing direction; in this way the impact width or footprint of the batwing otter boards is equivalent to the width of the framework shoe. This otter board was designed for use in a prawn trawl fishery in Australia, and has not been widely adopted by fishers elsewhere. This otter board reduces bottom contact by approximately 86% compared to conventional otter boards, and reduces drag by approximately 18%.

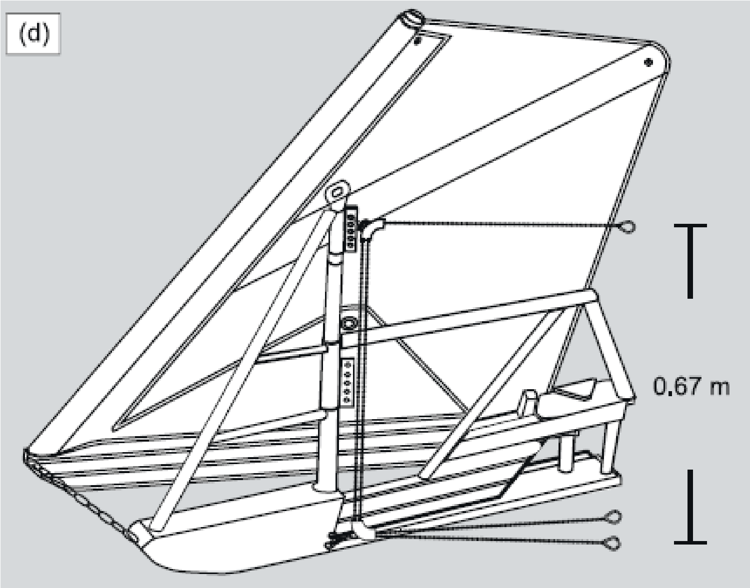

Figure 19. The batwing otter board. The bottom of the foil is hinged to the towing frame and a chain at the leading edge restricts angle of attack. Source: McHugh *et al*., 2015.

7.1.6 Semi-pelagic otter boards

A relatively new development in otter board design are semi-pelagic otter boards (Figure 20). These otter boards are typically a high aspect-ratio, multi-foil designs that can be used clear of the seabed, although many can also be used while tending the seabed. They are also very hydrodynamically efficient (high lift to drag ratio), very stable in the water column, and can be used to replace bottom-tending otter boards.

Several efforts have been made to evaluate the performance of these otter boards in fisheries targeting shrimp (DeLouche & Legge, 2004; He *et al*., 2006) and fish (Eayrs *et al*., 2012; Eayrs, 2014a, 2014b; He, 2014). These efforts have usually involved the replacement of conventional bottom-tending otter boards, with little or no modification to sweeps or other gear components. Additional efforts using semi-pelagic otter boards are based on deliberate attempts to raise the sweeps from the seabed; these studies are described in paragraph 7.2 *Sweep and bridle modifications*. To ensure the otter boards are clear of the seabed, less towing warp can be used compared to that when using bottom-tending otter boards. Acoustic monitoring sensors attached to each otter board are then used to monitor their height above the seabed, and warp length adjusted to either raise or lower the otter boards. The dynamic movement of other trawl components may result in fluctuation in otter board height, as may movement of the trawler in a sea or swell, particularly in shallower waters. Sometimes this fluctuation may result in the otter boards briefly rising to 5 m or more above the seabed (CRISP, 2017).

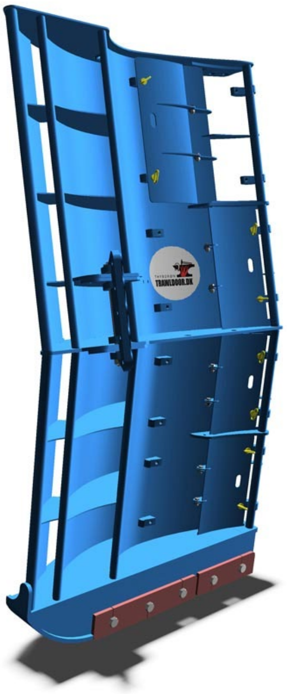

Figure 20. Semi-pelagic otter board constructed by Thyborøn Skibssmedia A/S. Source: http://thyboron-trawldoor.dk/products/semipelagic-trawldoors/.

In the study reported by Eayrs *et al*. (2012) and Eayrs (2014a), the fisher simply replaced his bottom-tending otter boards with semi-pelagic otter boards, and made no changes to warp to depth ratio. While the absence of scratch marks and polish on the bottom of the otter board shoe indicated that 95% of the shoe was clear of the seabed, the remainder was clearly in contact with the seabed. Acoustic sensors were not used by the fisher, as reduction of consumption and not seabed clearance was his primary reason for using these otter boards. Underwater video of these otter boards is available at https://www.youtube.com/watch?v=NzOndGXJRiU.

Fuel savings are often reported as a result of using these otter boards, although frequently this is accompanied by catch loss, particularly if the otter boards lift the anterior section of sweep clear of the seabed. Some of these reports indicate that fuel savings up to 20% or more may be realised, although in the long term around 10% seems more reasonable given the relative contribution of otter board to the total combined drag of all trawl components. Despite the risk of catch loss, these otter boards are increasingly being used by fishers, particularly in industrial fisheries in North America and Europe to reduce fuel consumption.

7.1.7 Controllable otter boards

In recent years substantial efforts have been made to develop otter boards that can be remotely controlled to increase their height above the seabed or the spread of the net (Figure 21). These otter boards are designed with adjustable foils or vents that respond to an acoustic signal from the trawler (CRISP, 2012; Open Access Government, 2014). The vents are opened or closed on demand to alter the hydrodynamic performance of the otter board, resulting in control of their vertical movement.

The extent of use of these otter boards is unknown, and may be limited by the capital cost of new otter boards and associated acoustic equipment. There are challenges with variable acoustic communication between trawler and otter boards (CRISP, 2016) although some fishers have already transitioned and are using these otter boards (Hansen, 2018). Excellent videos describing the design and operation of these otter boards, including underwater footage, is available at https://www.youtube.com/watch?v=Mk0BlS_lalU and https://www.youtube.com/watch?v= KNCqMLImC7Y. Additional information and videos are available at http://mld.one/.

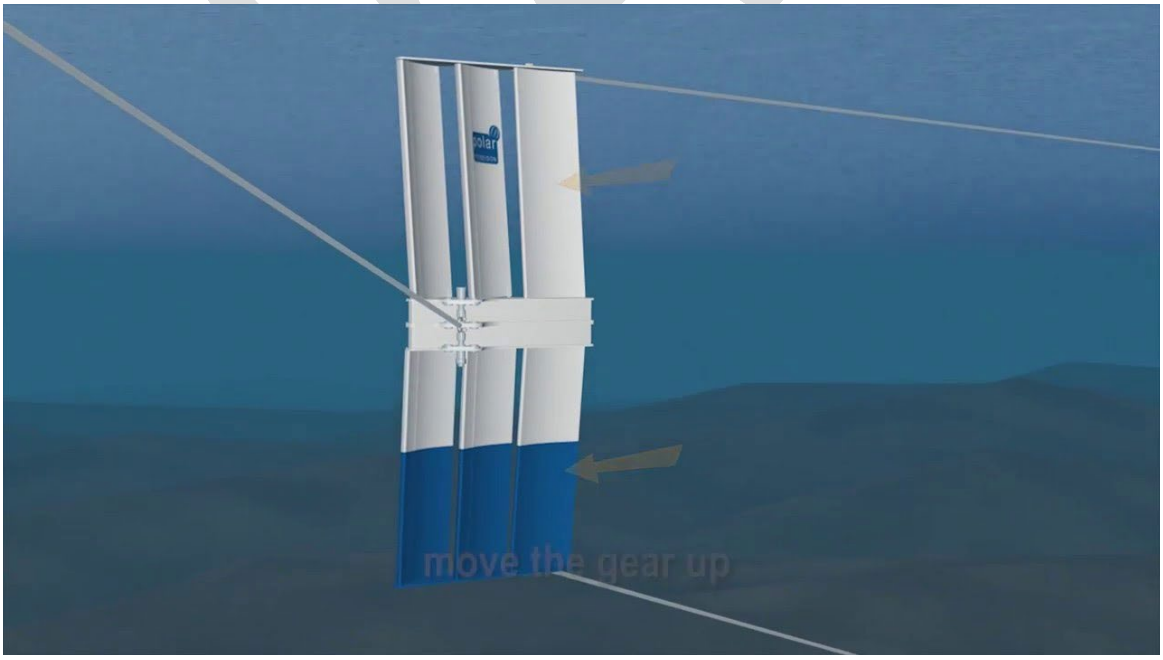

Figure 21. Controllable otter boards. By opening the upper vents and leaving the lower vents closed, otter board height above the seabed is increased. Source: Notus electronics.

7.1.8 Other otter board options

Over the years several innovative otter board designs have been tested to reduce seabed contact, and while they provide useful food for thought, their practicality and functionality is debatable.

An early effort to reduce seabed contact was the addition of two steel balls hanging from the bottom of a rectangular flat otter board (Figure 22). Known as the Hong Kong device, one ball was located near the leading edge of the otter board and the other near the trailing edge (FAO, 1974; Garner, 1978). Each ball was held in a cradle so they could spin around a horizontal axle to facilitate passage over hard, rocky ground and reduce damage to the otter board. The leading ball measured 220 mm in diameter and the trailing ball 180 mm in diameter, and each cradle was suspended from 300 mm chain droppers. A horizontal buoyancy chamber was also attached to the otter board, filled with polyurethane foam. This chamber rendered the otter board slightly positively buoyant, and it remained upright and stable in the water column should the trawler stop with the trawl net fouled on the seabed. It is unknown how widely this otter board was used.

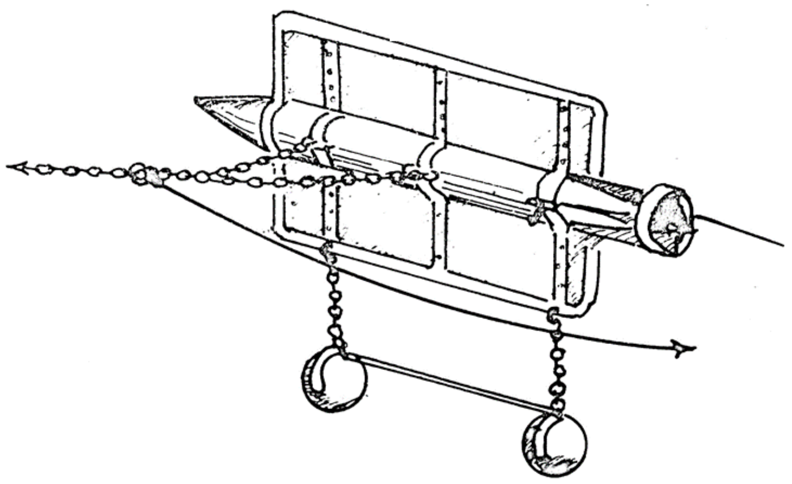

Figure 22. Floating otter board or Hong Kong Device. Source: Garner, 1978.

A similar and more recent attempt to produce an otter board with components that rolled over the seabed was the Le Beon Panneau a Roue Type LBR (SEAFISH *et al.*, 1993). This was an otterboard with a large steel wheel attached to the leading edge of a foil and a steel ball attached to the inside of the foil (Figure 23). No evidence describing the purpose of the wheel has been found although it is likely to have been designed to roll as the otter board was towed forward. As the steel ball rotated around a horizontal axle, it probably served to stablise the otter board and prevent it falling inward. It is unknown if this otter board was towed at low angles of attack, thereby reducing fuel consumption, although this would appear to be a logical outcome. There is no evidence to suggest this otter board was widely used, and it is likely to be cumbersome and difficult to use and stow onboard. Failure to orientate the wheel in the direction of tow will result in it being towed laterally and scraping seabed sediments, and fouling of moving parts by mud and other debris is also highly likely.

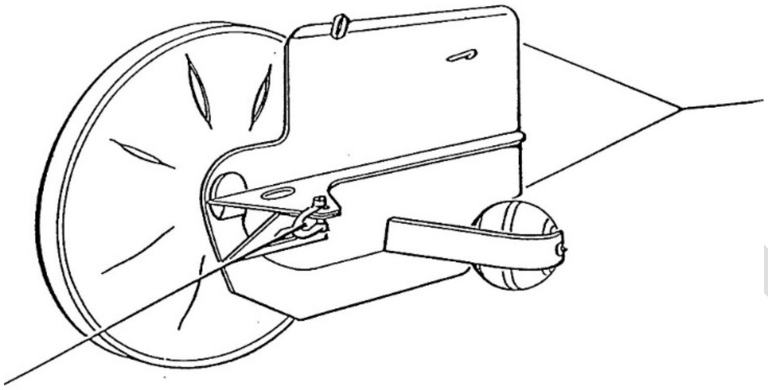

Figure 23. Le Beon Panneau a Roue Type LBR otter board. Source: SEAFISH *et al*., 1993.

7.2 Sweep and bridle modification

There are three key options available to modify sweeps and bridles to reduce seabed contact. They are:

- Reduce sweep and bridle diameter and weight per unit length
- Use shorter sweeps and bridles
- Elevate the sweeps and bridles clear of the seabed

7.2.1 Reduce sweep and bridle diameter and weight per unit length

Sweeps and bridles are commonly constructed from steel wire rope or combination rope, which is strands of steel wire rope covered with polypropylene fibre twisted together to form a rope. The diameter of sweeps and bridles on small trawlers may be 25-75 mm and up to 100 mm or more on larger trawlers. The breaking strain of these ropes needs to be sufficient to tow the trawl under all operating conditions, including rapid increases in tension due to intermittent snubbing or ploughing of trawl components in the seabed.

In some fisheries, small rubber discs (cookies) are added to protect the sweep and lower bridle from abrasion and damage, and to increase their weight to ensure bottom contact. The diameter of these discs is typically 75-150 mm, although the same sized discs are usually used along the entire sweep or bridle. It is unclear if their additional surface area and weight results in deeper penetration of the seabed or greater damage to benthos. In water, these discs lose around 75% of their in-air weight (Larsen *et al*., 2019).

Some fishers have replaced their steel sweeps and bridles with light-weight, ultra-high-performance materials such as Spectra™ or Dyneema™. These ropes have a very high strength to weight ratio and they float, thereby potentially reducing seabed contact. They are, however, more expensive that steel wire ropes per unit length and there is limited evidence of superior longevity, although they can be threaded through a flexible plastic hose for increased abrasion resistance. Recently, He *et al*. (2015) replaced steel wire bridles with polypropylene rope in a pandalid shrimp fishery (sweeps are not used in this fishery), and while no reference was made to mitigating seabed contact, this modification significantly reduced catches of unwanted flatfish and other species with little impact on the shrimp catch. Seabed clearance using these bridles was estimated to be 0.1-0.6 m. In a similar study, Guyonnet *et al*. (2008) used lightweight ropes with dropper chains to facilitate herding of fish and minimise catch loss underneath the ropes, although it is unclear if seabed contact was reduced or otherwise.

7.2.2 Shorter sweeps and bridles

This option is sometimes used by fishers to improve trawl manoeuvrability, particularly when trawling over hard seabed, in the vicinity of reefs, or on seamounts. This reduces the likelihood of trawl components impacting the seabed, potential hook-ups, and damage to the trawl net. Shorter sweeps and bridles may also be used when the target species does not respond to being herded into the trawl and they are caught in large aggregations or “marks”.

The use of shorter sweeps and bridles means a proportional reduction in the footprint or swept width of the sweep or bridle per unit time, e.g. if sweep length is halved the swept-width of the sweep is also halved. However, relatively few studies have attempted to quantify the impact of sweep length on catching efficiency. In a notable example, Engas & Godo (1989) reported increased catch rates of adult Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) when sweep length was increased from 20 m to 120 m. They also reported that smaller individuals were underrepresented in the catch when longer sweeps were used, implying that sweep length has a size selective effect on some species, possibly because smaller individuals become exhausted by the herding process and are overrun by the approaching sweep. It is also possible that shorter sweeps do not tend the seabed as closely (He & Winger, 2010), lacking sufficient weight to sag and contact the seabed, and being more sensitive to any vertical movement of the otter boards or net.

7.2.3 Elevate the sweeps and bridles clear of the seabed

Three options are available to elevate sweeps and bridles clear of the seabed. One option is to increase buoyancy by adding flotation to the sweeps and bridles and/or the trawl net. This modification was attempted by Morse *et al*. (2010) with some success although low catch rates hampered full evaluation. Similar efforts were made by He *et al*. (2015) and Guyonnet (2008) using light-weight, positively buoyant rope. Their results were promising but it remains unclear if sufficient height can be achieved to avoid emergent benthic organisms such as sea grass, sponges, and corals.

A similar potential option is the use of helical or helix ropes (Plate 4). These are in effect two ropes bound together, comprising a small diameter rope twisted around the surface of the main rope (Kebede *et al*., 2020). By protruding from the surface of the main rope, the additional rope generates lift as water flows over the rope surface. They are also positively buoyant. These ropes have been used to construct large meshes and increase the opening of midwater trawl nets, and are sometimes referred to as self-spreading trawls because they allow for the use of smaller otter boards, headline flotation, and foot rope weights. While there is some use of these ropes in midwater trawl fisheries around the world, no evidence could be found indicating their use as replacement sweeps and lower

Plate 4. Helical ropes. Source. Kebede *et al*. (2020).

bridles in a bottom trawl fishery, or as replacement meshes in the construction of a bottom trawl net. This is may be a reflection of the limited historic interest by fishers to reduce seabed contact by sweeps and lower bridles. However, they may only have limited potential given a lack of equivocal evidence from other studies suggesting these components can be lifted by buoyancy forces alone.

The second option is to fit the sweeps with large rubber discs (Plate 5). This option has been extensively tested in the Bering Sea Flatfish Fishery with encouraging results (Rose *et al*., 2010a and Rose *et al.*, 2010b). In this fishery, multiple rubber discs were held together to form a cluster and then retrofitted to the sweeps and lower bridles at 9 m intervals. Three treatments were tested, discs measuring 10, 15, and 20 cm in diameter, and they raised the clearance of the sweep and lower bridle by 5, 7.5, and 10 cm above the seabed respectively. These discs reduced sweep and lowered bridle impact by 95% compared to a standard trawl, and there was no significant difference in the catch ratio (control/experimental) of any species using the 15 cm and 20 cm discs. The cluster larger discs also significantly reduced the damage and mortality of sea whips and crabs. Evidence suggests that the impact of this modification on the commercial catch is different between day and night, due to

Plate 5. Cluster discs attached to trawl sweeps. Source: J. Gauvin. Alaska Seafood Cooperative.

variation in ambient light levels and reaction of various fish species (Ryer *et al*., 2010). In this fishery, sweeps and bridles are now required to be elevated at least 6.35 cm above the seabed using elevating devices spaced no less than 9.1 m apart (Federal Register, 2019). Devices that produce a clearance of up to 8.9 cm must be no more than 19.8 m apart, and devices that produce a greater clearance must be no more than 29 m apart. Elevating devices must be no more than 56.4 m from the net or door bridles (backstrops).

Preliminary testing of a similar elevated sweep using 20 cm diameter discs, was reported in the Gulf of Maine by Eayrs & Pol (2014). The impact of this modification on the catch was not conclusive; there was a reduction in the catch of some commercial species but no reduction in the catch of others. The fisher involved in this study reported being able to operate this gear with little difficulty, and underwater footage of this gear in operation is available at https://www.youtube.com/watch?v=K2N5wJ2-_UM.

The final option is to use semi-pelagic otter boards to lift some or all of the sweeps clear of the seabed (Figure 24). This option involves the use of high aspect ratio otter boards and the use of clump weights

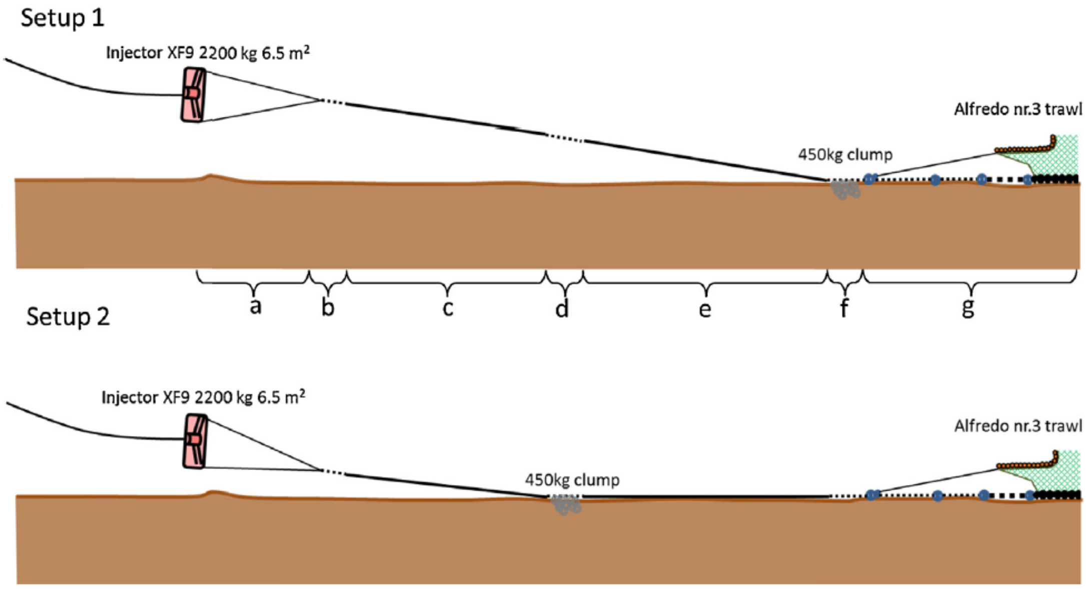

Figure 24. Experimental trawl gear. (a) 15.9 m backstrop, (b) 3 m backstrop extension, (c) 30 m of 30 mm sweep, (d) 4 m of 19 mm chain (attaching position for the clumps), (e) 45 m of 30 mm sweeps, (f) 4 m of 19 mm chain (attaching position for the clumps), (g) 45 m of ground gear composed of 19 mm chain (32 mm chain closest to the rockhopper), and the rockhopper. Source: Sistiaga *et al*., 2015.

to ensure some or all of the sweep is in contact with the seabed. Underwater footage of this option is available at https://www.youtube.com/watch?v=aouU-Aa9UoU. While this option successfully reduces seabed contact, it can also result in substantial catch loss. For example, Sistiaga *et al*. (2015) reported an average 33% reduction in the cod catch when sweeps were lifted clear of the seabed. This to be expected given the ability of the otter boards and sweeps to herd fish towards the approaching trawl is now compromised, and while not reported, the heavy clump weights presumably resulted in significant ploughing of seabed sediments.

7.3 Ground gear modifications

A range of options are available to modify the ground gear to mitigate seabed contact and habitat impact. These include;

- Reduce ground gear weight
- Increase the distance between rubber bobbins
- Wheels and rollers
- Plate gear/semi-circular ground gear
- Semi-pelagic trawl (French- or fork-rigged)
- Raised footropes and drop chains

7.3.1 Reduce ground gear weight

Reducing the weight of the ground gear seems like an obvious option to reduce the depth of seabed penetration by the various components of the ground gear. However, weight is often necessary to keep the ground gear in contact with the seabed (Valdemarsen *et al*., 2007; He & Winger, 2010) and to minimise the escape of fish underneath the ground gear and trawl net. In shallow waters, this can be a significant issue as motion of the trawler in heavy seas can result in lost bottom contact. Relatively few efforts appear to have been made to replace heavy with lighter ground gear without making other changes to the trawl, such as rigging changes to operate the trawl semi-pelagically (see semi-pelagic trawl section below for details). In a notable exception, He (2001) reduced the weight of ground gear in a shrimp trawl by 56%, and measured a 69% reduction in seabed contact without loss of catch. In heavy weather, an identified issue was loss of seabed contact and gear damage using the lighter gear.

7.3.2 Increase the distance between rubber bobbins

This option serves to reduce the number of bobbins in contact with the seabed. It will also reduce the overall weight of the ground gear, although is likely to result in loss of catch because the available escape window between adjacent bobbins is increased. It may also result in the trawl being less capable of riding over and clearing obstructions on the seabed.

7.3.3 Wheels and rollers

Several attempts have been made to replace conventional rubber bobbins with bobbins aligned with the direction of tow, or to use steel rollers (Plate 6). The use of bobbins aligned with the direction of tow is an attempt to overcome the scouring action of rubber discs and associated sediment resuspension, particularly along the quarters and wingends of the trawl. This modification has been successfully tested by Winger *et al*. (2018) and He & Balzano (2010) although it is unknown if this gear is being used commercially. The challenge with this gear is the complexity associated with ensuring each bobbin is aligned correctly for a given assumed wingend spread. It is also unknown how sensitive this gear is to variations in wingend spread that can be expected at over the range of normal operating conditions.

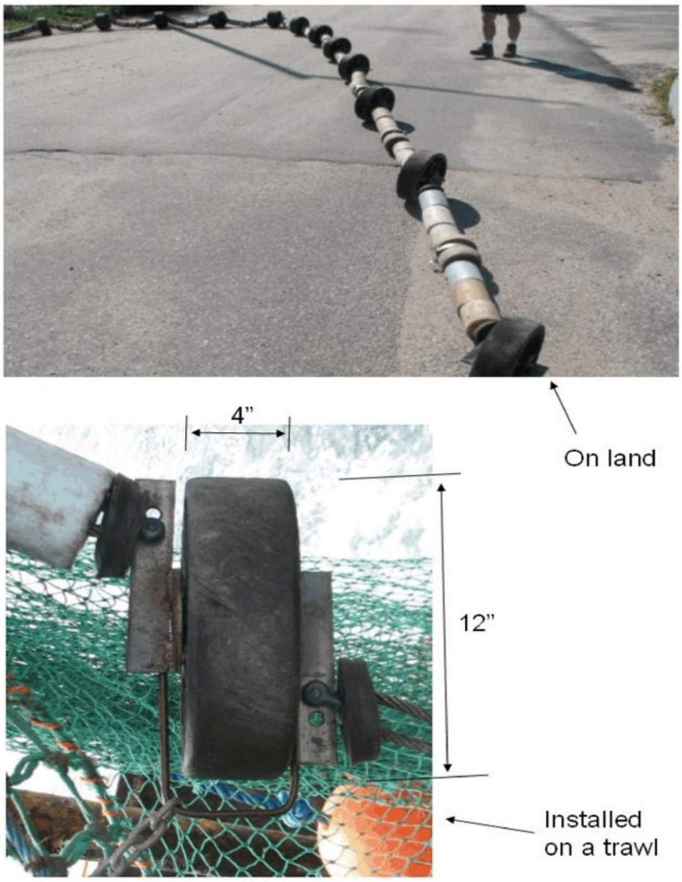

Plate 6. Aligned ground gear. Source. He & Balzano, 2010.

Steel rollers or bobbins that are air-filled lose up to 85% of their weight in air (Larsen *et al*., 2019), and are designed to roll over the seabed and reduce the scouring action of rubber discs and associated sediment resuspension. These outcomes have been achieved without loss of commercial catch and a fuel savings as much as 12% has been reported (Ball *et al*., 2002). Similar achievements have been recorded using roller ball gear on beam trawls (Caslake & Edwards, 2013); see https://www.youtube.com/watch?v=vlS7zRI2P9E for underwater video.

A unique variation to roller ball gear is to use large rolling tickler brushes. Called ‘street sweeper’ gear, this gear comprised of nylon brushes that were cylindrical in shape (Plate 7). They were located between the rubber discs and ensured the footrope stayed clear of the seabed. Apparently they also eliminated the scouring action of rubber discs and significantly reduced sediment resuspension, given their larger diameter, although concerns over increased catching efficiency using this gear resulted in it being banned in the United States (Cascorbi & Stevens, 2004).

Plate 7. Street sweeper gear. Source. Mike Pol, Massachusetts DMF.

7.3.4 Plate gear

This is a novel concept consisting of a series or 50 cm x 50 cm rubber or plastic plates (Plate 8) that replace conventional ground gear along the quarters and wings of the net (Valdemarsen & Hansen, 2004). The aim of this gear is to reduce drag and seabed contact, reduce catch loss under the trawl, and improve the handling ability of the trawl net.

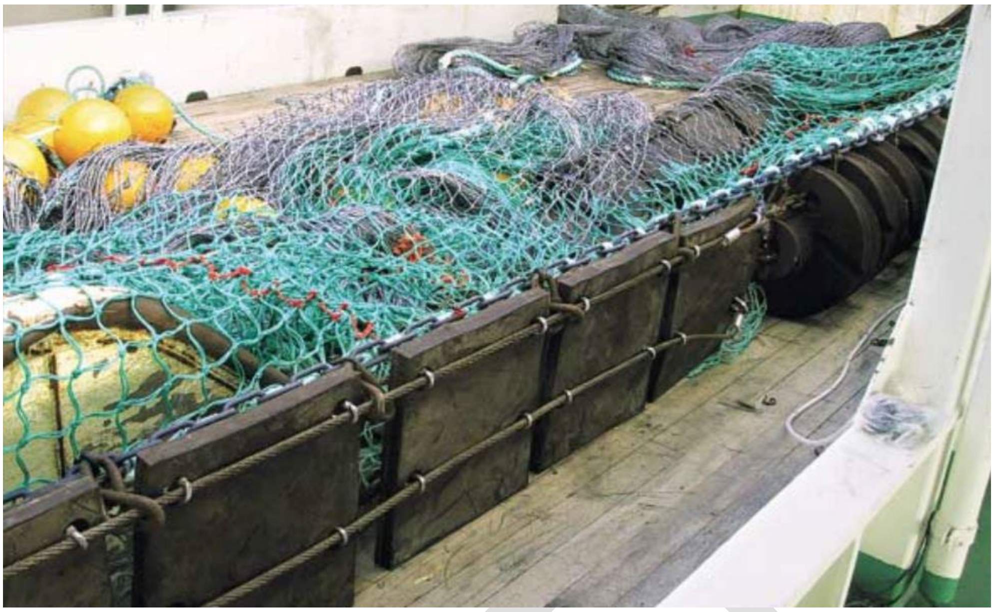

Plate 8. Plate gear. Source. Valdemarsen & Hansen, 2004.

The plates are aligned vertically and locked into position using two rows of steel wire rope or chain. Scale model testing in a flume tank found this ground gear reduced drag by 4% and increased wingend spread by 13% compared to conventional ground gear. Preliminary testing of this gear at sea has been completed, although the impact on drag was not reported. A spread increase was reported but the quantum of this increase was not provided. The plate gear easily passed over stony ground. Apparently, seabed contact can be varied by rigging the gear to either dive or lift; details were not provided but presumably this is achieved by adjusting the relative length of the wire ropes holding the plates vertically. It is also claimed this gear takes up less room and is easier to stow on the net drum.

Conceivably, plate ground gear simply glides over the top or rocks or other obstacles upon contact, although the bottom of each plate is likely in contact or very close to the seabed. The proportion of ground gear in seabed contact is probably higher than that for conventional ground gear using rubber discs. The anticipated increase in wingend spread conceivably means smaller otter boards are required to spread open the trawl, with concomitant reduction in weight and substate penetration depth

A similar modification is the use of semi-circular plates (Plate 9) to replace conventional ground gear (Brinkhof *et al*., 2017). Designed specifically to reduce catch loss underneath the foot rope, it is claimed this modification can also reduce seabed contact. The plates were constructed from 34 mm thick high density prolyethylene, and they measured 50 cm wide and 51 cm in diameter, with an 8 cm spacing between plates. Overall, this ground gear was 30% lighter in water compared to the conventional gear,

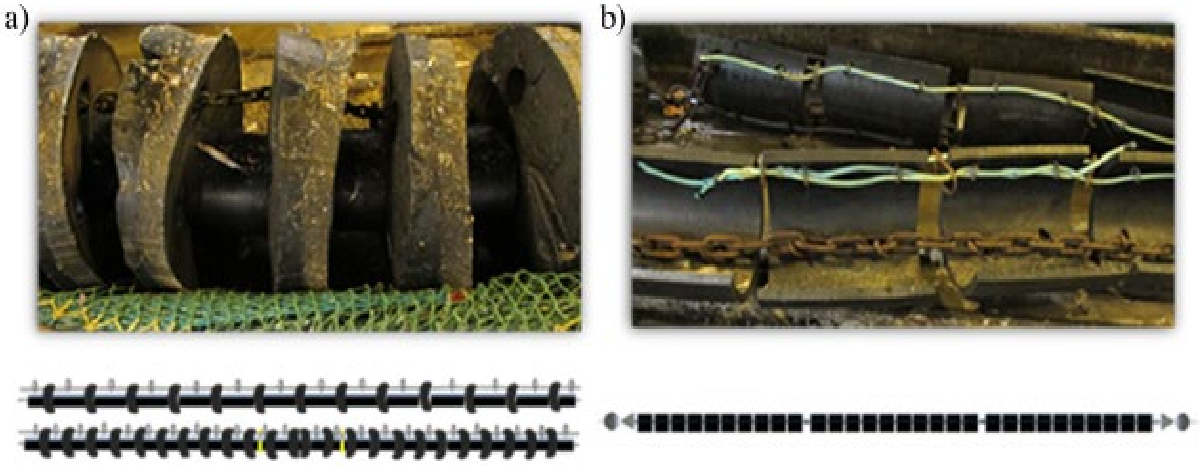

Plate 9. a) Conventional rock hopper ground gear and b) semi-circular spreading gear. Source: Brinkhof *et al*., 2017.

and underwater observations indicated substantially smaller sand clouds, indicative of less seabed disturbance. This ground gear also returned sooner to the seabed following encounter with large obstacles.

7.3.5 Semi-pelagic trawl (French- or fork-rigged trawl)

This style of trawl is a hybrid between a bottom and a midwater trawl. Ground gear, if used, is typically very light. Heavy weights may be attached to the lower wingends, and sometimes a small number of additional weights are used. In contrast to bottom trawls, the upper bridle (or fly wire) is lengthened and attached directly to the towing warp (Figure 25).

It is thought that this style of trawl was designed to land fish located a short distance above the seabed, particularly in uneven or rocky fishing grounds (Garner, 1978). An early example of this trawl is the Breidfjord floating trawl from Iceland (United States. Patent Office, 1956), although its use by French fishers (FAO, 1972) probably resulted in reference to this trawl being French-rigged. Presently, there appears to be little evidence of widespread commercial use of this trawl.

However, in recent years some interest has been shown in this trawl design to reduce seabed contact (He & Winger, 2010). This trawl has been tested successfully in an inshore groundfish fishery off the southwest English coast, and the trawl footrope settled approximately 1.8 m clear of the seabed (Arkley & Caslake, 2004). The impact on catch was not reported. A similar version, known as the ‘Julie

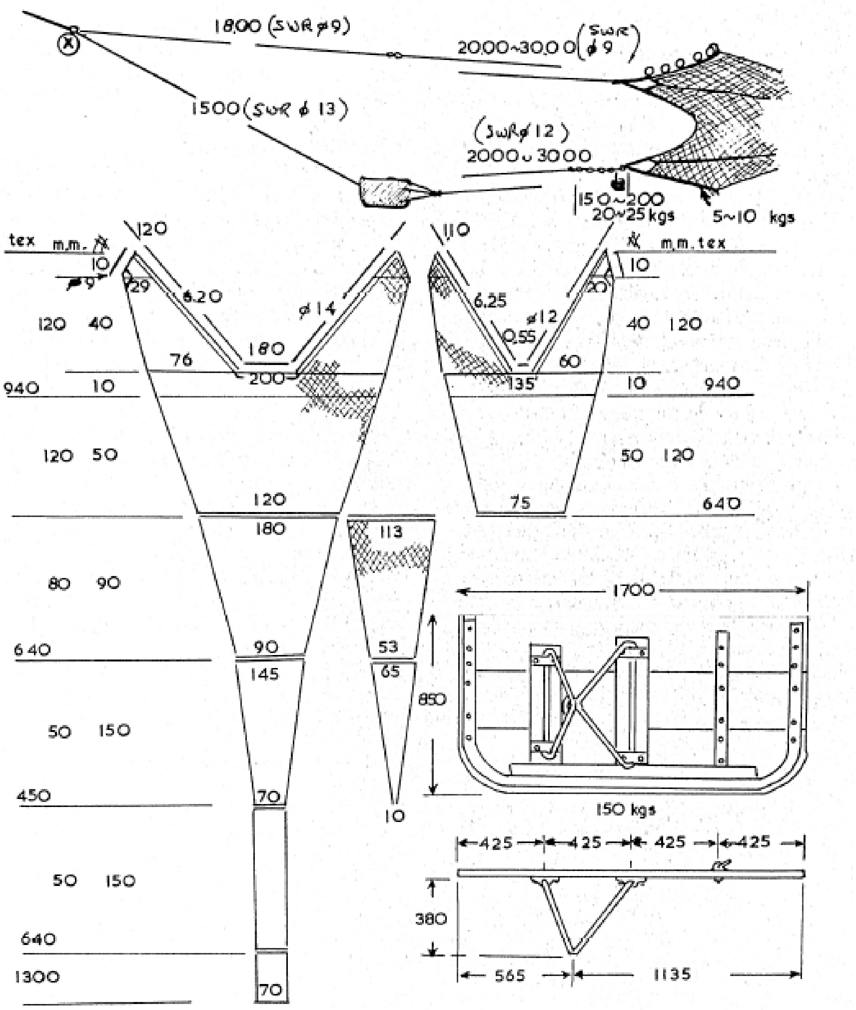

Figure 25. A detailed net and rigging plan for a semi-pelagic trawl. Note the upper bridle is lengthened and attached directly to the towing warp. Source. Garner, 1978.

Anne' trawl, was tested in fishery targeting mainly *Lutjanus* spp. in northern Australia (Ramm *et al.*, 1993). This was a four-seam trawl with equal headline and footrope length (38 m). Headline flotation was 115 kg and the footrope was weighted using a 60 kg weight attached to each wingend and 7 x 10 kg lengths of chain attached to the center of the footrope. The fly wire was attached to the warp wires 37 m ahead of the otter boards. The nominal seabed clearance was 0.3 m and vertical opening of the trawl was 10 m. Catch rates of *Lutjanus* spp. between this trawl and a control were similar and catches of benthic invertebrates were significantly reduced. Under water video indicated trawl wingends were approximately 1 m clear of the seabed and 0.3 m in the center of the footrope. It was estimated that the wingend weights and chains caused furrows 10-30 cm wide and 5-10 cm deep, but this was equivalent to around 3% of the swept width of the trawl.

7.3.6 Raised footropes and drop chains

Several attempts have been made to remove the ground gear and elevate the footrope well clear of the seabed. In the northeastern United States, a raised footrope trawl and a so-called ‘sweepless’[9] trawl was tested in the whiting (*Merluccius bilinearis*) fishery (Figure 26). The raised footrope trawl replaced the ground gear with a long horizontal chain connected to the footrope via 1 m long drop chains (Shepard *et al.*, 2004). The sweepless trawl was similar to the raised footrope trawl with the exception that the horizontal chain was removed. In the absence of the ground gear, numerous 1 m long drop chains were attached to the footrope, and the target footrope height is achieved either by using heavier chain, more chain, or by adjusting the relative length of the upper and lower bridles (He & Winger, 2010). Testing of these trawls have confirmed retention of whiting while reducing catches of non-target flatfish (Shepard *et al.*, 2004). Footrope height was 30 - 60 cm above the seabed. The ‘sweepless’ trawl is now mandated for use in the whiting fishery, based on demonstrable reduction in non-target fish.

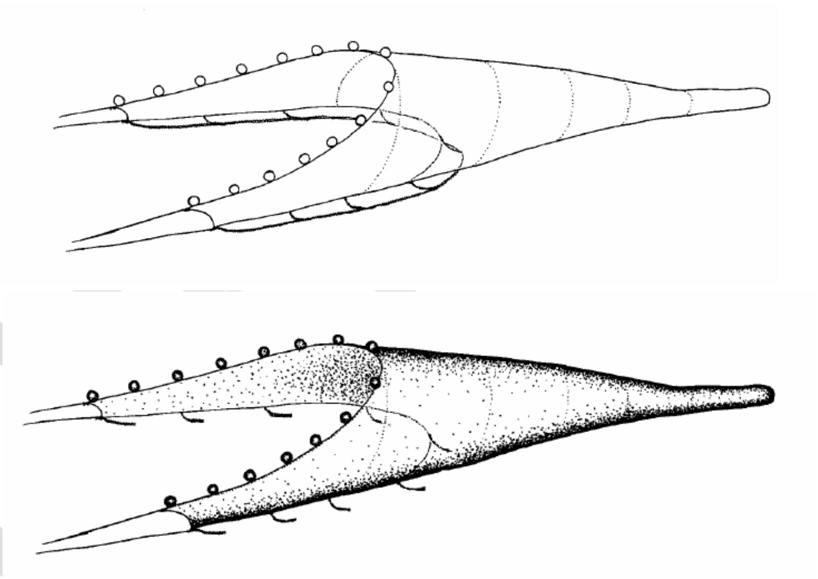

Figure 26. The raised footrope trawl (upper) and the ‘sweepless’ trawl (lower). Source. Shepard *et al.*, 2004.

A similar trawl has also been tested in the Australia’s northern finfish fishery (Brewer *et al.*, 1996). This trawl was developed in response to difficulties testing a modified Julie Anne trawl and to simplify

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[9] In parts of the United States, the ground gear is called the sweep, and sweeps are called ground cables.

rigging and handling. The conventional ground gear was replaced with five dropper chains with weights attached (Figure 27). Bridles and sweeps were kept short to improve manoeuvrability and control, and otter boards were oversized to over-spread the trawl and lift it clear of the seabed. This trawl significantly reduced the capture of benthic organisms without compromising catch rates of commercial species.

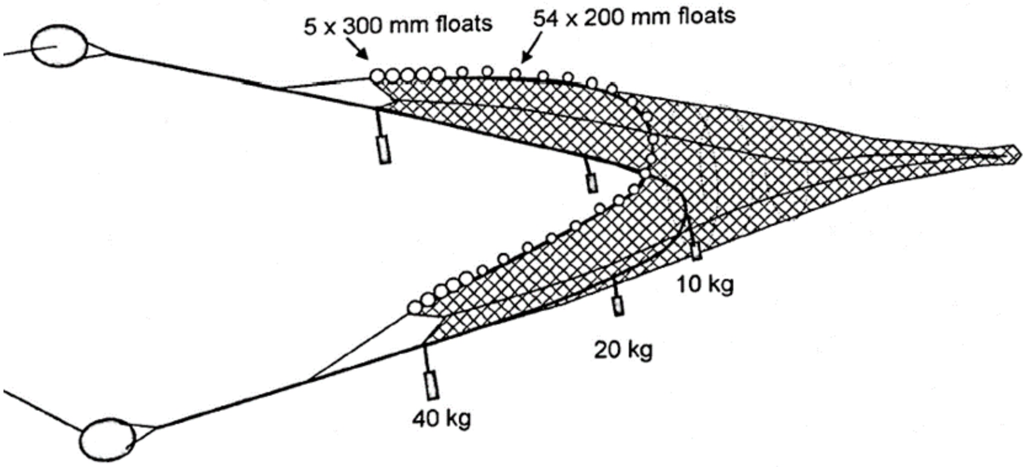

Figure 27. Semi-pelagic trawl with ground gear replaced with weights. Source. Brewer *et a*l., 1996.

Drop chains have also been tested in an Australian prawn trawl fishery. Known as a soft-brush ground gear, the traditional ‘Texas’ drop ground chain arrangement (Figure 28) was replaced with a 6 mm diameter high performance polyethylene rope threaded through 74 oval floats measuring 90 mm long by 60 mm diameter (Broadhurst *et al*., 2015). The ‘texas’ drop ground chain is usually a few chain links shorter than the footrope in order to stimulate prawns from the seabed and into the trawl. The polyethylene rope was approximately 4% shorter than the foot rope, so that the trailing dropper chains could similarly stimulate prawns into the trawl. Between each float, a 260 mm long dropper chain was attached (Figure 29 & Figure 30). An identical dropper chain was attached to the center of each float using plastic zip-ties. Four out of 5 floats were drilled to achieve neutral buoyancy, and the ground gear attached to the shoes of a beam trawl 100 mm above the seabed. This resulted in the floating rope suspended above the seabed and approximately 160 mm of each chain dropper in contact with the seabed. This ground gear reduced seabed contact by 63% compared to conventional ground gear, and there was no difference in the prawn catch. It also had little impact on several bycatch species, although the catch of one species of catfish (*Arius graeffei*) was significantly increased.

Figure 28. Typical ‘Texas’ drop ground chain arrangement. Source: Sterling, 2008.

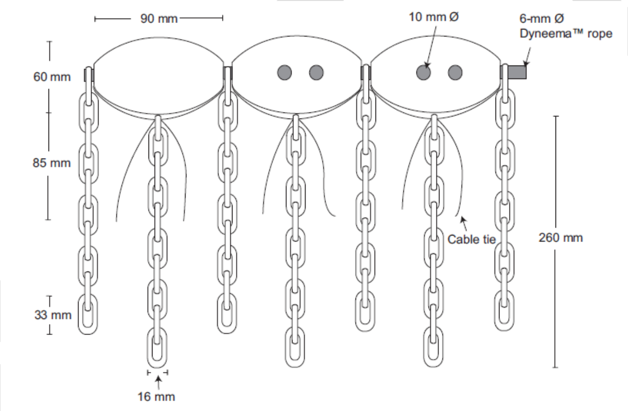

Figure 29. Soft-brush ground gear. Source. Broadhurst *et al*., 2015.

Figure 30. Soft-brush ground gear testing in a flume tank. Source. Sterling, 2008.

8 Application to New Zealand bottom trawl fisheries

The following questions are fundamental to considering the application of gear modifications described in this review in the New Zealand context:

1. What are the relative merits of each gear modification to reduce seabed contact?
2. Which gear modifications can conceivably be applied by the NZ bottom trawl fleet?
3. Does this fleet have the skill and expertise to introduce and apply these modifications?

The relative merits and operational considerations associated with each gear modification to reduce seabed contact are provided in Table 3. This table provides a first-order comparison of each modification within each category, *Otter board*, *Sweeps and bridles*, *Ground gear*, compared relative to conventional trawl gear. It also facilitates prioritisation of these modifications based on important operational considerations. No attempt is made to compare modifications between categories given the different impact of each category on the seabed.

The most effective otter board modifications are the use of semi-pelagic otter boards or controllable otter boards. Both options have the potential to eliminate otter board contact with the seabed when operated correctly. Their impact on the catch should also be low, unless they also lift the forward section of sweeps clear of the seabed. Their design is inherently fuel efficient, and when used clear of the seabed, fuel consumption due to seabed friction is eliminated. However, the cost of semi-pelagic otter boards can be NZD$10,000 or more depending on their size, and the cost of controllable otter boards is likely to be significantly higher. Further, their complexity challenges immediacy of application and ease of use.

The addition of flotation, cluster discs, or the use of semi-pelagic otter boards appear to be the most effective options in reducing seabed contact by sweeps and lower bridles. Flotation and cluster discs provide a relatively low-cost option, with relatively low impact on the catch but high reduction in seabed contact. They are also relatively easy to use. The use of semi-pelagic otter boards to deliberately lift the forward section of sweeps clear of the seabed may result in significant catch loss. The most effective ground gear option appears to be use of a semi-pelagic trawl with French or fork rigging, and trawls with raised footropes. Both options involve removal of the ground gear and elevation of the bottom of the trawl to clear the seabed. They can both provide good fuel savings although their immediacy of application and ease of use is relatively low. The risk to catch is also high, unless targeting aggregating species or towing at higher trawl speed.

Based on primary author knowledge and experience there is little doubt that most if not all of these modifications can be applied by the New Zealand trawl fleet, notwithstanding subtle differences in trawl design and operation between this fleet and elsewhere. Many of the relatively complex modifications have been successfully tested in multiple fisheries around the world, for example, semi-pelagic otter boards have been tested in New Zealand, Australia, Europe, and the United States, and in some instances, they are now being used regularly by fishers. Sweeps with cluster discs have been tested on the east and west coast of the United States, as well as Newfoundland and Labrador, and raised footrope trawls have been developed in Australia and the United States. Simply put, it appears these modifications can be adapted to suit most local trawl gear, albeit with some adjustment to suit different sized gear and vessels.

There is also little doubt that New Zealand trawl fishers have the skill and expertise to apply and use these modifications. Many of these options are simple adjustments to existing gear and practice, and can be applied quickly and easily. Others however may necessitate provision of technical advice, particularly when attempting more revolutionary changes such as semi-pelagic or controllable otter boards. This advice can be provided by otter board manufacturers, net makers, fishing technologists, researchers, or fishers that have prior experience, although many fishers may choose to go it alone and apply a trial and error approach. There is also little evidence to suggest that the adoption of any modification is limited by vessel size or engine power, and in fact some modifications can reduce engine demand through drag reduction. That said, in some instances deck modification may be required, for example, increasing the flanges on the net drum to accommodate sweeps fitted with bulky cluster discs. The need for modification will depend on a case-by-case basis.

Finally, the economic implications of these modifications on the New Zealand trawl fleet should also be considered as this may challenge their level of commitment to reduce seabed contact. While many of these modifications have the ability to reduce fuel consumption, with little or no impact on catch, others place the catch at risk, particularly when fishers are learning to apply them. There is also the possibility that catch rates are consistently reduced depending on where and how the modification is used, and the purchase cost of some is high, thus eroding the promised benefits of fuel saving.

Table 3. Generalised relative operational considerations of each gear modification to mitigate seabed contact by bottom trawl gear, within each category - Otter board, Sweeps and bridles, Ground gear - and normal anticipated limits of operation. L-Low, M- Medium, H-High.

	OPERATIONAL CONSIDERATION					
	Reduction in Seabed Contact	**Impact on Catch**	**Fuel Saving**	**Capital Cost**	**Immediacy of application[1]**	**Ease of use[2]**
Otter boards						
Reduced warp to depth ratio	L	L	L	L	H	H
Increased towing speed	L	M	L	L	H	H
Adjusted otter board heel & tilt	L	L	L	L	H	H
Use of lighter materials	L	L	L	M	L	M
Reduced angle of attack	M	L	M	L	H	M
Use of semi-pelagic otter boards	H	L	H	H	L	M
Use of controllable otter boards	H	L	H	H	L	L
Sweeps and bridles						
Reduced diameter & weight	L	M	L	L	M	H
Shorter sweeps & bridles	M	M	L	L	M	H
Additional flotation	H	M	L	L	M	H
Additional cluster discs	H	M	L	M	L	M
Use of semi-pelagic otter boards	H	M	H	H	L	L
Ground gear						
Reduced ground gear weight	L	M	L	L	H	H
Increased distance between bobbins	L	M	L	L	M	H
Wheels and rollers	M	L	M	M	M	H
Plate gear/semi-circular ground gear	M	L	M	M	L	M
Semi-pelagic trawl	H	H	H	H	L	L
Raised footropes and drop chains	H	H	H	M	L	L

1. Defined broadly as how quickly fishers can apply the gear modification and achieve optimal performance.
2. Defined as the ease with which the gear modification can be applied on a day-to-day basis.

9 Discussion and Recommendations

This review has described numerous efforts worldwide to modify trawl gear to reduce seabed contact and habitat impact. Many of these efforts have attempted to reduce the swept area or footprint of the trawl, usually by lifting the gear clear of the seabed. This is a logical approach, not only because it eliminates seabed contact but also because it can avoid most if not all benthic organisms. It also eliminates the challenge of trying to minimise or 'lighten' seabed contact, based on the questionable assumption that lighter contact equates to less habitat impact or damage.

Modifications that should eliminate seabed contact include semi-pelagic otter boards, flotation or cluster discs attached to sweeps and lower bridles, and removal of ground gear to 'fly' the trawl over the seabed. Whilst these options can solve the issue of seabed contact, it is important to recognise their potential to negatively impact the catch and day-to-day handling of the trawl gear. Therefore, any attempts in New Zealand to evaluate their efficacy should also evaluate their impacts on catch, fuel, immediacy of application, and ease of use. It will also be important to estimate the amortisation (pay-back) period associated with their purchase and the wider associated (social licence, environmental, fishery) benefits, thus providing fishers as much information as possible to evaluate their financial and operational opportunities. Close collaboration with these fishers will also be essential at this time, including widely sharing information describing the performance of these modifications.

This review is potentially an important early step toward reducing seabed contact by trawl gear in New Zealand. Realising this outcome requires additional steps and the following recommendations are provided for guidance.

1. Share this review with the New Zealand trawl industry and seek their feedback, particularly with respect to concerns about and interest in reducing seabed contact, and their ideas for eliminating or mitigating impact through gear modification.

2. Conduct an audit of trawl gear used in New Zealand. This would serve to identify and quantify variation in otter boards, sweeps and bridles, and ground gear, provide an understanding of the size and weight of these components, and to an extent, help understand how they are being used and what mitigations are already in place. This information could then help refine estimates of swept area,

allow estimation of potential reduction in swept area through gear modification, and help prioritise efforts to modify these components.

3. Consider interviewing fishers as part of the audit process, seeking information about their concerns associated with seabed contact and habitat impact, and asking how they have or would like to reduce this contact. Asking about their needs in the context of reducing seabed contact would also be useful.

4. Take deliberate steps to forge close relationships with industry bodies, fishing companies, and individuals. This includes establishing clear and regular channels of communication and building trust. It includes taking steps to understand industry perceptions, beliefs, and concerns associated with reducing seabed contact through gear modification, and it involves taking steps to assuage those concerns, such as evaluating the impact of gear modification against these concerns during future research. It also includes fostering and enabling close collaborating with the industry during future research processes and facilitating their engagement during all phases of the research, from goal-setting to extension (outreach) of results to all stakeholders. In short, it includes searching for 'win-win' outcomes for the environment and fishing industry. This has been the premise of many projects globally to reduce trawl impacts.

5. Consider mechanisms for making modified trawl gear available to industry to test at low-cost or free of charge. There is little evidence to suggest that fishers will voluntarily purchase expensive new equipment for the sole purpose of experimentation or to reduce seabed contact. The adoption of high-aspect ratio otter boards or other new gear by the fishing industry usually occurs organically over a period of time, and not as the result of findings by researchers, even if research was completed using commercial vessels and practice (Eayrs & Pol, 2018). One option to fast-track this process is to provide low-risk and low-cost opportunities for fishers to test this gear on their vessels, and allowing them access to a suite of modified gears of different sizes. For example, a range of semi-pelagic otter boards could be made available for testing at no cost for a limited period from a local net maker, with an understanding that the fisher could purchase the otter boards if satisfied with their performance. Supporting this initiative, options for flexible, low-interest finance should also be considered

through a local lending institution to encourage the purchase of these otter boards, perhaps even at a subsidised rate if enough fisher sign up for a bulk discount. A example of this approach is described in Eayrs & Pol (2014). The use of sustainability linked loans could also be considered incentivise this in New Zealand, building on the examples of Westpac in Western Australian MSC certified fisheries and Westpac in New Zealand with Contact Energy.

6. Consideration should be given to a holistic approach to mitigating seabed contact, by understanding how improved operational efficiency can reduce the footprint and other environmental impacts of trawling and by contributing to the development of a strategic, long-term plan to facilitate modernisation of the trawl fleet. For example, in a fishery governed by a QMS, improved operational efficiency can result in less fishing time, fuel consumption, and trawl footprint. In some circumstances it may also improve the quality and value of the catch. These outcomes not only help to reduce seabed contact, but they provide additional environmental and economic benefits. For example, use of efficient fishing gear can reduce fishing time, bycatch, fuel consumption, and greenhouse gas emissions. Reduced fuel consumption and improved catch value can improve fleet profitability and viability, which incentivises additional improvements and change, such as investment in modern fishing vessels and gear. A move towards fleet modernisation can further reduce fishing time and environmental impacts, and accelerates the removal of old, less efficient, and more damaging vessels.

   Associated with this it is important to be cognisant that there is very little understanding outside the fishing industry of how spatial access adjustments would affect seafood production, quota values and Annual Catch Entitlement (ACE) values. These are critical to model through, and understand the industry’s need to do so, such that the industry can understand the implications of such decisions, the transitional costs and, the potential financial and other benefits. In the case of Moana New Zealand for example, annual dividends returned to the 58 Iwi nationally are invested in social, environmental and economic development initiatives across the country. Given their (and their Iwi owner/shareholder) kaitiakitanga value, choices in favor of the environment may well be possible yet without understanding the implications to the dividend, these choices remain opaque.

7. Further extending this holistic approach, consideration should also be given to a collaboration with seafood sector leaders to establish agreed critical principles associated with protecting benthic habitats, protecting the livelihoods of the catching sector and subsequent supply chain, and respecting Treaty of Waitangi obligations and the importance of the dividends to Māori (in the case of Moana New Zealand). It also includes argreeing to short, medium and long-term actions that are required to reduce seabed impacts, and what the potential might be for regenerating marine ecosystems and underpinning quota rights if such a collaborative, respective and principled approach were taken. Terra Moana Ltd has a proposed framework to develop in this respect.

10 Glossary of terms

Aspect Ratio	In otter board parlance, aspect ratio refers to the ratio between otter board height and length. The aspect ratio of a rectangular flat otter board is typically around 0.5 i.e. otter board length is twice otter board height. Contemporary otter boards are usually constructed using one or more cambered foils with an aspect ratio of 2-3:1 or higher.
Bosom	The middle part of the headline or footline, usually extending normal to the direct of tow.
Benthic	Occurring at or relating to the bottom of the ocean or other body of water.
Benthos	The organisms the live on or in the seabed or bottom of a body of water.
Biota	The plants and animals found in a specific region, such as on the continental shelf, in an estuary, or in a particular habitat type.
Catching efficiency	The probability of catching fish or other animals of a given species within the area affected or influenced by the fishing gear, per haul or soak time. It is commonly used in reference to commercially valuable species that are equal to or greater than the minimum legal landing size.
Catch rates	The volume of fish or other commercial species landed per unit time, or per haul or soak time.
Drag	Drag is a force resisting the forward motion of the trawl system and it increases exponentially by the square of the towing speed (Drag $\propto$ velocity^2), all things held equal.
Footrope	The line to which netting in the bottom panel is attached. Sometimes known as the fishing line. The ground gear is usually attached directly to the footrope using chain droppers or other means. Sometimes a secondary line, called a bolsh line, serves as an attachment point for the ground gear. This line is similar in length to the footrope and ground gear. It is also attached to the footrope, and protects

	the footrope from abrasion and damage caused by the ground gear and seabed contact.
Ground gear	That part of the trawl gear attached to the bottom of the trawl net. It usually comprises a combination of chains, rubber discs, and bobbins. In some parts of the world it is called foot gear or a foot rope. In the United States it is called a sweep.
Rugosity	A measure of surface roughness or the variation in the height of the seabed.
Shoes	That part of a beam trawl or otter board in contact with the seabed. The shoe is usually constructed from steel and extends along the length of the otter board. Heavy weights are sometimes added to the shoe to keep the otter board upright, particularly in the water column, and ensure bottom contact. The leading edge of the shoe is often curved to help the otter board pass over rocks and other obstacles on the seabed.
Swept area	The area of seabed swept by the trawl gear. Swept area is a function of the distance between the otter boards and the distance trawled per unit time. It serves as a proxy for seabed contact because it is assumed that the otter boards, sweeps, lower bridles, and ground gear fully contact the seabed.
Quarters	That part of the trawl headline or footline between the bosom and wings of the net. Sometimes referred to as shoulders or gussets.

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12 Appendix A - Otter board modification

Reference: De Louche & Legge, 2004.

Title: Reducing seabed contact while trawling: A semi-pelagic trawl for the Newfoundland and Labrador shrimp fishery.

Objective/s: Eliminate seabed contact by the trawl doors without catch loss.

Study details

Location: Gulf of St. Lawrence and Labrador Sea.

Timing (year): 2004

Depth (m): 96-99 m.

Target species: Pink shrimp (*Pandalus borealis*).

Habitat characteristics:

Gear type and dimensions: Data was collected from two fishing trips.

Control gear: A commercially-used two-seam 980 shrimp trawl with bottom-tending otter boards. Upper and lower bridles measured 36 m and the sweep measured 18 m. Trawl mesh size was 50 mm.

Experimental gear: In the first trip the bottom-tending otter boards were replaced with Poly-Ice Elcazador otter boards. These otter boards weighed 550 kg and surface area was 2.8 m^2. In the second trip a different trawler was used. On this trawler larger otter boards were tested, weighing 850 kg each with a surface area of 3.6 m^{2,} and the sweep was removed.

No. of tows/tow duration: In the first trip, data was collected from 7 tows; data from the control and experimental gear was collected from 4 and 3 tows respectively. Tow duration was 2.5-4.0 hours. In the second trip data was collected from 9 tows; data from the control and experimental gear was collected from 3 and 5 tows respectively. Tow duration was 2.0-3.5 hours.

Towing speed: No detail provided.

Other study details: Netmind acoustic sensors were used to measure otter board spread and a depth sensor used to measure otter board height above the seabed.

Key findings/outcomes

Impact on benthos and habitat: No detail provided.

Impact on target catch: In trip one the catch per hour was higher using the experimental gear, although if warp length was too short, catch rates were decreased.

Impact on bycatch: Bycatch was substantially less using the semi-pelagic otter boards, although no specific detail was provided.

Impact on fuel consumption: No detail provided.

Ease of use: Replacing bottom-tending otter boards with semi-pelagic otter boards only required them to be changed over and less trawl warp to be used. Otter board spread was around 17% higher using the semi-pelagic otter boards despite reducing warp length by up to 33%. For many tows seabed contact was minimal (Plate A 1). The heavier semi-pelagic otter boards were in seabed contact, sometimes for the entire tow duration.

Cost: No detail provided.

Safety risk: No detail provided.

Future recommendations/work: Future suggested work included replacing the 850 kg otter boards with lighter otter boards, although it was recognised that this may present new challenges in heavy tidal flows. A more extensive testing program also needs to be introduced.

Plate A-1. Shoe of semi-pelagic otter board indicating limited seabed contact.

Consultant notes

- Excessing otter board weight can present challenges keeping them clear of the seabed. Reducing warp length is an option, although the authors noted that low catches may have been a result of using too little warp. This suggests that catch loss underneath the trawl may have occurred.
- Based on this study it seems that replacing bottom-tending otter boards with semi-pelagic otter boards appears to be a relatively straight forward exercise, only requiring them to be changed over and reduced trawl warp. This however assumes that acoustic sensors are available to monitor otter board height above the seabed.

Reference: He *et al*., 2006.

Title: Design and test of a semi-pelagic shrimp trawl to reduce seabed impact.

Objective/s: Evaluate the catching efficiency of a semi-pelagic shrimp trawl system in the Gulf of Maine.

Study details

Location: Gulf of Maine, USA.

Timing (year): 2002-04

Depth (m): 55-92

Target species: Pink shrimp (*Pandalus borealis*).

Habitat characteristics:

Gear type and dimensions: Traditional shrimp trawling in the Gulf of Maine uses bottom-tending otter boards and a high opening 4-seam trawl. Short sweeps and bridles are used although shrimp are not herded into the trawl; catch rates are influenced by the area of the trawl mouth. Flume tank testing helped identify how the trawl should be rigged using otter boards clear of the seabed. The new otter boards were tested in 2003 and 2004. In 2004, a trawler using a traditional trawl was used as a control.

Control gear: No detail was provided other than traditional fishing gear was used.

Experimental gear: Poly-Ice El Cazador otter boards were used in this experiment. They measured 1.7 m high x 1.24 m wide and weighed 240 kg in air. In the 2003 trials, this gear was rigged with 45 m sweeps and 9 m bridles (Figure A-1). The bridles attached to the headrope and middle panel were attached to an upper sweep, and the bridle attached to the ground gear was attached to a lower sweep. The upper sweep was attached to the top of the otter board and the lower to the bottom of the otter board.

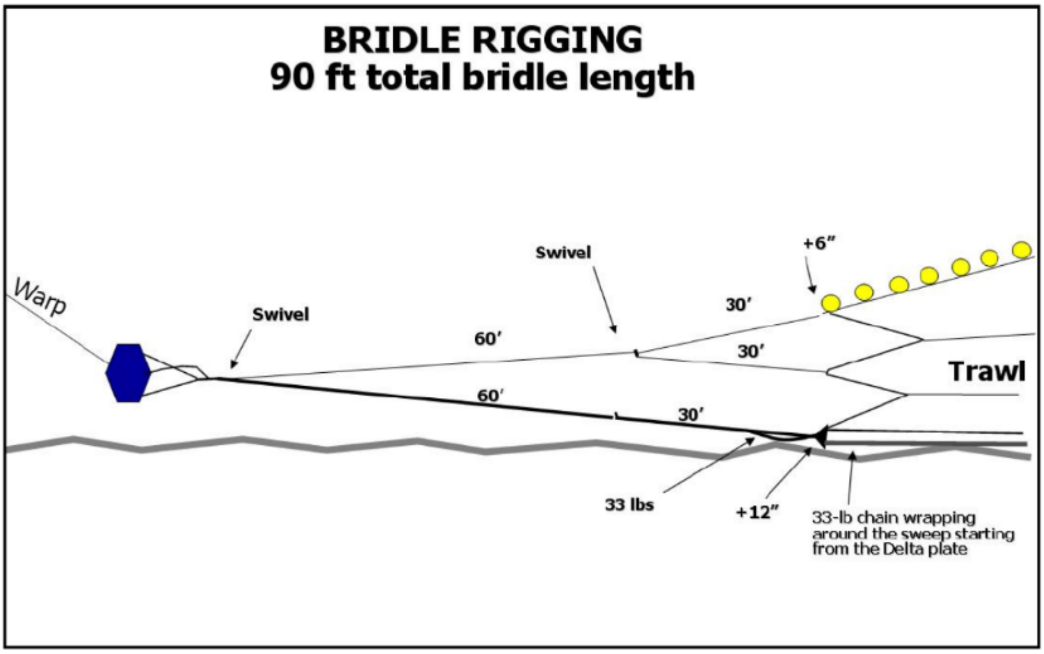


Figure A-1. The rigging arrangement used in 2004. Source: He *et al*., 2006.

No. of tows/tow duration: In 2003 and 2004, 38 and 34 one-hour tows were completed respectively.

Towing speed: The trawl was towed at 1-1.3 ms^{-1}.

Other study details: In 2004, the sweep and bridle combination was replaced. This new combination featured 18 m sweeps and 9 m bridles (Figure w). The bridle attached to the headrope and middle panel were attached to an upper sweep, and the bridle attached to the ground gear was attached to a lower sweep. The two sweeps were attached to a single point behind the otter board.

Key findings/outcomes

Impact on benthos and habitat: To ensure the otter boards remained clear of the seabed, marks were made on the trawl warps to record warp length to the nearest fathom (1.83 m). Typically, to maintain clearance the warp was about 5.5-18 m shorter than that used for traditional trawls. The otter boards were easy to use during deployment and retrieval. Otter board spread reasonably steady during operation and wingend spread was relatively constant. Otter board clearance, measured using acoustic sensors, was steady while the trawl was towed in a straight line, although while turning, the inside otter board contacted the seabed. The aft 30% of the otter board shoe area was polished, confirming some bottom contact during turning. It was suggested that a need to use sophisticated (and costly) acoustic sensors to monitor otter board clearance was unsuitable for this fishery.

Impact on target catch: In 2003, the catch rate was highly variable between days and tows, which is characteristic of the fishery although there was little overall difference in hourly catch rates compared to other trawlers at the time of the study. In 2004, catch rates were significantly lower than the control trawl, although as experience was gained with the new sweep and bridle arrangement, these differences were not significant. The size of shrimp caught by the experimental trawl were significantly larger than those caught in the control trawl. It was postulated that smaller shrimp may have escaped underneath the trawl.

Impact on bycatch: No detail provided.

Impact on fuel consumption: No detail provided.

Ease of use: The application of semi-pelagic otter boards was also challenged by rough bottom and limited number of straight-line tows.

Cost: No detail provided.

Safety risk: No detail provided.

Future recommendations/work: No detail provided.

Consultant notes

- Traditionally the Gulf of Maine shrimp fishery has operated for only 3 or 4 months each year. Fishers are usually engaged in other fisheries at other times, including groundfish trawling and/or gillnetting, trapping lobsters, etc. Vessel size is around 16 m and very few fishers use acoustic sensors to monitor gear performance. These reasons were likely used to justify not recommend semi-pelagic otter boards in this fishery.
- Trawl mesh size in this fishery is typically 50 mm, and a Nordmore grid is used to reduce fish bycatch (He *et al.*, 2007).
- This research focussed on semi-pelagic otter boards in a shrimp fishery, however the challenge of achieving and maintaining a desired otter board clearance above the seabed apply irrespective of target species.

Reference: Eayrs *et al*., 2012 and Eayrs, 2014a.

Title: Evaluating the efficacy of semi-pelagic otter boards to reduce environmental impact and improve profitability in the New England ground fish fishery: A win-win for fishermen and the environment.

Objective/s: Evaluate the ability of semi-pelagic otter boards to i) maintain the catch of commercially important species, ii) reduce the consumption of diesel fuel during the trawl operation, and iii) reduce or eliminated otter board contact with the seabed, in comparison to contemporary bottom-tending otter boards.

Study details

Location: Gulf of Maine, USA.

Timing (year): 2011

Depth (m): 70 m +/- 26.9 m

Target species: Atlantic cod (*Gadus morhua*)

Habitat characteristics: Not specified, but the area is known to be dominated by sand and soft mud.

Gear type and dimensions: The control and experimental otter boards were evaluated using an alternate haul experimental design on a typical bottom trawler (Plate A-2). The same trawl net was attached to both sets of otter boards. Over a 5-day period each otter board was tested twice per day before replacement using an A-A-B-B experimental protocol (A – semi-pelagic doors, B – bottom-tending doors). Fishing location, towing speed, and trawl-net rigging and operation, including amount of warp wire paid out, was determined by the captain and mirrored normal commercial fishing practice. Fishing depth was recorded at a random time once for each tow. Tow duration was deemed to commence as soon as the warp wire was no longer paid out and to cease as soon as hauling the trawl commenced.

Control gear: The bottom-tending otter boards were a typical multi-foil design with a surface area of 2.25 sq. m and a weight of 485 kg (Plate A-3).

Experimental gear: The semi-pelagic otter boards were similarly constructed with multi-foils but with a higher aspect ratio (height to length ratio). They were Type 14 otter boards purchased from Thyboron Skibssmedie A/S in Denmark. The surface area of the semi-pelagic otter boards were only 1.75 sq. m and they weighed 440 kg, a reduction of 22% and 9% respectively compared to the bottom-tending otter boards.

No. of tows/tow duration: Data was collected from 16 two-hour tows (n = 8 tows for each type of otter board).

Towing speed: Towing speed was 2.9 kts (1.5 m^{-1}).

Other study details: The F/V Lisa Ann II was used in this study measuring 16 m. A Floscan fuel flow meter was fitted to the vessel prior to the experiment to measure the boat's fuel consumption when each otter board was being used, and a Notus acoustic trawl mensuration system was used to measure and record the distance between the otter boards during each tow. To monitor otter board contact with the seabed, the otter boards were visually inspected at the completion of each tow for signs of bottom contact, including scratch marks or polish on the shoe.

Plate A-2. The F/V Lisa Ann II used in the sea trials. Image courtesy of S. Eayrs.

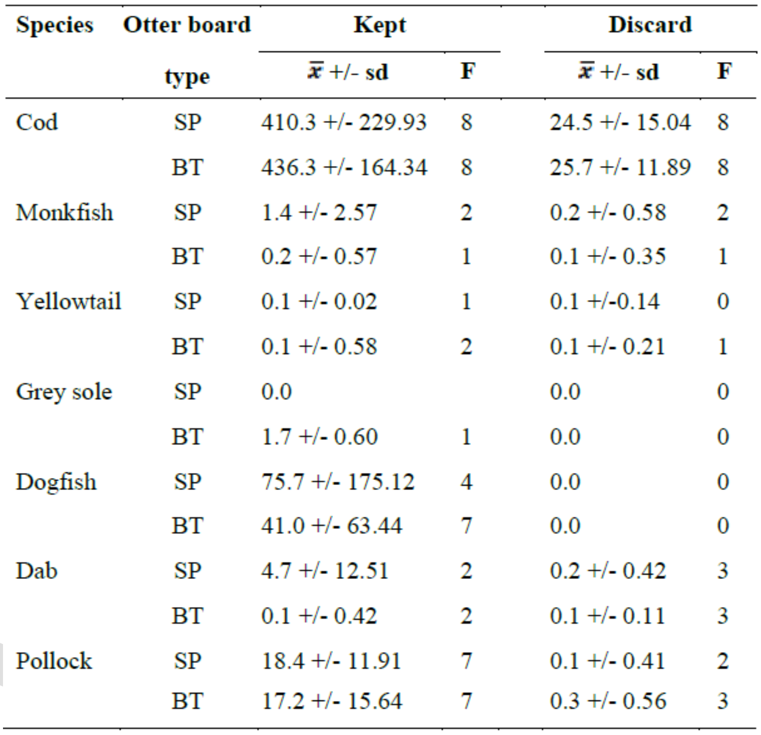
Plate A-3. The traditional otter board (outside) and the semi-pelagic otter board (inside). Note the difference sizes of each otter board. Image courtesy of S. Eayrs.

Key findings/outcomes

Impact on benthos and habitat: Visual inspection of shoes of the semi-pelagic doors indicated polish on the posterior edge of the shoe and anteriorly on the outer edge of the shoe. It was estimated that approximately 95% of the door shoe did not contact the seabed at any time during any tow. It was not possible to determine if this contact was consistent of intermittent during any or all tows. In contrast, the shoes of the bottom-tending doors indicated approximately 95% of the door shoe was in contact with the seabed during each tow.

Impact on target catch: A total of 827 cod were landed and measured using the semi-pelagic otter boards with a mean length of 65.3 +/- 8.06 cm. In contrast a total of 993 cod were landed and measured using the bottom-tending otter boards with a mean length of 64.8 +/- 8.47 cm. The mean weight of cod caught using the bottom-tending otter boards exceeded the semi-pelagic otter boards by 26 kg, although this was not significantly different ($p<0.05$)(Table A-1).

Table A-1. Mean standardised kept and discarded (undersized) weights (kg) of dominant species, by otter board type. SP = Semi-pelagic otter boards, BT = Bottom-tending otter boards. F = frequency of occurrence (tows).



Species	Otter board	Kept		Discard	
	type	$\bar{x}$ +/- sd	F	$\bar{x}$ +/- sd	F
Cod	SP	410.3 +/- 229.93	8	24.5 +/- 15.04	8
	BT	436.3 +/- 164.34	8	25.7 +/- 11.89	8
Monkfish	SP	1.4 +/- 2.57	2	0.2 +/- 0.58	2
	BT	0.2 +/- 0.57	1	0.1 +/- 0.35	1
Yellowtail	SP	0.1 +/- 0.02	1	0.1 +/-0.14	0
	BT	0.1 +/- 0.58	2	0.1 +/- 0.21	1
Grey sole	SP	0.0		0.0	0
	BT	1.7 +/- 0.60	1	0.0	0
Dogfish	SP	75.7 +/- 175.12	4	0.0	0
	BT	41.0 +/- 63.44	7	0.0	0
Dab	SP	4.7 +/- 12.51	2	0.2 +/- 0.42	3
	BT	0.1 +/- 0.42	2	0.1 +/- 0.11	3
Pollock	SP	18.4 +/- 11.91	7	0.1 +/- 0.41	2
	BT	17.2 +/- 15.64	7	0.3 +/- 0.56	3

Impact on bycatch: No detail provided.

Impact on fuel consumption: The mean fuel consumption for the semi-pelagic and bottom-tending otter boards was 8.4 gph +/- 0.63 and 9.5 gph +/- 0.63 respectively. Overall the fuel consumption was reduced by 12.0% when the semi-pelagic doors were used.

Ease of use: There was no difference in the handling ability of either otter board type; the fisher had been voluntarily using the semi-pelagic otter boards for two years prior to this study (and still does to this day).

Cost: The cost of a pair of semi-pelagic otter boards is around $10,000 depending on otter board size. A first order estimation of their amortization was 15 months based on typical fishing practice at the time of the study.

Safety risk: No detail provided.

Future recommendations/work: No detail provided.

Consultant notes

- The use of semi-pelagic otter boards is a viable alternative to tradition bottom-tending otter boards. The results of this study found very little impact on the target catch and a significant fuel saving. The fisher involved in this study has been voluntarily using these otter boards for many years, which is a telling development. Several other fishers in the region have now also transitioned to these otter boards.
- Mean spread of the semi-pelagic otter boards were approximately 5% less than the bottom-tending otter boards. The fisher in this study indicated that reduction was of little consequence.
- While not included in the report, the skipper claims that the warp to depth ratio used for both otter board types is the same, and that he simply replaced the bottom-tending otter boards with the semi-pelagic otter board without additional modification.

Reference: Eayrs, 2014b.

Title: Development and introduction of a Low Impact Semi Pelagic (LISP) trawl.

Objective/s: To i) quantify the performance of the LISP trawl gear on the commercial groundfish catch, including flounders, and other benthic vertebrates and invertebrates, ii) quantify the performance of LISP trawl gear on fuel consumption, and iii) describe any handling or operational issues associated with the use of LISP trawl gear during commercial fishing practice.

Study details

Location: Georges Bank, USA.

Timing (year): 2014

Depth (m): No detail provided, but trawling activity is typically

Target species: Mixed species including Haddock (*Melanogrammus aeglefinus*), Atlantic cod (*Gadus morhua*), dogfish (*Squalus acanthias*), and Blackback flounder (*Pseudopleuronectes americanus*).

Habitat characteristics: Not specified, but the area is known to be dominated by sand and soft mud.

Gear type and dimensions: The control and experimental otter boards were evaluated during separate fishing trips due to an inability to change otter boards at sea. Fishing location, towing speed, and trawl-net rigging and operation, including amount of warp wire paid out, was determined by the skipper and mirrored normal commercial fishing practice.

Control gear: This gear comprised of bottom-tending otter boards and sweeps.

Experimental gear: LISP trawl gear included the use of semi-pelagic trawl doors with a surface area of 3.0 m^2 and weighing 1,000 lbs. The raised sweeps measured 15 fathoms with 25 cm diameter roller bobbins attached to the sweep every 5 fathoms (Figure A-2).

No. of tows/tow duration: Two 10-day trips; 26 tows in trip 1 and 19 in trip 2. Tow duration was left to the discretion of the skipper. Tow duration in trip 1 averaged 3.2 h (range: 0.5 - 6.75 h) and in trip two it averaged 4.1 h (range: 1.0 - 5.25 h). Tow duration was deemed to commence as soon as the warp wire was no longer paid out and to cease as soon as hauling the trawl commenced.

Towing speed: 2.8 to 3.2 knots (1.44 - 1.65 m^{-1}).

Other study details: The F/V Nobska was used in this study, measuring 30 m. Fuel data was logged automatically by computer at one-minute intervals. Otter board spread was measured using Notus acoustic trawl mensuration sensors. The skipper also changed nets during the first trip. Changing trawl nets mid-trip was not anticipated and an unexpected development that complicated evaluation of LISP trawl performance. In trip 1, 48 hauls were completed with a low opening trawl net and 10 hauls with a high opening trawl net. In trip 2, 18 hauls were completed with a low opening trawl net and 17 hauls with a high opening trawl net.

Key findings/outcomes

Impact on benthos and habitat: The semi-pelagic otter baords exhibited no polish or shine on the shoes until weight was added to allow them to reach the seabed. Following further adjustments, no shine was evidenced on the shoes for the remainder of trip 1. The raised sweeps were also generally devoid of wear, as well as mud, seaweed, or other debris with the exception of the first roller bobbin and the lower bridle just ahead of the net. Limited video footage confirmed the semi-pelagic doors were mostly clear of the seabed and only the bobbins of the semi-pelagic ground cables contacted the seabed.

Impact on target catch: In trip one approximately 41 000 kgs of groundfish were landed and in trip two just over 13 000 kgs of groundfish were landed. Landings during both trips were dominated by dogfish, haddock, cod, skates, and pollock (*Pollachius virens*).

Catch comparison using the low opening trawl net indicated no significant difference ($p<0.05$) in catches of haddock and pollock, but a significant reduction in catches of cod, blackback flounder, pollock, skate, and dogfish. Using the high opening trawl net, there was no significant difference in catches of haddock, blackback flounder, pollock, and skate, but a significant reduction in cod and dogfish.

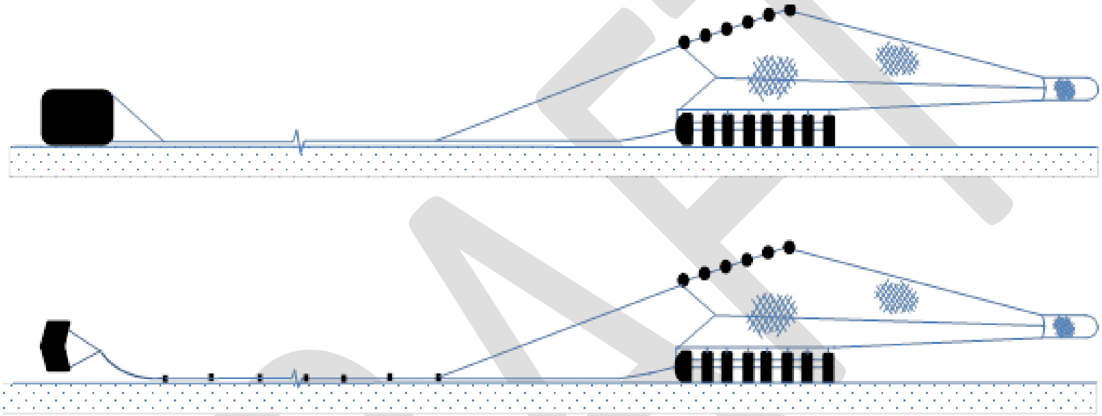


Figure A-2. The standard, bottom tending trawl system (top) and the trawl with semi-pelagic otter boards and raised sweeps (bottom). Note the use of small rubber bobbins to life the sweeps clear of the seabed. Image courtesy of S. Eayrs.

Impact on bycatch: No detail provided.

Impact on fuel consumption: In trip 1 the average combined rate of fuel consumption using the low and high opening trawl nets was just below 132 litres per hour. In trip two the combined average rate of fuel consumption for both trawl nets was a highly significant 19% less than that for trip 1. In trip 2, there was a highly significant 13% reduction in fuel consumption when the high opening trawl net was replaced with the low opening trawl net.

Ease of use: The following are paraphrased comments from the skipper and crew regarding the LIPS trawl:

- Didn't sink [the otter boards] nearly as fast as the traditional setup; otter boards seemed to wallow behind the boat. Had to slow down and let them “catch” before deploying as “normal.”
- Traditional otter boards would easily be at a spread of 320 [97 m] or 330 feet [100 m] with this setup. (Traditional otter boards were spreading at 268 ft [81 m])
- The otter boards are too small and light for their net and the boat, if you try to steam at all with them the doors “take off”

- We were catching a lot more fish right here last week...the catch composition is not much different
- The otter boards are one size too small.
- Normally we burn 750-800 gallons a day [2840 litres to 3030 litres] and this trip we've been burning about 600 [2270 litres] (although the tides and weather could play into that as well)
- Video suggest the angle of the otter board was much too sharp, which further indicates the doors were too small

Cost: No detail provided.

Safety risk: No detail provided.

Future recommendations/work: Future work should include efforts to continue to document fuel savings of both semi-pelagic otter boards and raised ground cables as well as their longevity in the fishery compared to traditional gear. A new study should be considered to more rigorously quantify the impacts of this gear on the seabed.

Consultant notes

- The combined use of semi-pelagic otter boards and raised sweeps was an attempt to explore the impact of this gear on commercial catches, fuel consumption, and ease of use. It made no effort to evaluate the impact of raised sweeps on benthic impact and benthos.
- Limited underwater video indicated the semi-pelagic otter boards and raised sweeps were operating as expected, with minimal bottom contact.
- This study was challenged by the experimental design, and further confounded by the unexpected change in nets part way through trip 1 as well as modification to the semi-pelagic otter boards to ensure their operation closer to the seabed.
- The author indicates this study serves as a demonstration of the potential catching performance of this gear, and that care is required interpreting the results of this study.

Reference: He, 2014.

Title: Using Semi-Pelagic Doors in Groundfish Trawls to Improve Fuel Efficiency.

Objective/s: Evaluate the ability of semi-pelagic otter boards to i) replace bottom-tending otter boards and ii) evaluate performance based on fuel consumption and catch.

Study details

Location: Southern New England and mid-Atlantic waters, USA.

Timing (year): 2014

Depth (m): 53 m to 274 m

Target species: Summer flounder (*Paralichthys dentatus*) and monkfish (*Lophius americanus*)

Habitat characteristics: Not specified; the area is known to be dominated by sand and mud.

Gear type and dimensions: The control and experimental otter boards were evaluated during separate fishing trips due to an inability to change otter boards at sea. The same trawl net was used during both fishing trips. Fishing location, towing speed, and trawl-net rigging and operation, including amount of warp wire paid out, was determined by the captain and mirrored normal commercial fishing practice. Fishing depth was recorded at a random time once for each tow. Tow duration was deemed to commence as soon as the warp wire was no longer paid out and to cease as soon as hauling the trawl commenced.

Control gear: NETS Hi-Lift otter boards were used as a control, each weighing 640 kg with a surface area of 3.5 m^2 (Plate A-4).

Experimental gear: This study used NETS Gull Wing semi-pelagic otter boards (Plate A-5) weighing 400 kg each with a surface area of 3.0 m^2 similarly constructed with multi-foils but with a higher aspect ratio (height to length ratio). The surface area of the semi-pelagic otter boards were only 1.75 sq. m and they weighed 440 kg, a reduction of 22% and 9% respectively compared to the bottom-tending otter boards.

No. of tows/tow duration: Two 10-day trips; 26 tows in trip 1 and 19 in trip 2. Tow duration was left to the discretion of the skipper. Tow duration in trip 1 averaged 3.2 h (range: 0.5 - 6.75 h) and in trip two it averaged 4.1 h (range: 1.0 - 5.25 h).

Towing speed: 2.8 to 3.2 knots (1.44 - 1.65 m^{-1}).

Other study details: The F/V Apollo was used in this study measuring 23 m. Floscan fuel flow meter was fitted to the vessel prior to the experiment to measure the boat's fuel consumption when each otter board was being used.

Key findings/outcomes

Impact on benthos and habitat: Visual inspection of shoes of the semi-pelagic doors indicated polish on the posterior edge of the shoe and anteriorly on the outer edge of the shoe. It was estimated that approximately 95% of the door shoe did not contact the seabed at any time during any tow. It was not possible to determine if this contact was consistent of intermittent during any or all tows. In contrast, the shoes of the bottom-tending doors indicated approximately 95% of the door shoe was in contact with the seabed during each tow.

Impact on target catch: Summer flounder and monkfish comprised about 88% of total landings. The overall catch rate of the Hi-Lift (Trip 1) and Gull-Wing doors (Trip 2) was 35 and 105 kg/hr, respectively.

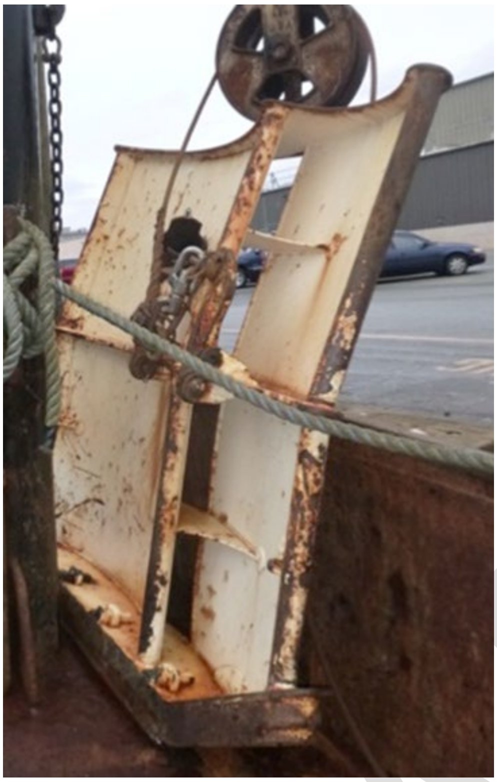


Plate A-4. The Gull wing otter board. Image courtesy of P. He.

Plate A-5. The Hi-Lift otter board. Image courtesy of P. He.

Impact on bycatch: There were more discarded fish during Trip 1 compared to Trip 2. About 93% of the total catch during Trip 1 was discards and only about 68% during Trip 2.

Impact on fuel consumption: The mean fuel consumption for the semi-pelagic and bottom-tending otter boards was 24.3 gph +/- 3.00 and 33.9 gph +/- 4.4 respectively, a 28% reduction. Overall, the fuel consumption was reduced by 12.0% when the semi-pelagic doors were used.

Ease of use: There was no difference in the handling ability of either otter board type; the fisher had been voluntarily using the semi-pelagic otter boards for two years prior to this study (and still does to this day).

Cost: No detail provided.

Safety risk: No detail provided.

Future recommendations/work: The author recommended that more rigorous controlled testing is required to definitively quantify savings.

Consultant notes

- It was not possible to use an alternate haul experimental design. The control otter boards were exclusively used in trip 1 and the semi-pelagic otter boards in trip 2. Subsequently care is required interpreting the results of this study.
- The skipper was very positive about the performance of semi-pelagic otter boards, noting ease of use and spreading ability.

Reference: Jones, 2015.

Title: Trials of semi-pelagic trawl doors.

Objective/s: The objectives were to i) set up the semi-pelagic doors and establish minimum depth of operation, ii) determine fuel consumption, and iii) determine the impact of lifting trawl doors off the seabed on catch-rates and size composition

Study details

Location: Hawke Bay, NZ.

Timing (year): 2014

Depth (m): 50 m to 93 m

Target species: Tarakihi (*Nemadactylus macropterus*), gurnard (*Chelidonichthys kumu*), and barracouta (*Thyrsites atun*).

Habitat characteristics: Not specified.

Gear type and dimensions: The control and experimental otter boards were evaluated during separate fishing trips due to an inability to change otter boards at sea. The same trawl net was used during both fishing trips, a 33 m Albatross bottom trawl.

Control gear: Price engineering conventional otter boards were used as a control, weighing 135 kg each with a surface area of 1.6 m^2 (Figure A-3). They were fished on the seabed only.

Experimental gear: Polar Fishing Gear Jupiter J45 semi-pelagic otter boards, weighing 196 kg each and with a surface area of 1.45 m^2. Both were fished on and off the seabed. When fished off the seabed a 46 kg weight and a 3 m extension were added to each sweep to keep the sweep in seabed contact. An additional 45 m sweep was added between the otter boards and the weight.

No. of tows/tow duration: Nineteen tows were attempted but data was used from only sixteen tows, due to operational problems. Four tows were completed with the semi-pelagic otter boards in seabed contact, seven tows with these otter boards clear of the seabed, and 5 tows with the conventional otter boards. Tow duration was one hour.

Towing speed: 2.4 to 2.9 knots (1.23 - 1.49 m^{-1}).

Other study details: The F/V Nancy Glen 2 was used in this study measuring 11.5 m. A Maretron fuel flow meter was fitted to the vessel prior to the experiment to measure the boat's fuel consumption when each otter board was being used. Otter board spread and headline height data was collected using a Marport fish monitoring systems. Contact of the sweeps on the seabed was investigated using NIWA-designed bottom contact sensors. They were used only when the semi-pelagic otter boards were used. Trawl mensuration data, towing speed, engine revolutions and fuel consumption were recorded manually every 5 minutes during each tow.

Key findings/outcomes

Impact on benthos and habitat: Visual inspection of shoes of the semi-pelagic doors indicated polish on the posterior edge of the shoe and anteriorly on the outer edge of the shoe. It was estimated that approximately 95% of the door shoe did not contact the seabed at any time during any tow. It was not possible to determine if this contact was consistent of intermittent during any or all tows. In contrast, the shoes of the bottom-tending doors indicated approximately 95% of the door shoe was in contact with the seabed during each tow.

Impact on target catch: The mean standardised catch (excluding nuisance species - spikey dogfish, carpet sharks, and eagle rays) for the conventional otter boards and the semi-pelagic otter boards in bottom contact averaged 18.3 +/- 0.34 kg/km^2 and 18.8 kg/km^2 respectively. The mean standardised catch (excluding nuisance species) of the semi-pelagic otter boards when clear of the bottom ranged was 15.8 +/- 0.44 kg/km^2.

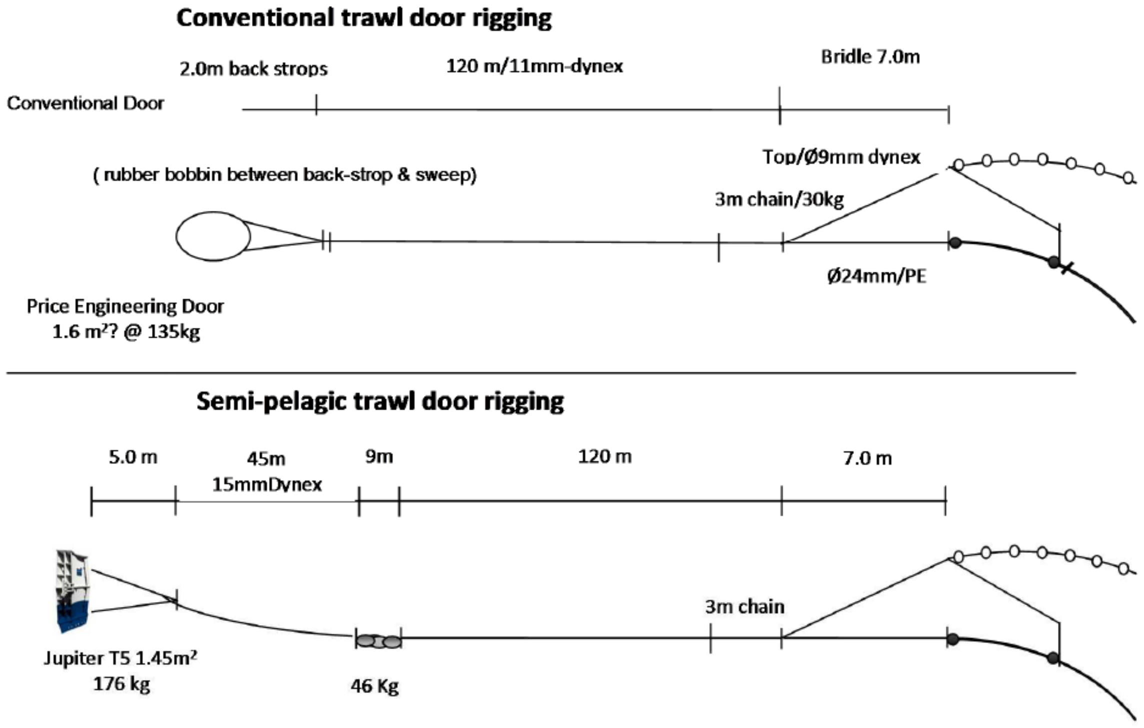


Figure A-3. The control (conventional) bottom trawl and the semi-pelagic trawl.

Impact on bycatch: No detail provided.

Impact on fuel consumption: The mean fuel consumption for the conventional otter boards and the semi-pelagic otter boards in bottom contact averaged 18.8 +/- 0.34 litres/hr and 18.3 litres/hour respectively. The average fuel consumption of the semi-pelagic otter boards when clear of the bottom ranged was 15.8 litres/hour.

Ease of use: The spread of the semi-pelagic otter boards was highly variable when fished clear of the seabed, ranging from 58-91 m. Headline height was 3.4-4.3 m. When these otter boards were in seabed contact, spread ranged from 86-100 m and height was 2.5-3.1 m. The spread using the conventional otter boards was 65-73 m and headline height was 3.2-3.4 m. The ends of the 120 m sweeps were lifted clear of the seabed for substantial periods, when the semi-pelagic otter boards were operated clear of the seabed.

Cost: No detail provided.

Safety risk: No detail provided.

Future recommendations/work: The author recommended that more rigorous controlled testing is required to definitively quantify savings.

Consultant notes

- The inward tilt of the semi-pelagic otter boards was frequently in excess of 15 degrees. The optimum tilt angle for these otter boards is unknown, however, excessive inward tilt may compromise the spreading force and cause instability, resulting in reduced spread. Note that while higher spread is not unexpected when these otter boards were in seabed contact, due to ground shear, the measured reduction when not in seabed contact is substantial.
- It is possible that the semi-pelagic otter boards were too large in this study. They were 30% heavier than the conventional otter boards, and when used in seabed contact, they produced substantially more spread. Assuming the conventional otter boards were optimally spread, higher spread may result in loss of seabed contact and escape of fish underneath the ground gear. Headline height should also be decreased, as was evident when using these otter boards in seabed contact.
- The results of this study should be treated as indicative only, given the relatively few tows that were completed.

13 Appendix B - Sweep and bridle modification

References: Rose *et al*., 2010a and Rose *et al.,* 2010b.

Title: Effective herding of flatfish by cables with minimal seafloor contact

Objective/s: Evaluate the effect of raised sweeps on flatfish capture and seafloor contact

Study details

Location: Bering Sea, Alaska

Timing (year): 2006

Depth (m): 70-117

Target species: Yellowfin sole (*Limanda aspera*), Northern rock sole (*Lepidopsetta polyxystra*), Flathead sole (*Hippoglossoides elassodon*), Arrowtooth flounder (*Atheresthes stomias*), Alaska pollock (*Theragra chalcogramma*), and Pacific cod (Gadus *macrocephalus*).

Habitat characteristics: Unconsolidated mixture of sand and mud.

Gear type and dimensions: Twin trawl system. Identical two-seam nets with 200 mm mesh netting in wings and body of the trawl, 130 mm codends. Distance between each door and central clump weight was approximately 80 m.

Control gear: Sweeps measured 180 m and constructed from 5 cm dia. combination rope.

Experimental gear: Multiple rubber discs were clustered together to form a 'cluster disc'. Each cluster disc was attached to the sweep at 9 m intervals, measuring 15 (6 inch), 20 (8 inch), or 25 cm (10 inch) in diameter (Plate B 1). These raised the clearance of the sweep of 5, 7.5, and 10 cm above the seabed respectively. The length of each cluster disc was approximately equal to their diameter. Sweep length and construction identical to control gear.

Plate B 1. Cluster discs. Source: Rose *et al*., 2010a.

No. of tows/tow duration: A total of 61 hauls were completed, including 19, 26, and 16 hauls with the 15, 20, and 25 cm cluster discs respectively. Tow duration ranged from 33 to 150 mins.

Towing speed: No details provided.

Other study details: The 47 m F/V Cape Horn factory trawler was used in this study.

Key findings/outcomes

Impact on benthos and habitat: Sonar imagery confirmed the unmodified sweeps (control gear) produced a continuous cloud of disturbed sediment as a result of contact (skimming) with the seafloor. Cloud density increased when the sweep contacted a high point on the seafloor. Cloud intensity varied due to sweep vibration during the tow. A sediment cloud only appeared directly behind each cluster disc, and occasional sweep contact with high points on the seafloor. Contact area of the discs was reduced to about 5% of total area swept by the sweeps (Figure B 1), although the density of the sediment cloud was higher than that for the control sweeps.

The impact of elevated sweeps on sea whips (*Halipterus* sp.) was evaluated in a controlled study over one year (Figure B 2). Sea whips are a species of soft coral that can grow more than 1 m high, and are highly susceptible to damage by passing trawl gear. After one year there was significantly fewer upright and undamaged sea whips following impact by the control gear, compared to those impacted by the elevated 20 cm sweep.

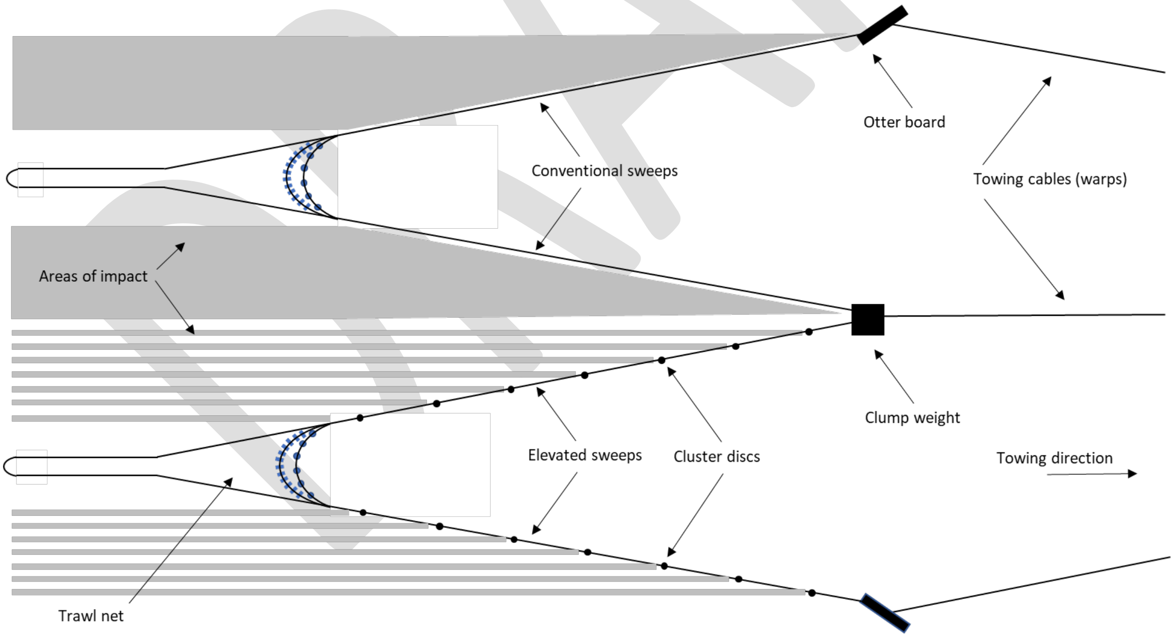


Figure B 1. Comparison of seabed area impacted (shaded) by each sweep. Adapted from Rose *et al*., 2010a.

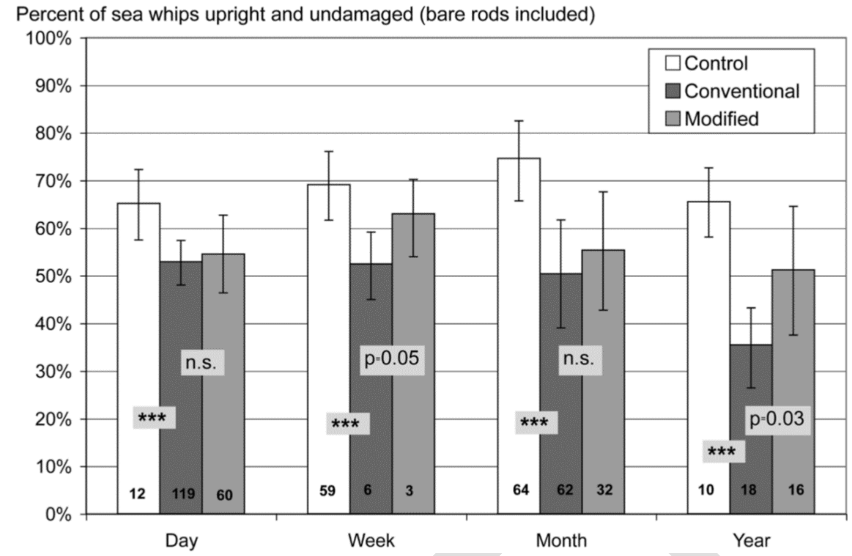


Figure B 2. Proportion of undamaged sea whips using conventional and 20 cm elevated (modified) sweeps, compared to control observations. Sample sizes are indicated in each column. Source: Rose *et al*., 2010b

Impact on target catch: There was no significant difference in the catch ratio (control / experimental) of any species using the 15 cm (6 inch) and 20 cm (8 inch)discs, with the exception of an increase in pollock (Figure B 3). Using the 25 cm (10 inch) discs, the catch of northern rock sole and flathead sole decreased significantly, the catch of pollock increased significantly, and the catch of yellowfin sole and arrowtooth flounder decreased but not significantly. With one exception there was no significant difference in the catch ratio (control / experimental) of any species by commercial size category, irrespective of cluster disc dia. There was a significant reduction in Alaska pollock using the smaller discs, although this was attributable to a low catch rate at the time of the study.

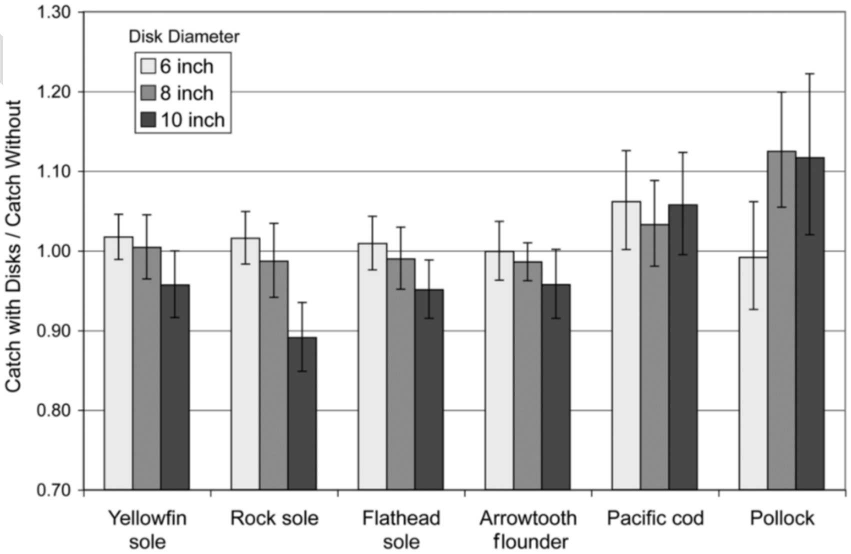


Figure B 3. Catch ratios of major species with 15 cm (6 inch), 20 cm (8 inch), and 25 cm (10 inch) cluster discs. Source: Rose *et al*., 2010a.

Impact on bycatch: The mortality of crab bycatch was substantially reduced using the 20 cm elevated sweep (Figure B 4). Mortality was evaluated using a six-part reflex-mortality test.

Impact on fuel consumption: A potential reduction was proposed due to reduced seabed contact by the experimental sweep. Alaskan fishers have progressively used longer sweeps to increase swept area and enjoy cost-savings relative to the use of larger nets to sweep the same area (Rose et al., 2010b).

Ease of use: The experimental gear would require some adaptation by fishers. The cluster discs would take up more room on the net drum, requiring larger drum flanges or shorter sweeps to be used, unless drum space is already available. Deployment and retrieval may be more complicated because the experimental sweeps will not wrap around the net drum as evenly as the control sweeps. Durability of the experimental sweeps may be greater due to reduced seabed abrasion.

Cost: No detail provided.

Safety risk: No detail provided.

Future recommendations/work: No detail provided.

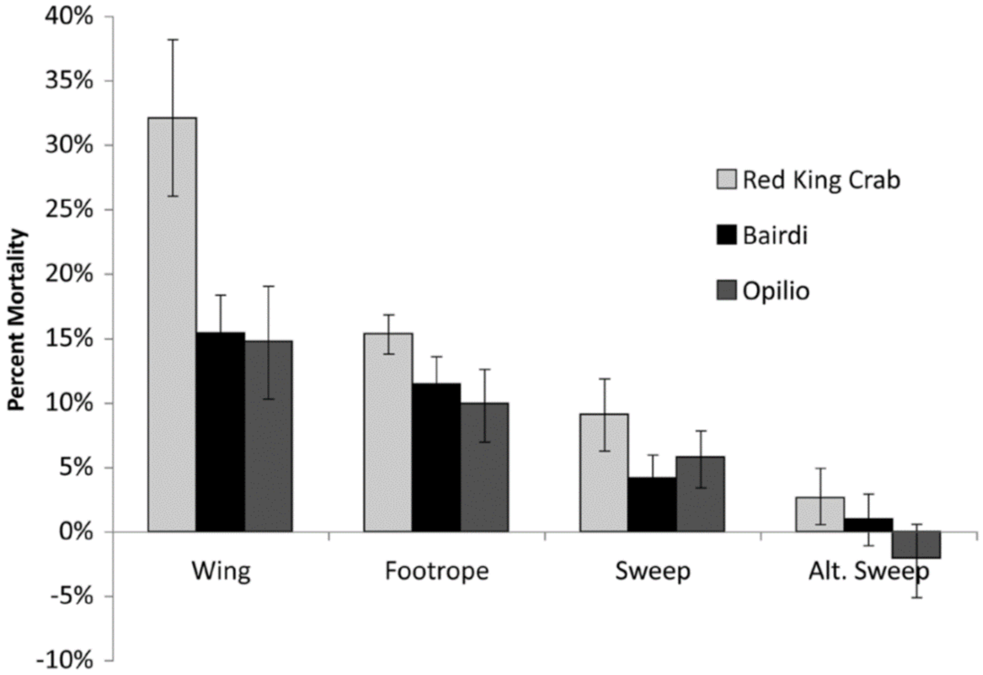


Figure B 4. Mortality rate of major crab species with 15 (light grey), 20 (black), and 25 cm (dark grey) cluster discs. Source: Rose *et al.*, 2010b.

Consultant notes

- This modification has the potential to substantially reduce bottom-trawl impact on the seabed, as well as damage to infauna and epifauna. It does not eliminate seabed disturbance or impact on the epifauna, but the results of these studies highlight the potential of elevated sweeps in trawl fisheries.

- Over 80% of trawl drag is produced by the trawl warps, otter boards, and trawl netting (SEAFISH, IFREMER, & DIFTA, 1993) so any fuel saving due to the experimental sweeps will be minor. Furthermore, any saving due to reduced seabed contact will be minor. Furthermore, any saving due to reduced seabed contact will be offset to an extent by the weight of the cluster discs and their relatively intense penetration of the substrate. It is therefore likely that any fuel saving will be minor or negligible.

- This gear modification has potential to reduce seabed contact in NZ bottom-trawl fisheries where the substate is characterised by sand, mud, or gravel sediments. It is a relatively cheap modification that can be used in any single-boat bottom-trawl operation and requires the purchase of rubber discs from a net maker and their attachment to the sweeps. Rose *et al*. (2010) describe how cluster discs can be attached to the sweep and held in place. Cluster discs can be attached to existing sweeps although each individual disc will require a single cut to be made from the center to the outer edge; this will allow the disc to be fitted over the sweep. The discs will need to be tightly compressed and held in place to avoid them falling off during operation. An alternative is to attach the discs (without a cut) prior to sweep attachment to the trawl, sliding and locking them in place. This modification can be made by commercial fishers.

Reference: Ryer *et al*., 2010.

Title: Flatfish herding behaviour in response to trawl sweeps: a comparison of diel responses to conventional sweeps and elevated sweeps

Objective/s: Evaluate the effect of raised sweeps on flatfish capture during the day and night

Study details

Location: Bering Sea, Alaska

Timing (year): 2007

Depth (m): 70-117

Target species: Yellowfin sole (*Limanda aspera*), Northern rock sole (*Lepidopsetta polyxystra*), Flathead sole (*Hippoglossoides elassodon*), Arrowtooth flounder (*Atheresthes stomias*), Alaska plaice (*Pleuronectes quadritubercalatus*), and Pacific Halibut (*Hippoglossus stenolepis*)

Habitat characteristics: Unconsolidated mixture of sand and mud.

Gear type and dimensions: Twin trawl system. Identical two-seam nets with 200 mm mesh netting in wings and body of the trawl, 130 mm codends. Distance between each door and central clump weight was approximately 80 m.

Control gear: Sweeps measured 180 m and constructed from 5 cm dia. combination rope.

Experimental gear: Sweep length and construction identical to control gear. Multiple rubber discs were clustered together to form a ‘cluster disc’. Each cluster disc was attached to the sweep at 9 m intervals, measuring 25 cm in dia. thus raising the clearance of the sweep to 10 cm above the seabed. The length of each cluster disc was approximately equal to their diameter.

No. of tows/tow duration: A total of 16 hauls were completed with the 25 cm cluster discs respectively. Tow duration ranged from 33 to 150 mins.

Towing speed: No details provided.

Other study details: The 47 m F/V Cape Horn factory trawler was used in this study

Key findings/outcomes

Impact on benthos and habitat: See Rose et al. (2010) for details.

Impact on target catch: Total catch of target species decreased during the day when the 10 cm cluster discs were used, but remained much the same as the control gear during the night. Catches of Northern rock sole, Flathead sole, Arrowtooth flounder, and Alaska plaice decreased during the day when the 10 cm cluster discs were used, but not for Yellowfin sole or Pacific Halibut. no impact of the 10 cm cluster discs on fish length, day or night.

Impact on bycatch: No detail provided.

Impact on fuel consumption: See Rose et al. (2010) for details.

Ease of use: See Rose et al. (2010) for details.

Cost: No detail provided.

Safety risk: No detail provided.

Future recommendations/work: No detail provided.

Consultant notes

- There is evidence that flatfish will respond to the approaching elevated sweep and escape capture during day time, most likely by swimming below the sweep. At night time the impact of the elevated sweep was negligible.

Reference: Chapman, 2014.

Title: Fishing efficiency and bottom contact effects of trawling with low-contact ground cables.

Objective/s: Investigate how a simple, inexpensive ground cable design similar to that used in Rose *et al*. (2010) affects trawl selectivity and seabed impact in the Gulf of Maine.

Study details

Location: Gulf of Maine, USA.

Timing (year): 2013

Depth (m):

Target species: Winter flounder (*Pseudopleuronectes americanus*), Dab (*Hippoglossoides platessoides*), Witch flounder (*Glyptocephalus cynoglossus*), Silver hake (*Merluccius bilineraris*), Winter skate (*Leucoraja ocellate*), and Yellowtail flounder (*Limanda ferruginea*).

Habitat characteristics:

Gear type and dimensions: Two similar trawlers towed a similar two-seam net side-by-side, one with a commercially-used sweep and the other with an elevated sweep. Both trawlers measured 13.6 m. The sweeps were exchanged between vessels at the end of each day.

Control gear: The commercially-used sweep was constructed using small rubber discs (cookies) measuring approximately 100 cm in diameter.

Experimental gear: The elevated sweep was identical to the commercially-used sweep with the addition of 20 cm dia. rubber discs spaced 1 fathom (1.8 m) apart.

No. of tows/tow duration: A total of 24 hauls were completed. Tow duration was 60 mins.

Towing speed: No details provided.

Other study details: The 47 m F/V Cape Horn factory trawler was used in this study.

Key findings/outcomes

Impact on benthos and habitat:

Impact on target catch: The elevated sweep significantly reduced the capture of Witch flounder, Dabs, and Yellowtail flounder, but not Winter flounder, silver hake, or skates. Noteworthy was that one vessel caught more Witch flounder and Silver hake regardless of which sweep was being used. To retain the same catch of Witch flounder, Dabs, and Yellowtail flounder, and total flatfish using the elevated sweeps, fishing effort would need to increase by 36%, 22%, 22%, and 18% respectively.

Impact on bycatch: No detail provided.

Impact on fuel consumption: No detail provided.

Ease of use: No detail provided.

Cost: No detail provided.

Safety risk: No detail provided.

Future recommendations/work: Future suggested work included assessing (quantifying) the magnitude of reduced seabed contact compared to the standard sweep. It also included evaluating the effect of elevated sweep on Witch flounder and Silver hake given the confounding boat effect identified in this study.

Consultant notes

- The recommendations for future work have not yet been acted upon.
- Video footage is available at https://www.youtube.com/watch?v=K2N5wJ2-_UM.

Reference: Morse *et al*., 2010.

Title: The use of positively buoyant ground cables and sweep to reduce seabed contact and to enhance species selectivity.

Objective/s: Modify an existing groundfish trawl so that sweeps, bridles, and ground gear were clear of the seabed during operation.

Study details

Location: Gulf of Maine, USA.

Timing (year): 2007 & 2008

Depth (m):

Target species: Atlantic cod (Gadus morhua), haddock (*Melanogrammus aeglefinus*), American plaice or dab (*Hippoglossoides platessoides*), grey sole (*Glyptocephalus cynoglossus*), hake spp (*Urophycis* spp.), pollock (*Pollachius virens*), and redfish (*Sebastes marinus*.

Habitat characteristics: Sand and mud.

Gear type and dimensions: This project built upon the outcomes of initial testing reported in Morse & Pinkham, 2006.

Control gear: This was a two-seam bottom trawl used commercially to catch cod, flounder, and other groundfish. The headrope and footrope measured 16.8 m and 21.3 m respectively. Mesh size throughout the trawl measured 152 mm. The codend was constructed from double-mesh netting with a mesh size of 163 mm. The ground gear comprised an 11 mm diameter combination rope threaded through 6.4 mm diameter rubber discs (cookies). At 31 cm intervals larger rubber discs were fitted, measuring 20 cm along the wings, 25 cm in the gussets (quarters) and 30 cm in middle (bosom) of the sweep[10].

Experimental gear: The experimental gear was tested in two configurations (treatments), a so-called cod rig and a haddock rig. The cod rig had 24 kg of chain attached to each lower wingend that was allowed to drop 0.5 m to the seabed, while the haddock rig used the same chain limited to 0.9 m. Both rigs had a total of twenty-five 200 mm diameter floats attached along the headrope and ten similar sized floats attached along the lower bridle. The exact location of each float was not provided.

No. of tows/tow duration: Data was collected from 18 pairs of tows (control and experimental gear) using the cod rig and 20 pairs of tows for the haddock rig. Tow duration for each rig was 120 mins.

Towing speed: No details provided.

Other study details: The F/V Jeanne C was used in this study measuring approximately 15 m.

Key findings/outcomes

Impact on benthos and habitat: A reduction in habitat impact was not quantified. Photographic images indicated scouring of the seabed by the wingend weights of the experimental gear. Images also showed the groundgear clear of the seabed (Plate B 2). It was estimated that the wingends of the cod rig were 0.3-0.6 m above the seabed and the bosom of the groundgear was higher. In the haddock rig the wingends were 0.6-1.0 m clear of the seabed.

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[10] In Morse *et al*. (2010) the groundgear is referred to as the sweep, and sweeps are referred to as ground cables. This nomenclature is commonly used in the USA.

Plate B 2. Port side wing with wingend weight extended to the seabed. Estimated height was 60 cm. Source: Morse et al., 2010

Impact on target catch: With the cod rig there was no significant difference in catches of cod, haddock, pollock, and grey sole, but there were significant differences in American plaice, monkfish, and skate. There was no significant difference in length frequency distributions for any of the commercial species. Using the haddock rig there was a significant difference in catches of all species except pollock, but no significant difference in length frequency distributions for any species. It was noted that catch rates of all commercial species was low, during both testing periods, irrespective of rig used.

Impact on bycatch: No detail provided.

Impact on fuel consumption: No detail provided.

Ease of use: A key rationale for using an off-bottom trawl with groundgear still attached was that it provided a measure of protection against contact with a rough seabed.

Cost: No detail provided.

Safety risk: No detail provided.

Future recommendations/work: Additional testing in areas of higher fish abundance.

Consultant notes

- This modification has demonstrated an ability to lift the lower bridle and ground gear clear of the seabed while trawling. The wingend weights provide a means of regulating to some extent the height of the ground gear above the seabed. However, in rough weather this height will vary as the trawl responds to vessel induced movement transmitted through the warp wires. It is also likely to be inconsistent along the length of the groundgear.

Reference: Guyonnet *et al*., 2008.

Title: Modified otter trawl legs to reduce damage and mortality of benthic organisms in the North East Atlantic fisheries (Bay of Biscay).

Objective/s: Evaluate the effect of raised bridles (legs) on finfish selectivity, damage and mortality of finfish and other animals, and short-term effects on benthic communities.

Study details

Location: Bay of Biscay. Brittany, France

Timing (year): 2005

Depth (m): 63

Target species: Multiple species including red gurnard (*Chelidonichthys kumu*), European hake (*Merluccius merluccius*), anglerfish (*Lophius piscatorius*) and sole (*Solea solea*).

Habitat characteristics: Mud and sand

Gear type and dimensions: Two-seam fish trawl with 44 mm mesh netting in wings, reducing to 33 mm in the codend. Alternating haul experiment, between control and experimental gear. A specialised dredge (AQUAREVE sled-dredge) was used to sample macro- and mega-fauna before and after intensive trawling.

Control gear: Trawl bridles were constructed from 18 mm dia. steel cable. Bridle length was not provided.

Experimental gear: Trawl bridles were constructed from lightweight 14 mm dia. Dyneema rope with 4 mm dia. galvanised chain droppers measuring 60 cm attached at 50 cm intervals (Plate B 3).

Plate B 3. Chain droppers attached to a dyneema sweep. Source: Guyonnet *et al*., 2008.

No. of tows/tow duration: A total of 36 hauls were completed, 18 with the control gear and 18 with the experimental gear. Tow duration was 120 mins for each haul.

Towing speed: 1.7 ms^{-1}

Other study details: The F/V Gewn Drez was used in this study.

Key findings/outcomes

Impact on benthos and habitat: There was no significant difference in species richness (diversity), community structure, or biomass. There was also no significant difference in the proportion of damaged crustaceans or echinoderms, although damage was significantly increased with the control gear. The species richness and abundance of the macrofauna including epifauna was unaffected by the bridle modification, as was damage to these animals. Multidimensional analysis of macrofauna abundance data confirmed similarity between the experimental gear and sled data, and significant difference with the control data.

Impact on target catch: There was no significant difference in target catch weight between control and experimental gears. Length frequency distributions were significantly different for red gurnard, European hake, anglerfish and sole, but not for many other species such as Norwegian lobster (*Nephrops norvegicus*) and Atlantic mackerel (*Scomber scombrus*).

Impact on bycatch: There was no significant difference in bycatch weight between control and experimental gears.

Impact on fuel consumption: No detail provided.

Ease of use: No detail provided.

Cost: No detail provided.

Safety risk: No detail provided.

Future recommendations/work: No detail provided.

Consultant notes

- The lengths of the bridles were not provided. From the description of the experimental gear, it is unclear if the chain lengths were attached at both ends 50 cm apart. An image in the manuscript suggests they were attached at one end only, acting as 'droppers'.
- It is unclear if seabed contact will be reduced by this modification, and if so, by how much. The use of buoyant or lighter materials to reduce contact is laudable, however, the ends of the bridles are attached to a heavy sweep and groundgear in close contact with the seabed.
- Damage to megafauna was higher with the control gear, possible resulting from the droppers passing overhead rather than a 'slicing' action by the lower bridle.
- Based on experience with similar modifications, handling of the chains can be problematic during deployment from the net drum. As the net is wound on the drum, the unattached end of each chain can potentially fall through the trawl meshes, and then becomes fouled during deployment, potentially tearing meshes. They could also be a safety risk and strike crew as the net is wound around the net drum.
- No appreciable fuel saving is anticipated from the experimental gear, because the difference in bottom contact is minor and drag induced from the bridles is a small fraction of total drag. The combined drag from sweeps and bridles is an estimated 7% of total trawl drag (SEAFISH *et al*., 1993).

This gear modification has potential to reduce seabed contact in NZ bottom-trawl fisheries where the substate is characterised by sand, mud, or gravel sediments. It is a relatively cheap modification requiring purchase of chain lengths to attach to the bridles. This modification reduces the 'slicing' action of the lower bridles, although as the clearance beneath the bridles is likely to change little, it may provide modest to no benefit.

Reference: He *et al*., 2015.

Title: Reduced herding of flounders by floating bridles: application in Gulf of Maine Northern shrimp trawls to reduce bycatch.

Objective/s: Evaluate the effect of raised bridles on finfish selectivity and the shrimp catch.

Study details

Location: Gulf of Maine, USA

Timing (year): 2011

Depth (m): 90-155 m

Target species: Northern shrimp (Pandalus borealis)

Habitat characteristics: Mud and sand

Gear type and dimensions: The trawl net was a two-seam shrimp trawl fitted with a Nordmore grid. The same otter boards were used to spread the control and experimental gear.

Control gear: Bridles were constructed from steel wire roped measuring 27.7 m; the diameter of the upper bridle was 9.5 mm and the lower was 15.9 mm (Figure B 5).

Experimental gear: Bridles were constructed from buoyant, high-strength polypropylene rope measuring 27.7 m; the diameter of the upper and lower bridles was 15.9 mm.

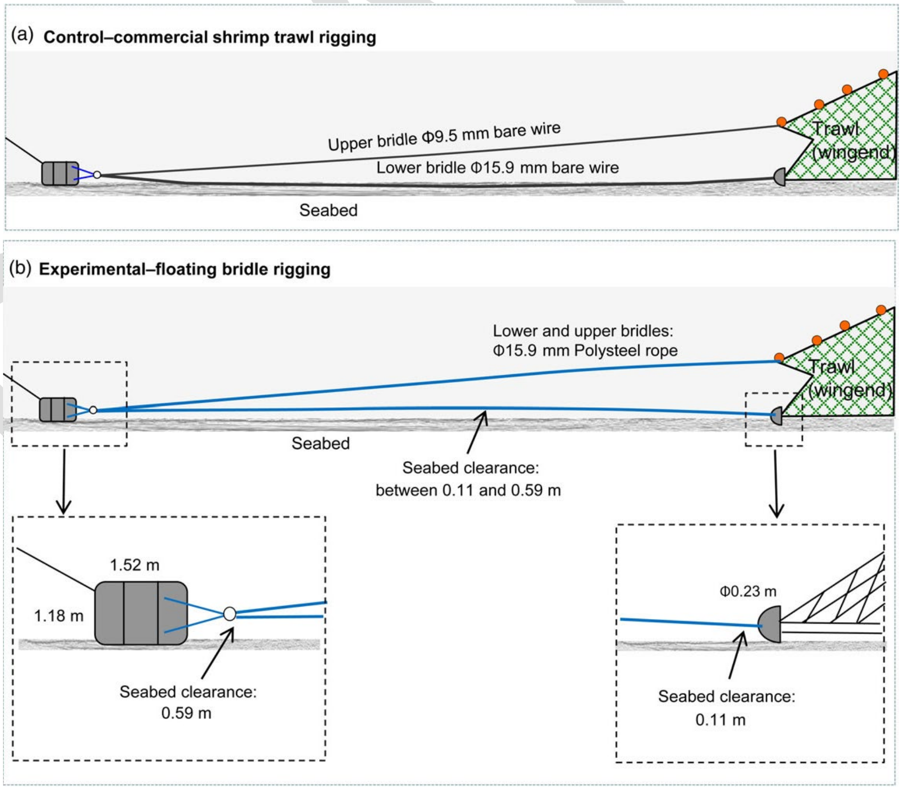


Figure B 5. Rigging of the control and experimental trawl. Source: He *et al*., 2015.

No. of tows/tow duration: An alternate haul protocol was applied, and data from 30 pairs of tows was collected (60 tows in total). Tow duration was 60 mins for each haul (except for two pairs of hauls when it was reduced to 30 min each). All tows were completed during the day time.

Towing speed: 1.1-1.2 ms^{-1}

Other study details: The F/V North Star was used in this study, measuring 13.7 m.

Key findings/outcomes

The otter board and upper wingend spread were virtually identical between control and experimental gear. It was inferred that lower wingend spread was 39-43% of otter board spread.

Impact on benthos and habitat: No detail provided.

Impact on target catch: There was non-significant 3.7% reduction in target catch between control and experimental gears, and no difference in shrimp size (length).

Impact on bycatch: Total bycatch was significantly reduced by almost 15%, and the catch of some flatfish species was reduced by almost 20%.

Impact on fuel consumption: No detail provided.

Ease of use: No detail provided, although reference was made to this "easy" modification.

Cost: No detail provided.

Safety risk: No detail provided.

Future recommendations/work: No detail provided.

Consultant notes

- This gear modification was successful because sweeps are not required and bridle length was short. However, this study provides insight into the potential application of light-weight bridle materials to mitigate or eliminate seabed contact.
- While not documented, the experimental bridles are expected to reduce seabed contact and damage to the benthos, by passing over most organisms.
- It is a relatively cheap modification although the cost of polypropylene material is likely higher than that for steel wire rope.
- A reduction in fuel consumption is not expected using this modification. This is because the drag generated by bridles in seabed contact is minuscule compared to the drag generated by other trawl components.
- It is not anticipated that these bridles would be any more difficult to handle than those constructed from steel wire rope. Because they are light-weight they may in fact be easier to handle and therefore pose less of a safety risk.

Reference: Sistiaga *et al*., 2015.

Title: Effect of lifting the sweeps on bottom trawling catch efficiency: A study based on the Northeast arctic cod (*Gadus morhua*) trawl fishery.

Objective/s: Quantify the effect of raised sweeps on the catching efficiency of a bottom trawl.

Study details

Location: Barents Sea, Norway

Timing (year): 2013

Depth (m): 260-300 m

Target species: Atlantic cod (*Gadus morhua*)

Habitat characteristics:

Gear type and dimensions: The trawl net was an Alfredo No. 3 bottom trawl with a headline of 36.5 m and a footrope of 19.2 m. The trawl was built entirely 80 mm mesh netting. Sweep length was 75 m (Figure B 6). The otter boards were high aspect ratio Injector XF9, weighing 2, 200kg each and with a surface area of 6.5 m^2. A 450 kg clump weight constructed from a 16 m length of chain was attached to each sweep to maintain seabed contact.

Experimental gear 1: The clump weight was attached to the end of the sweep closest to the trawl (Setup 1).

Experimental gear 2: The clump weight was attached to the end of the sweep 45 m from the trawl (Setup 2).

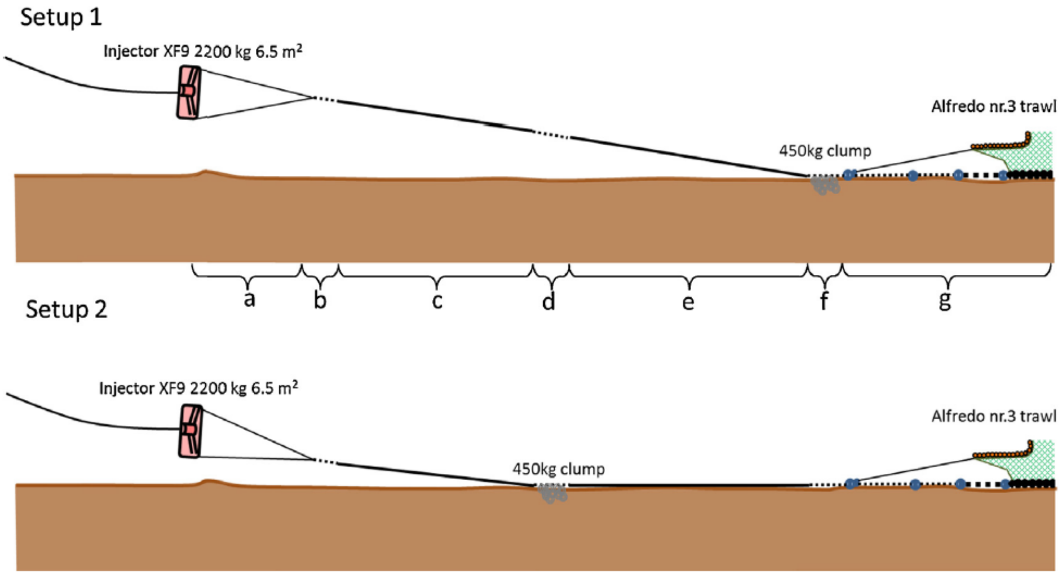


Figure B 6. Experimental trawl gear. (a) 15.9 m backstrop, (b) 3 m backstrop extension, (c) 30 m of 30 mm sweep, (d) 4 m of 19 mm chain (attaching position for the clumps), (e) 45 m of 30 mm sweeps, (f) 4 m of 19 mm chain (attaching position for the clumps), (g) 445 m of ground gear composed of 19 mm chain (32 mm chain closest to the rockhopper), and the rockhopper. Source: Sistiaga *et al*., 2015.

No. of tows/tow duration: An alternate haul protocol was applied, and data from 32 tows (16 pairs) was collected. Average tow duration was 72 mins for each haul. All tows were completed during the day time, although in near total darkness at high latitudes in November.

Towing speed: 1.8 ms^{-1}

Other study details: Acoustic mensuration sensors were used to measure otter board and lower wingend spread. Additional sensors were used to measure otter board height above the seabed.

Key findings/outcomes

Otter board spread, wingend spread, and headline height were almost identical between experimental gears (setups). Experimental gear 1 (Setup 1) otter board height was approximately double experimental gear 2 (Setup 2). This was to ensure the clump weights were the first gear component in seabed contact.

Impact on benthos and habitat: No detail provided.

Impact on target catch: Experimental gear 1 caught on average 33% few cod than experimental gear 2, and sometimes as high as 50% for some cod lengths (Figure B 7).

Impact on bycatch: No detail provided.

Impact on fuel consumption: No detail provided.

Ease of use: No detail provided.

Cost: No detail provided.

Safety risk: No detail provided.

Future recommendations/work: No detail provided.

Consultant notes

- This study has highlighted the important of sweeps in contact with the seabed to herd fish into the approaching trawl. It has also highlighted the importance of acoustic mensuration sensors to monitor otter board position and ensure the clump weights were the first component in seabed contact.
- While not stated by the authors, a reduction in non-target fish could be expected using experimental gear 2, because the herding ability of sweeps is compromised by this rigging change.
- Elevating otter boards and sweeps above the seabed will eliminate their impact on the seabed, although this outcome is compromised in this study by the heavy clump weights that likely heavily ploughed the seabed. It is unclear if this is an appropriate trade-off.
- While also not stated by the authors, it is anticipated that fuel consumption, ease of use, cost, and safety risk was little different between experimental gears. The effect of additional sweep in contact with the seabed (Experimental gear 2) is unlikely to noticeably increase fuel consumption.
- Any benefits in fuel consumption between the experimental gears and a normal, bottom-tending trawl will be eroded to an extent by ploughing of the clump weights in the seabed. It is not possible to determine the extent of their impact on fuel consumption without further experimentation.
- The experimental gears may result in deployment and hauling delays while fitting and removing the clump weights, compared to a normal, bottom-tending trawl. Safety risk may also be increased while handling these heavy weights.

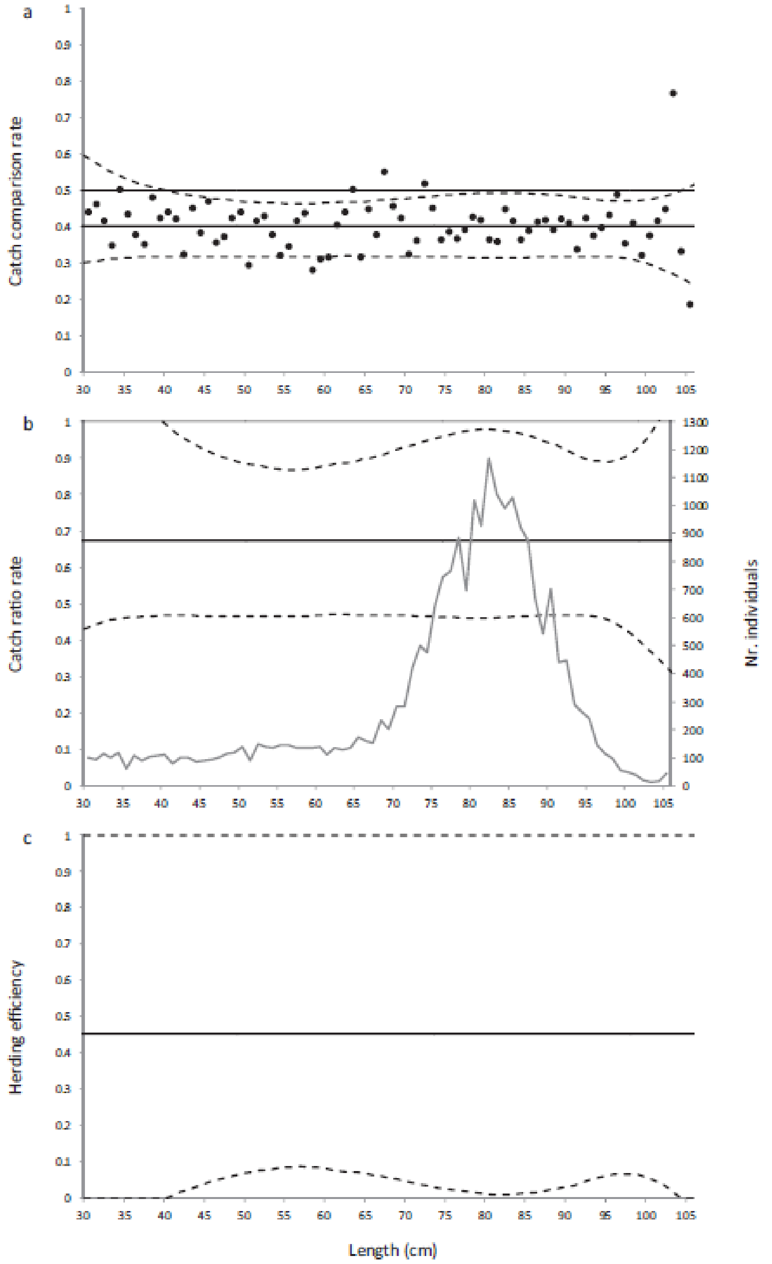


Figure B 7. Experimental gear 1 compared to 2. (a) Average catch rate (full line) and confidence intervals (dashed lines). The line at 0.5 represents equal catching efficiency between gears; (b) average catch ratio (full line) and confidence intervals (dashed lines), and size distribution (grey line) for cod; and (c) average herding efficiency (full line) and confidence intervals (dashed line) for cod between 30 cm and 106 cm in length. Source. Sistiaga *et al*. (2015).

14 Appendix C – Ground gear modifications

Reference: He & Balzano, 2010.

Title: Design and test of a wheeled groundgear to reduce seabed impact of trawling.

Objective/s: Design, test, and evaluate the potential of wheeled groundgear in whiting and ground fish trawls.

Study details

Location: Gulf of Maine, USA

Timing (year): 2007

Depth (m): No detail provided.

Target species: No detail provided.

Habitat characteristics: No detail provided.

Gear type and dimensions: The ground gear was constructed using rubber discs 100 mm wide and 300 mm in diameter (Figure C 1).

No. of tows/tow duration: No detail provided, other than the groundgear was tested over 4 days.

Towing speed: No detail provided.

Other study details: The stated focus of the fieldwork was the operation and handling of the groundgear.

Key findings/outcomes

The fieldwork was based close to shore to minimise steaming time to and from port each day. Catches were minimal. Underwater observations were hampered by sand clouds masking the ground gear. There was no difference in engine power requirements to tow this or conventional ground gear.

Impact on benthos and habitat: No detail provided.

Impact on target catch: No detail provided.

Impact on bycatch: No detail provided.

Impact on fuel consumption: No detail provided.

Ease of use: The ground gear was easy to handle by the usual number of crew.

Cost: No detail provided.

Safety risk: No detail provided.

Future recommendations/work: It was suggested that future work will include ensuring the wheels work in all fishing conditions and that they self-adjust to the towing direction to ensure free rolling. Testing in a flume tank was also suggested.

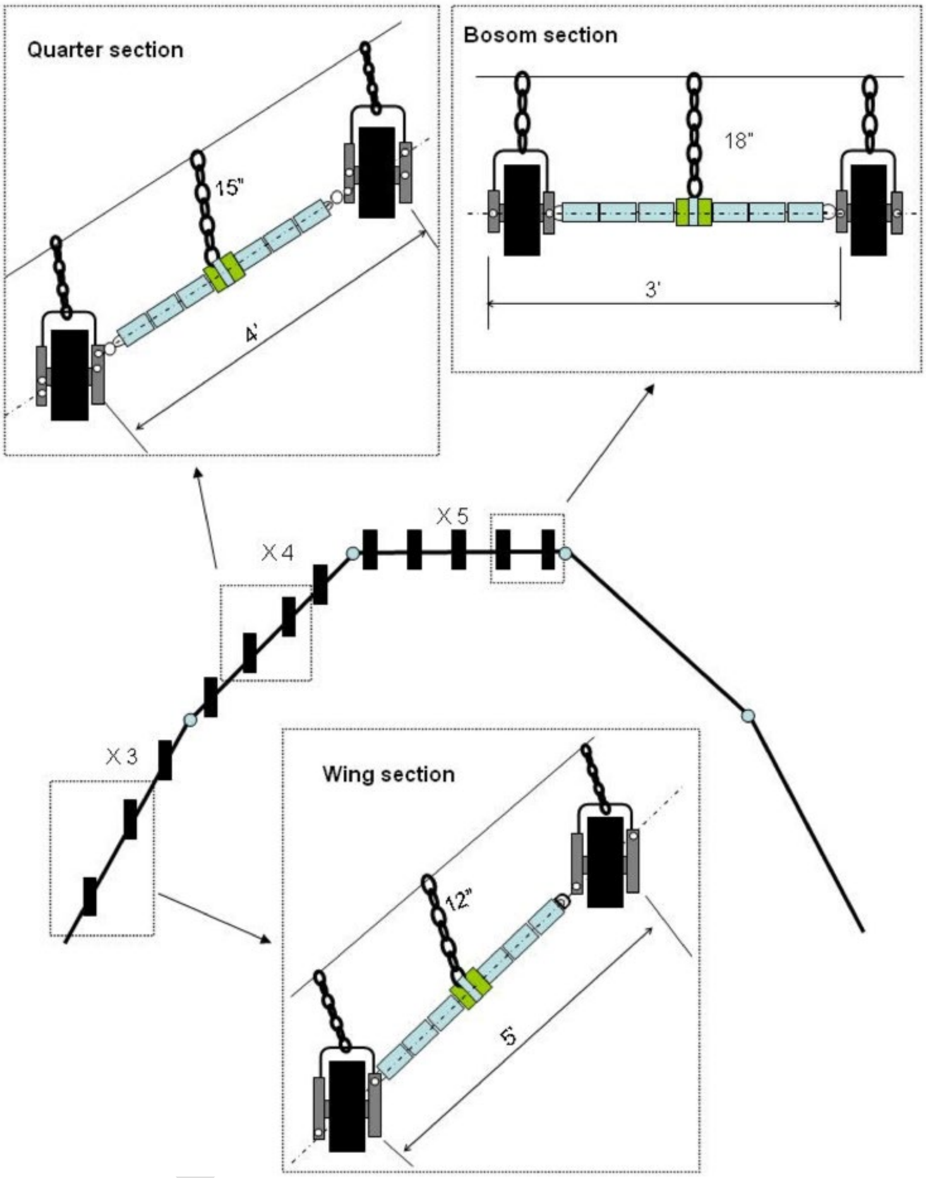


Figure C 1. Wheeled groundgear with important dimensions indicated Source: He & Balzano, 2010.

Consultant notes

- This ground gear has the potential to ensure that rubber discs are not towed laterally across the seabed (Plate C 1), resulting in ploughing and sediment disturbance. This is challenged by the fact that wingend spread is not a constant, between or within tows, hence why the development of self-adjusting wheels was recommended by the authors of the report. The successful development of this ground gear may reduce its footprint by an estimated 20-30%.

- As the authors note, this is not a new idea, being tested in the 1940s in Germany. A lack of progress since then may simply reflect disinterest in reducing seabed contact and/or perceived notions regarding the complexity of this ground gear.
- Testing in a flume tank would permit a first order estimation of the angle of the trawl footrope relative to the direction of tow for a given wingend opening (spread). This would help identify what angle is necessary to avoid shearing and for the wheels to roll.
- It is interesting to consider the effect of this ground gear on wingend spread, given an outward force is produced by the shearing force of the rubber discs over the seabed. This outward force will be small relative to the spreading force of the otter boards, so any change may be negligible.

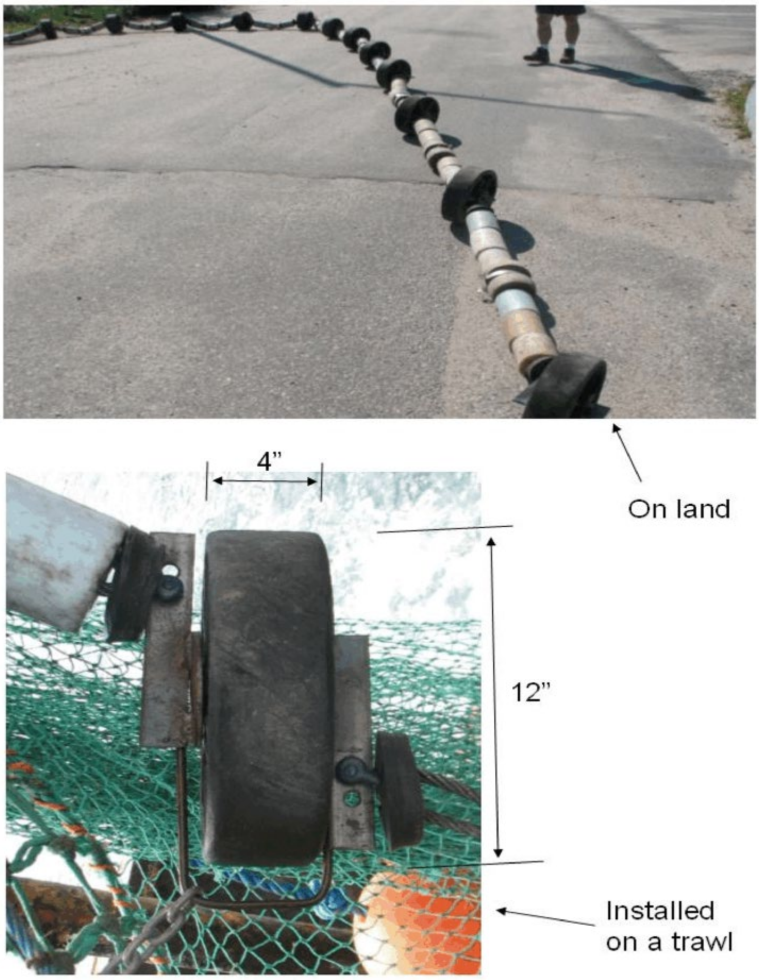


Plate C 1. Wheeled ground gear spread out for visual inspection (top) and close-up of a wheel. Source: He & Balzano, 2010.

Reference: Winger *et al.,* 2018.

Title: Comparative fishing to evaluate the viability of an aligned footgear designed to reduce seabed contact in northern shrimp bottom trawl fisheries.

Objective/s: Design, test, and evaluate the potential of wheeled groundgear while targeting northern shrimp (*Pandalus borealis*).

Study details

Location: West coast of Newfoundland, Canada.

Timing (year): 2012

Depth (m): 129-149 m.

Target species: Northern shrimp (*Pandalus borealis*).

Habitat characteristics: No detail provided.

Gear type and dimensions: The control and experimental trawl nets were identical four-seam inshore shrimp trawls. Headline length was 33.8 m and footrope length was 32.9 m. Mesh size was 45-100 mm. Flotation was provided using 203 mm diameter floats; 100 floats were attached to the headline, 18 to the footrope, and 5 to each of the upper selvedges (seams).

Control gear: A conventional 32.9 m rockhopper ground gear was used). It included 28 x 356 mm diameter rubber discs, 38 x 305 mm diameter rubber discs, and 2 x 356 mm diameter steel bobbins at either end of the ground gear.

Experimental gear: The experimental ground gear had all rubber discs aligned and facing parallel to the towing direction. Along the wings the discs had diagonally positioned center holes, each cut at individual angles depending on their relative position in the ground gear.

No. of tows/tow duration: An alternate haul testing protocol was applied. Twenty paired tows were completed. Tow duration was 15 minutes

Towing speed: 4.25 ms^{-1}

Other study details: Scale models of both ground gears were tested in a flume tank prior to sea trials. E-Sonar and Netmind acoustic sensors were used to measure otter board spread, wingend spread, and headline height.

Key findings/outcomes

Impact on trawl geometry: Scale model testing found that 69% of the seabed between the wings of the trawl were contacted by the conventional ground gear but only 27% was contacted with the aligned ground gear. This represents a 61% reduction in trawl footprint (Figure C 3).

At sea the mean otter board spread using the experimental ground gear increased by a statistically significant 2 m (~4%) compared to the conventional ground gear. Wingend spread was increased by 1 m, and there was a corresponding 0.3 m (~6%) reduction in headline height. It was speculated that this was because the aligned ground gear reduced seabed friction gear (shearing) and an associated reduction in trawl drag. This outcome was not measured in the flume tank, and believed to have negligible effect on the degree of seabed contact.

Impact on target catch: The trawl with the experimental ground gear caught 23% more shrimp. This was statistically significant ($p = 0.001$).

Impact on bycatch: Bycatch comprised less than 1.6% of the total catch weight, irrespective of ground gear type. Capelin and Greenland halibut collectively comprised 93.2% and 92.9% of the total number of individuals in the bycatch respectively. The trawl with the experimental ground gear caught significantly more of both species compared to the conventional trawl with conventional ground gear.

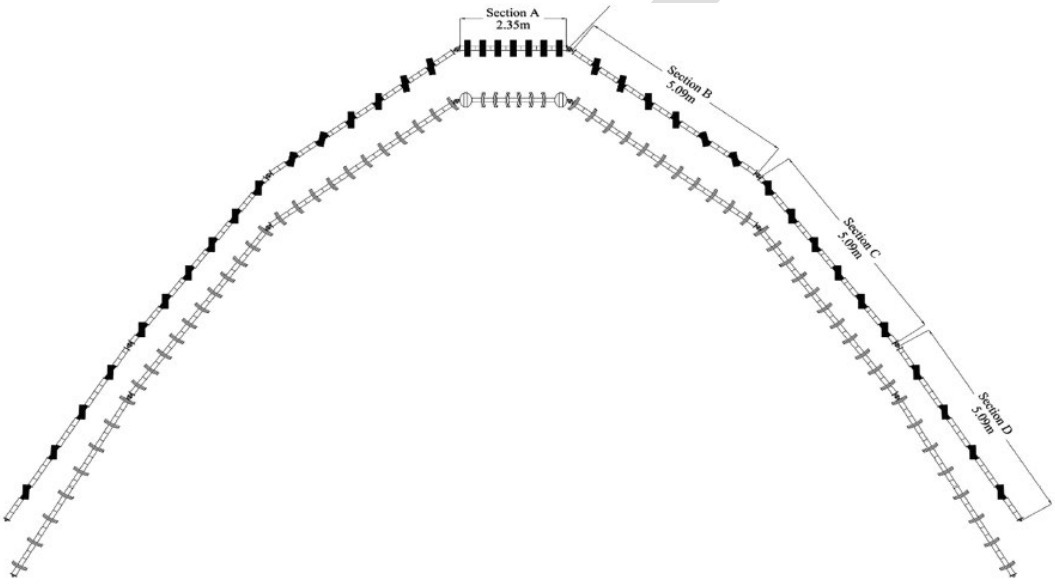


Figure C 2. Schematic of the experimental (upper) and conventional ground gear. Section A - bosom; Section B - bunt wing section; Section C - wing section; Section 4 - Wingtip sections. The bobbins in the wingtip sections of the conventional ground gear could be as much as 70 degrees out of alignment with the direction of tow. Source: Winger *et al*., 2018.

Impact on fuel consumption: No detail provided.

Ease of use: No detail provided.

Cost: No detail provided.

Safety risk: No detail provided.

Future recommendations/work: It was suggested that future work should include ensuring the wheels work in all fishing conditions and that consideration be given to how they can self-adjust to the towing direction to ensure free rolling.

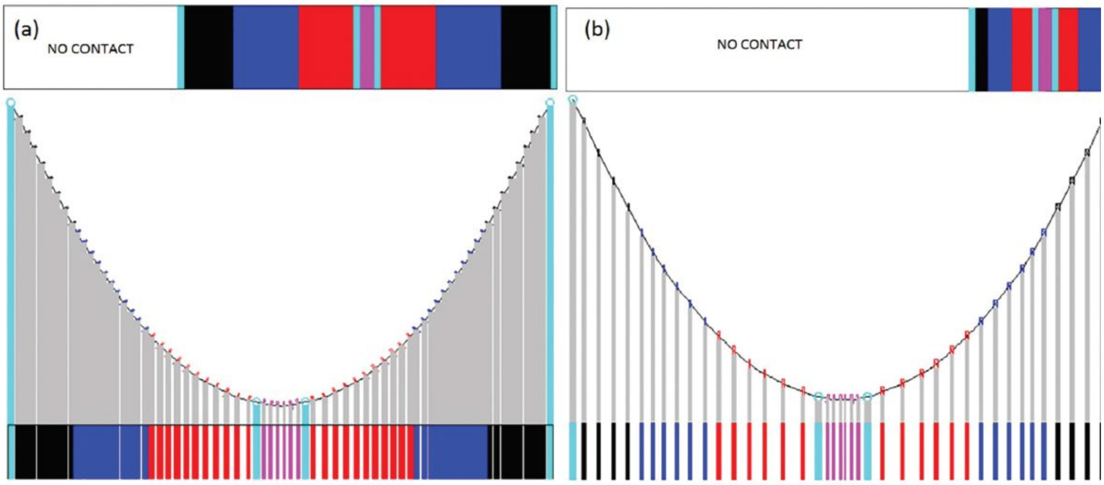


Figure C 3. The estimated proportion of seabed contact by the conventional ground gear (left) and the aligned ground gear (right). Colour coding represents the different footgear components or sections in seabed contact: Bobbins (green), wingtip sections (black), wing sections (blue), bunt wing sections (red), and bosom (purple). Source: Winger *et al*., 2018.

Consultant notes

- Testing in a flume tank was an important early step towards the development of this ground gear, given its complexity and need to visually estimate the angle of each section of ground gear relative to the direction of two.
- It would be useful to know the relative cost of this ground gear, and any handling challenges. A modest increase in cost is not an unreasonable expectation.
- Any drag reduction and associated fuel saving using the aligned ground gear is likely to be modest at best. There are two reasons for this: 1. Drag associated with conventional ground gear is usually less than 10% of the total trawl system (SEAFISH *et al*., 1993), hence it is unreasonable to expect any more than a drag saving of a few percent, and 2. Any reduction in drag was eroded by increased wingend spread. An increase in wingend spread usually inceases the profile area of the net (all things held equal), which in turn increases trawl drag. This increase is not usually offset by reduced headline height.

Reference: Ramm *et al*., 1993.

Title: Use of a semi-pelagic trawl in a tropical demersal trawl fishery.

Objective/s: Evaluate the potential of a new trawl design to reduce seabed contact and improve trawl selectivity in the Northern Finfish Trawl Fishery.

Study details

Location: Arafura Sea, Australia.

Timing (year): 1991

Depth (m): 43-55 m.

Target species: Mainly *Lutjanus* spp., *Lethrinus* spp.

Habitat characteristics: Soft mud and low-lying reef

Gear type and dimensions: A new semi-pelagic trawl was compared against a two-seam Paulegro bottom trawl. Both trawls were constructed of polyethylene netting. Both were spread using v-doors with a surface area of 3.45 m^2.

Control gear: The Paulegro trawl is commonly used in the fishery (Figure C 4). The headline length was 46 m and headline flotation was 160 kg. The ground gear comprised multiple rubber discs measuring 150 mm in diameter. Total ground gear weight was 500 kg. Sweeps and bridles both measured 50 m.

Experimental gear: A semi-pelagic trawl was designed and constructed for this study, known as the 'Julie Anne' trawl. This is a four-seam trawl with equal headline and footrope (38 m). Headline flotation was 115 kg and a 60 kg weight was attached to each lower wingend. Attached to the center of the footrope was 7 x 0.5 m dropper chains, each weighing 10 kg. Flywires were attached to the upper wingends. They measured 92 m and were attached to the towing warps 37 m ahead of the otter boards. The lower bridles were 65 m long and were attached to the otter boards.

No. of tows/tow duration: 28 tows were completed, 14 for each trawl. Tow duration was 180 minutes

Towing speed: No detail provided.

Other study details: No detail provided.

Key findings/outcomes

Impact on trawl geometry: Underwater video indicated the footrope of the Julie Anne trawl was 1 m clear of the seabed at the wingends and 0.3 m clear of the seabed at the center of the footrope. The two wingend weights and 7 chain droppers caused furrows in the seabed 10-30 cm wide and 5-10 cm deep. This was equivalent to 2 m (3%) of the swept width of the trawl between otter boards. In contrast the ground gear, sweeps and lower bridles of the Paulegro net contacted the seabed.

Impact on target catch: Catches of commercial species were approximately 23% higher using the Julie Anne trawl, although there was no significant difference in mean catch per tow of 10 taxa, including the two most dominant species.

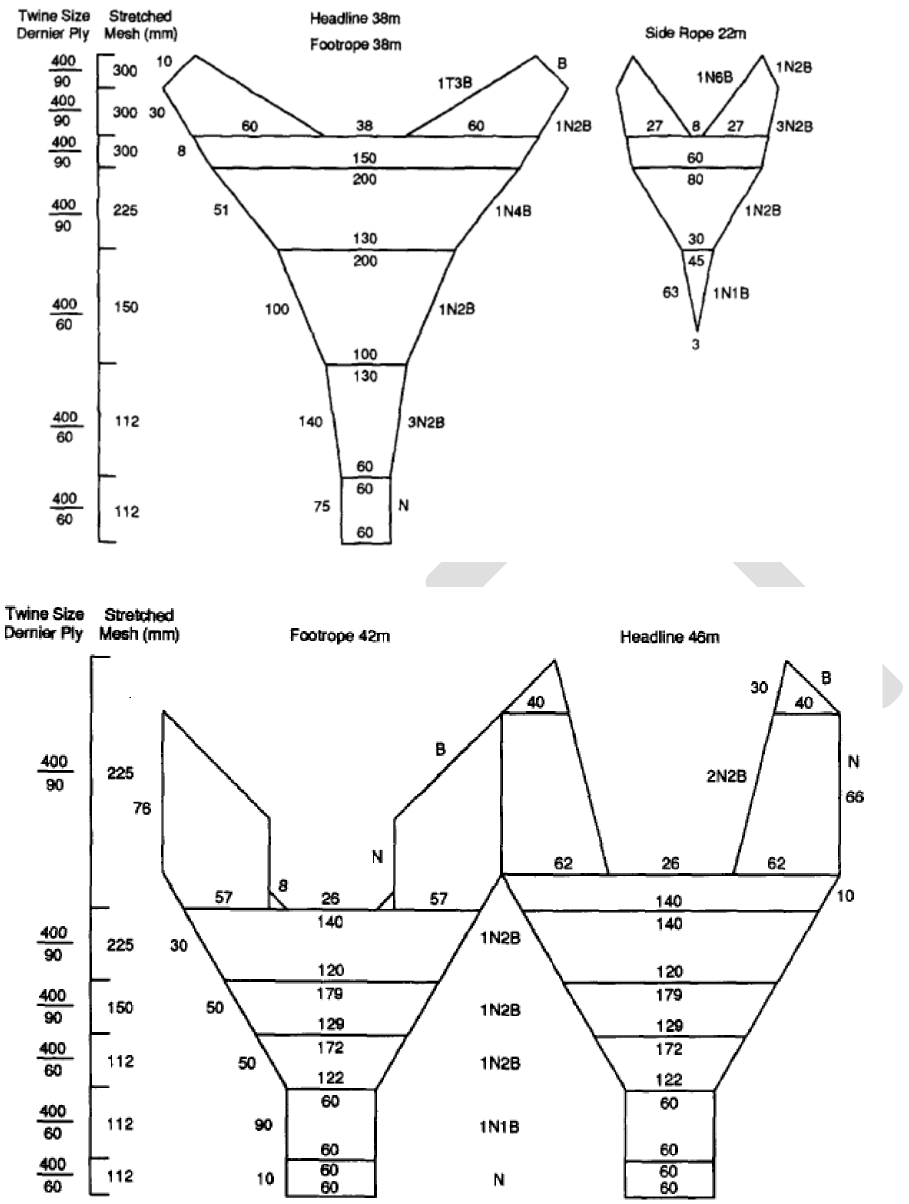


Figure C 4. Net plan of the Julie Anne trawl (upper) and the Paulegro trawl (lower). Source Ramm *et al*., 1993.

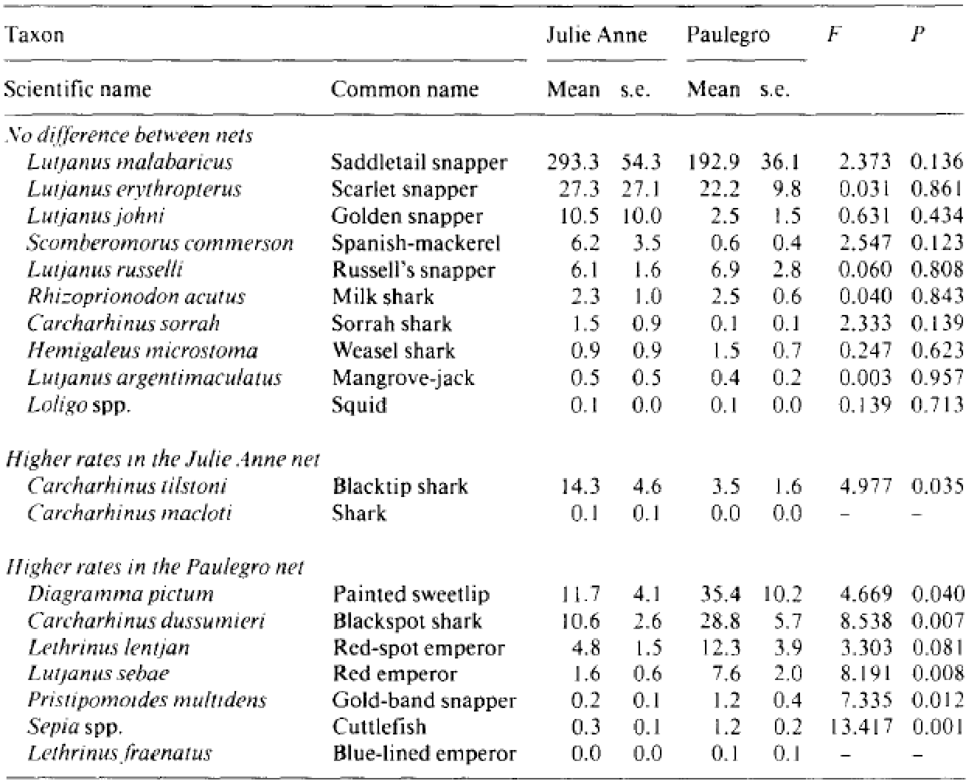
Key findings/outcomes

Impact on trawl geometry: Underwater video indicated the footrope of the Julie Anne trawl was 1 m clear of the seabed at the wingends and 0.3 m clear of the seabed at the center of the footrope. The two wingend weights and 7 chain droppers caused furrows in the seabed 10-30 cm wide and 5-10 cm deep. This was equivalent to 2 m (3%) of the swept width of the trawl between otter boards. In contrast the ground gear, sweeps and lower bridles of the Paulegro net contacted the seabed.

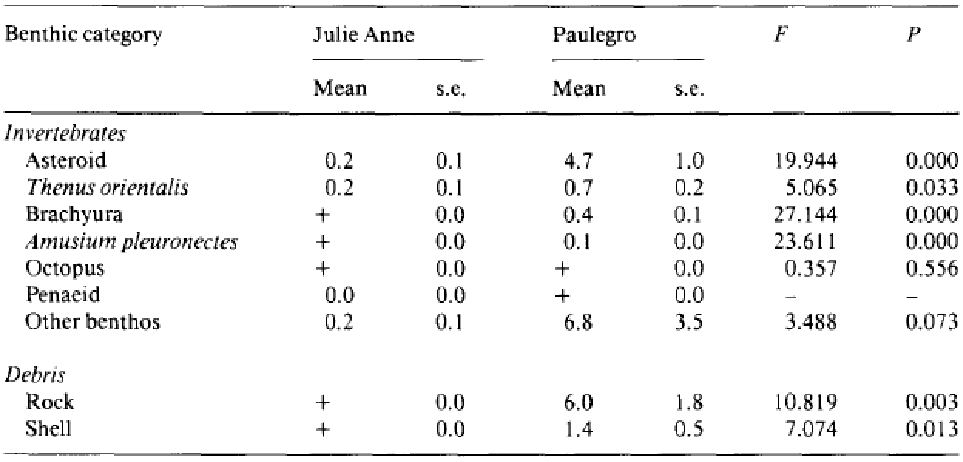
Impact on target catch: Catches of commercial species were approximately 23% higher using the Julie Anne trawl, although there was no significant difference in mean catch per tow of 10 taxa, including the two most dominant species.

Impact on bycatch: Catch rates of non-commercial species were 2.3 times higher in the Paulegro net. There was no significant difference in catches of 52 species of fish between trawls, including the most dominant non-commercial species (Table C 1). Catch rates for all benthic invertebrates, except octopus, and debris were significantly lower using the Julie Anne trawl, and the overall catch of benthos was only 3% of that retained in the Paulegro net.

Table C 1. Catches of commercial species, invertebrates, and debris from both trawls. Source. Ramm *et al.*, 1993



Taxon		Julie Anne		Paulegro		F	P
Scientific name	Common name	Mean	s.e.	Mean	s.e.		
No difference between nets							
Lutjanus malabaricus	Saddletail snapper	293.3	54.3	192.9	36.1	2.373	0.136
Lutjanus erythropterus	Scarlet snapper	27.3	27.1	22.2	9.8	0.031	0.861
Lutjanus johni	Golden snapper	10.5	10.0	2.5	1.5	0.631	0.434
Scomberomorus commerson	Spanish-mackerel	6.2	3.5	0.6	0.4	2.547	0.123
Lutjanus russelli	Russell's snapper	6.1	1.6	6.9	2.8	0.060	0.808
Rhizoprionodon acutus	Milk shark	2.3	1.0	2.5	0.6	0.040	0.843
Carcharhinus sorrah	Sorrah shark	1.5	0.9	0.1	0.1	2.333	0.139
Hemigaleus microstoma	Weasel shark	0.9	0.9	1.5	0.7	0.247	0.623
Lutjanus argentimaculatus	Mangrove-jack	0.5	0.5	0.4	0.2	0.003	0.957
Loligo spp.	Squid	0.1	0.0	0.1	0.0	0.139	0.713
Higher rates in the Julie Anne net							
Carcharhinus tilstoni	Blacktip shark	14.3	4.6	3.5	1.6	4.977	0.035
Carcharhinus macloti	Shark	0.1	0.1	0.0	0.0	–	–
Higher rates in the Paulegro net							
Diagramma pictum	Painted sweetlip	11.7	4.1	35.4	10.2	4.669	0.040
Carcharhinus dussumieri	Blackspot shark	10.6	2.6	28.8	5.7	8.538	0.007
Lethrinus lentjan	Red-spot emperor	4.8	1.5	12.3	3.9	3.303	0.081
Lutjanus sebae	Red emperor	1.6	0.6	7.6	2.0	8.191	0.008
Pristipomoides multidens	Gold-band snapper	0.2	0.1	1.2	0.4	7.335	0.012
Sepia spp.	Cuttlefish	0.3	0.1	1.2	0.2	13.417	0.001
Lethrinus fraenatus	Blue-lined emperor	0.0	0.0	0.1	0.1	–	–



Benthic category	Julie Anne		Paulegro		F	P
	Mean	s.e.	Mean	s.e.		
Invertebrates						
Asteroid	0.2	0.1	4.7	1.0	19.944	0.000
Thenus orientalis	0.2	0.1	0.7	0.2	5.065	0.033
Brachyura	+	0.0	0.4	0.1	27.144	0.000
Amusium pleuronectes	+	0.0	0.1	0.0	23.611	0.000
Octopus	+	0.0	+	0.0	0.357	0.556
Penaeid	0.0	0.0	+	0.0	–	–
Other benthos	0.2	0.1	6.8	3.5	3.488	0.073
Debris						
Rock	+	0.0	6.0	1.8	10.819	0.003
Shell	+	0.0	1.4	0.5	7.074	0.013

Impact on fuel consumption: No detail provided.

Ease of use: No detail provided.

Cost: No detail provided.

Safety risk: No detail provided.

Future recommendations/work: No detail provided.

Consultant notes

General comments:

- The Julie Anne trawl has demonstrated the efficacy of a fork-rigged trawl to reduce seabed contact. While reference to this style of trawl was made in fishery regulations, this trawl has not been used by local fishers.
- Follow up research using this trawl was attempted by CSIRO. The trawl was constructed in the U.K. and the net makers used lighter than requested netting material. They believed lighter netting would make it easier to fly the trawl over the seabed, but this had disastrous consequences. In short, the side panels would tear apart each time the net was deployed, requiring major repair. This was because the angle of the towing warps during trawl deployment resulted in the headline being pulled forward of the footrope, to such an extend that the side panels ripped apart. Ropes were eventually lashed to the side panels, extending from the upper seam to the lower seam on each side of the net. This was a temporary measure that did not really solve the problem. Ultimately this trawl was discarded, and a two-seam bottom trawl was modified to complete the study (see Brewer *et al*., 1995).

Reference: Brewer *et al*., 1996.

Title: Assessment of an environmentally friendly, semi-pelagic fish trawl.

Objective/s: Modify a bottom trawl to fish semi-pelagically to reduce seabed contact and habitat impact.

Study details

Location: Northeast Gulf of Carpentaria, Australia.

Timing (year): 1993

Depth (m): 41-58 m.

Target species: Saddletail snapper (*Lutjanus malabaricus*) and Crimson snapper (*L. erythropterus*).

Habitat characteristics: Smooth sand and soft mud, with a high density of epibenthic invertebrates (e.g. sponges, soft coral) protruding above the sea bed.

Gear type and dimensions: Two identical wing trawls were used, each with a headline length of 25.6 m and a fishing circle measuring 48.8 m. Mesh size was 50 mm through the entire trawl. Bridle and sweep lengths for both trawls measured 50 m and 40 m respectively. Single slot polyvalent otter boards were used weighing 1000 kg each with a surface area of 3.8 m^2.

Control gear: One trawl was fitted with conventional ground gear (referred to as Trawl 1 in Brewer *et al*.,1996) that weighted 170 kg in air. Headline flotation was 157 kg.

Experimental gear: The other trawl was fitted with experimental ground gear (). Two treatments of this ground gear were tested. Treatment 1 (Trawl 2a) had the ground rope removed and replaced with 5 weights: a 10 kg weight in the bosom, a 20 kg weight added to each quarter (gusset), and a 40 kg weight added to each wingend. The weights were connected to the trawl via drop chains to achieve a nominal footrope clearance of 0.4-0.5 m. Headline flotation was increased to 245 kg. Treatment 2 (Trawl 2b) was similar to Treatment 1 with the exception that ground gear weight was reduced by 20 kg and flotation was increased to 262 kg. The weights were attached to the trawl via drop chains to achieve a nominal footrope clearance of 0.8-0.9 m. The chain drops were uniform all 2.5 long and constructed from 10 mm chain.

A specialised beam trawl was tested in a flume tank with the end of each chain dropper attached at known heights. The number of links in contact with the floor of the flume tank was recorded at a range of towing speeds. A plot of height versus the number of unpolished links was then generated, and compared during the field work to achieve the nominal footrope clearance for each treatment.

No. of tows/tow duration: 108 tows were completed. Tow duration was 30 minutes

Towing speed: 1.8 ms^{-1}

Other study details: Warp to depth ratio was 3:1. Warp tension was measuring using by recording hydraulic oil pressure of each trawl winch. Otter board and wingend spread was measured using Scanmar acoustic sensors.

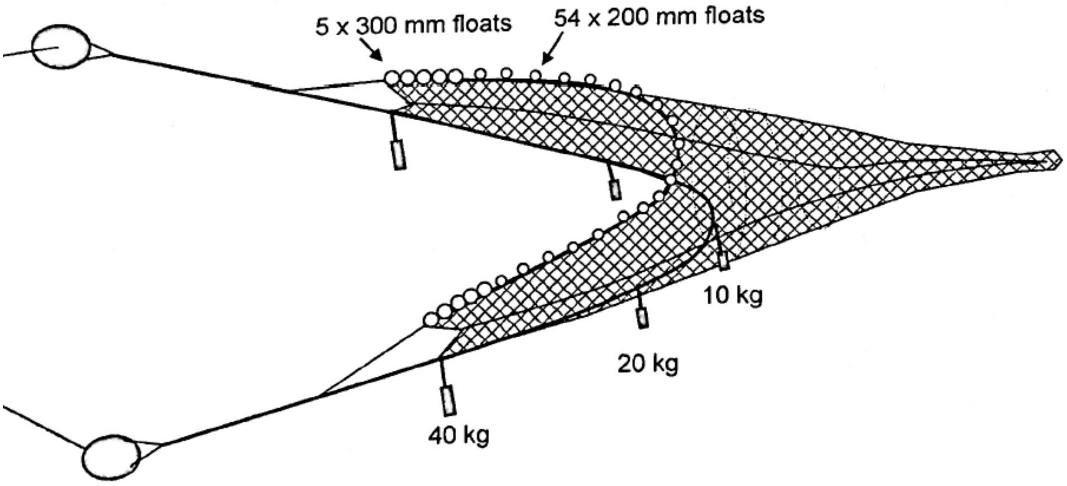


Figure C 5. The trawl rigged to fish semi-pelagically with a nominal footrope height of 0.4-0.5 m above the seabed. Source: Brewer *et al*., 1996.

Key findings/outcomes

Impact on trawl geometry: Compared to the conventional trawl, both treatments increased otter board spread and headline height, although mean warp tension was unchanged (Table C 2). Wingend spread for the conventional trawl was equivalent to 57% of headline length. Wingend spread for the treatments was not recorded. Underwater video indicated the footropes of both treatments were uniformly clear of the seabed for their entire length. Height above seabed was also steady.

Table C 2. Mean and standard error (in parentheses) of otter board spread, headline height, and warp tension. Source: Brewer et al., (1996).

Trawl	Otter board spread (m)	Headline height (m)[1]	Warp tension (t)
Conventional	66.8 (0.75)	2.3 (0.09)	2.00 (0.03)
Treatment 1	71.1 (0.39)	3.5 (0.09)	1.97 (0.03)
Treatment 2	68.7 (0.74)	4.1 (0.08)	1.98 (0.03)

1. This includes footrope clearance above the seabed.

Impact on target catch: There was no significant difference in catches of saddletail or crimson snapper between any trawl, although catches of both were higher when the footrope was 0.4 m above the seabed.

Impact on bycatch: Catches of sharks, other elasmobranchs, fish, sponges, epibenthic invertebrates, squid, and Moreton Bay bugs (*Thenus orientalis*) decreased significantly with increasing footrope clearance. There were significant differences in the catches of 68 species of fish between trawl types; all except seven of these species was caught in greater abundance in the conventional trawl. All seven are pelagic in habit.

Impact on fuel consumption: No detail provided.

Ease of use: No detail provided.

Cost: No detail provided.

Safety risk: No detail provided.

Future recommendations/work: No detail provided.

Consultant notes

- The short sweeps used in the fieldwork reflects a desire to ensure trawl manoeuvrability and a reflection of target-fishing behaviour by fishers.
- The otter boards used in the fieldwork were too large for the trawl and over spread the conventional trawl, which had a wingend spread equivalent to 57% of headline length; typically, fish trawls are spread to around 40% of headline length. Both treatments were also likely overspread, although this complements the other modifications and helps lift the footrope clear of the seabed. It also contributes to footrope stability and uniform clearance along its length.
- The fieldwork was completed in very calm conditions, but was ended prematurely due to an approaching cyclone and increasingly heavy weather. Data for the last few days were not included in the evaluation of trawl performance, primarily because movement of the vessel was transmitted along the warp wires, causing periodic lifting of the otter boards clear of the seabed and rapid increases and decreases in wingend height.
- Deployment of this trawl down the stern ramp was challenged by difficulties attaching the weights and ensuring they did not become entangled in the netting. Subsequently, additional time and care was required deploying the trawl. Additional time was also required removing the weights prior to hauling the trawl on a net drum.

Reference: Ball *et al*., 2002.

Title: The rollerball net: A new approach to environmentally friendly ottertrawl design.

Objective/s: Evaluate the efficacy of a roller ball trawl to mitigate seabed contact and allow the escape of benthic organisms.

Study details

Location: Galway Bay, Ireland.

Timing (year): 1999

Depth (m): No detail provided.

Target species: Sole (*Solea solea),* Plaice (*Pleuronectes platessa*), and rays (*Raja* ssp.)

Habitat characteristics: Muddy sand.

Gear type and dimensions: The trawl modifications were first tested in a flume tank, to provide first order estimates of the impact of the modifications on trawl performance. These trials confirmed the rollers turned freely in contact with the seabed. They also reduced drag by 12%.

Control gear: The control trawl was a two-seam design constructed from 80 mm mesh. Steel V-otter boards were used weighing 375 kg each in air, with 110 m sweeps and 37 m bridles. 11 x 203 mm floats were attached to the headline.

Experimental gear: The experimental trawl (roller ball trawl) was modified with the addition of 28 x 4 kg rollers attached to the ground gear along the wings and 6 x 2 kg rollers in the bosom region, with a total weight of 124 kg. The drop-out panel measured 6 m x 3 m and constructed from 90 mm square-mesh.

No. of tows/tow duration: 23 tows were completed, 12 with the roller ball trawl and the remainder with the control trawl. Tow duration using the roller ball trawl was 240 mins (4 tows) and 120 mins (8 tows) and for the control trawl it was 240 mins (4 tows) and 120 mins (7 tows).

Towing speed: 1.3 ms^{-1}

Other study details: No other detail provided.

Key findings/outcomes

Impact on trawl geometry: It was posited that the roller balls were not penetrating the seabed to the same extent as the control trawl. This was based on inspection of the commercial catch, where there was less silting of the gills using this trawl.

Impact on target catch: The roller ball trawl caught 14.5 +/- 4.6 kg of commercial species compared to 12.2 +/- 8.0 kg for the control trawl. This difference was not statistically significant. There was no significant difference in catches of dominant commercial species (Figure C 6) and no significant difference in length frequency distributions for ray, place, or sole.

Impact on bycatch: The discard catch was 30.8 +/- 6.2 kg and 22.0 +/- 10.4 kg for the roller ball and control trawls respectively. The roller ball trawl reduced catches of benthic invertebrates by 32% and debris by 66%. None of these differences were statistically significant.

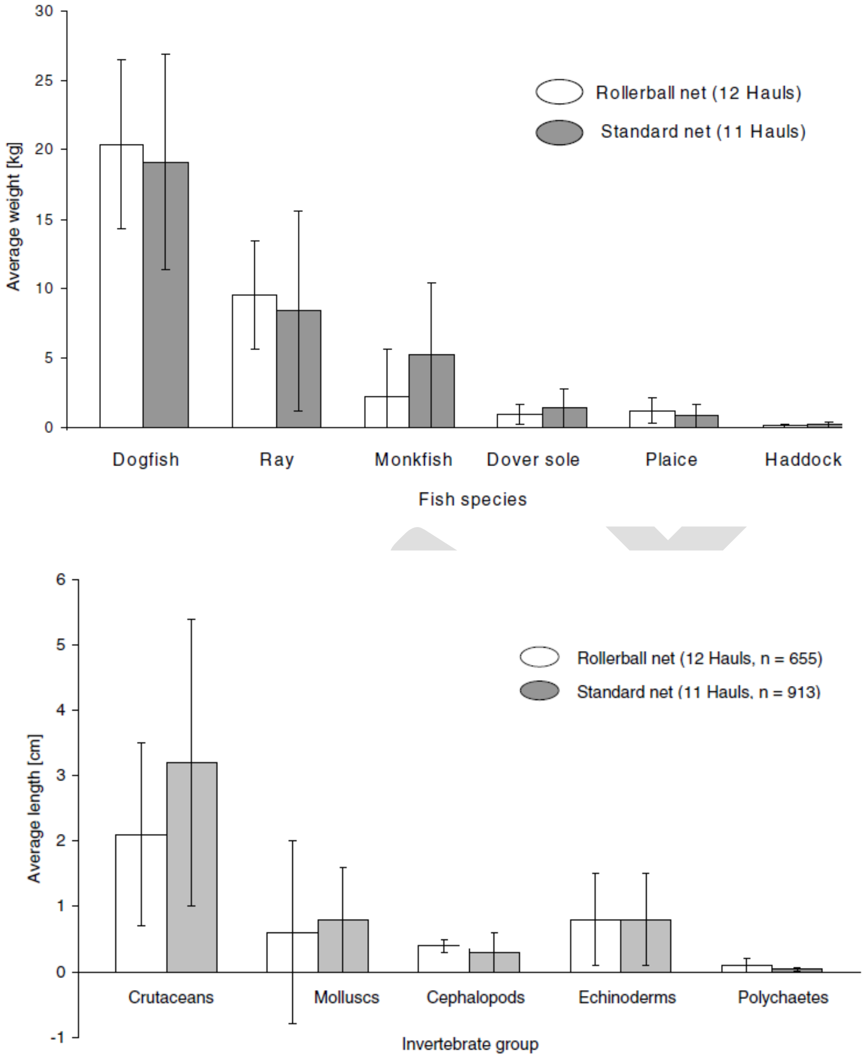


Figure C 6. Impact of Roller ball net on catches of commercial fish (upper) and invertebrates (lower). Source. Ball *et al*. (2002).

Impact on fuel consumption: A 12% fuel saving was estimated using the roller ball trawl because less engine power was required to towed the trawl at the desired towing speed.

Ease of use: No detail provided.

Cost: No detail provided.

Safety risk: No detail provided.

Future recommendations/work: No detail provided.

Consultant notes

- Preliminary evidence suggests the roller ball trawl reduces the incidence of sediment ploughing and resuspension. It also maintained the commercial catch and reduced fuel consumption by 12%.
- The otter boards used in the fieldwork were too large for the trawl and over spread the conventional trawl, which had a wingend spread equivalent to 57% of headline length; typically, fish trawls are spread to around 40% of headline length. Both treatments were also likely overspread, although this complements the other modifications and helps lift the footrope clear of the seabed. It also contributes to footrope stability and uniform clearance along its length.
- The fieldwork was completed in very calm conditions, but was ended prematurely due to an approaching cyclone and increasingly heavy weather. Data for the last few days were not included in the evaluation of trawl performance, primarily because movement of the vessel was transmitted along the warp wires, causing periodic lifting of the otter boards clear of the seabed and rapid increases and decreases in wingend height.
- Deployment of this trawl down the stern ramp was challenged by difficulties attaching the weights and ensuring they did not become entangled in the netting. Subsequently, additional time and care was required deploying the trawl. Additional time was also required removing the weights prior to hauling the trawl on a net drum.