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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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# Executive Summary

This report 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. Remedial efforts through gear modification are described, and their potential application by the New Zealand bottom trawl fleet is discussed, including relative impact on seabed contact (footprint), fisher profitability, and handling and operation of the trawl. Multiple recommendations are also provided to guide next-steps towards reducing seabed contact by this trawl fleet, including both inshore and deepwater vessels.

Around the world there have been numerous attempts by fishing technologists, fishers, and others to mitigate the benthic impacts of bottom trawling through gear modification. Most of these efforts have focused on eliminating seabed contact, and thus avoiding habitat impact by lifting trawl components into the water column, including the use of semi-pelagic trawl doors, elevated sweeps and bridles, and groundrope removal. Other efforts that have attempted to minimise or reduce seabed contact include increasing upper bridle length to lighten groundrope contact and increasing the diameter (surface area) of sweeps and lower bridles to reduce impact per unit area. These efforts have been tried in many fisheries, although efficacy is questionable because fishers cannot precisely control and regulate trawl contact with the seabed. Subsequently, quantifying the efficacy of these modifications is extremely difficult, and no reports were found in the literature describing the success of these modifications. Therefore, efforts to reduce seabed contact using these latter methods is not included in this report.

Not all methods described to reduce seabed contact are expected to be equally applicable across all New Zealand bottom trawl fisheries. Some may be better suited to inshore fisheries than deepwater fisheries. Several may also not be applicable at all, but their inclusion serves to stimulate ideas that may ultimately result in the development of new methods to reduce seabed contact by bottom trawl gear in New Zealand fisheries.

It is recommended that consideration be given to prioritising the testing of semi-pelagic trawl doors and cluster discs attached to sweeps and lower bridles, particularly in the inshore bottom trawl fishery. Each of these modifications has the potential to significantly reduce seabed contact, and efforts overseas to test these gears have shown encouraging results, despite presenting minor handling challenges. Semi-pelagic trawl doors are relatively more expensive than bottom-tending doors, but reduced fuel consumption, and a short amortisation (pay-back) period, makes them an attractive option to fishers. Their impact on target catch is negligible when operated correctly, and they can be used on bottom trawlers of all size ranges and engine power. The use of cluster discs is a relatively inexpensive option to mitigate seabed contact, and their immediacy of application is high. The possibility of catch loss underneath the sweep is a risk, however, particularly in fisheries that target flatfish or other species close to the seabed. Bottom trawlers of all sizes and engine power can conceivably apply this gear modification with success.

Other possible options to mitigate seabed contact include controllable trawl doors, trawls rigged with a raised footrope and drop chains, and semi-pelagic trawls. Controllable trawl doors provide benefits similar to semi-pelagic trawl doors, with the addition of control over their position in the water column. The expense of these doors, however, likely precludes their attractiveness to smaller fishing enterprises. It is also unclear if they can be operated whilst attached to a bottom trawl, as most efforts to date indicate use attached to a midwater trawl. Depending on the target species, raised footrope trawls and semi-pelagic trawls may not be a viable option due to catch loss underneath the trawl net.

As next-steps, we also recommend seeking feedback from the New Zealand bottom trawl industry on the potential for gear modification, impact reduction, and improved operational efficiencies. Also, a review of the 2020 Fisheries NZ and NIWA audit of New Zealand trawl gear, and collaboration with the seafood sector to establish agreed principles and objectives associated with protecting benthic habitats.

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# Acknowledgments

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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 greater 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 in length. 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 significantly to global food security, is a key economic driver, a major source of employment, and is 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, and removal, or mortality of benthic organisms, whilst 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; O'Neill & Ivanovic, 2016; Collie *et al*., 2017). Some of these impacts are observable for many years prior to recovery, particularly in deep water (Jones, 1992; Clark *et al*., 2016; Fisheries New Zealand, 2018b).

## 1.1 Trawl design and components

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 usually maintained by multiple floats attached to the headline. The horizontal opening of the trawl is maintained using trawl doors (sometimes called otter boards or just boards). Trawl doors also help keep the trawl net in contact with 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 trawl doors and the wingends of the net; they also help herd fish toward the mouth of the net. A heavy groundrope (sometimes called the ground gear), usually comprising a combination of steel wire rope, chain, and rubber discs or bobbins, helps ensure the trawl mouth remains close to the seabed. The groundrope also helps the trawl net pass over seabed obstacles and prevent the escape of fish underneath the net. The size (diameter) and weight of groundrope components is often selected by fishers and reflects the anticipated risk of damage to trawl netting as a result of contact with the seabed.

By its very nature, the catching efficiency of bottom trawling relies upon close and persistent contact with the seabed. Bottom trawling is usually restricted to relatively smooth substrates, such as mud, sand, gravel, or other low-relief substrates, to avoid snagging the seabed (hooking up) and damage to the trawl gear. As a general guide, trawl nets fitted with a chain groundrope or small-diameter rubber discs or bobbins signify that trawling usually occurs on smooth substrates, while nets fitted with large rubber discs or bobbins are often used where rocks or rock ledges may be encountered. There is, however, a limit to areas where bottom trawling activity can take place, as the rugosity of rocky outcrops, reefs, and other areas can make it impossible to use a bottom trawl without significant risk of damage, destruction, or loss of the trawl gear. This acts as a significant disincentive for fishers to avoid these areas, particularly when the cost of lost fishing gear and associated fishing time may approach one hundred thousand dollars or more.

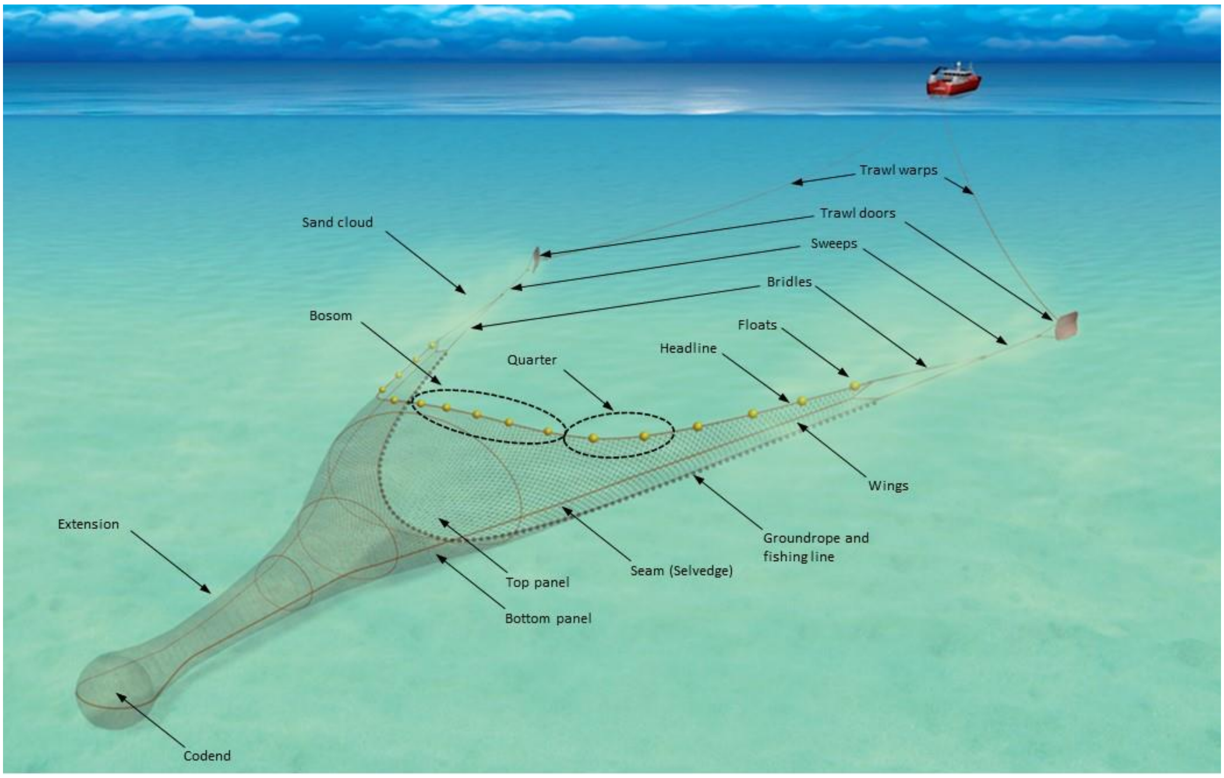


Figure 1. Bottom trawl with key sections and components labelled (not to scale). Image courtesy of Seafish Asset Bank.

## 1.2 Trawl concerns

International concerns over the impacts of bottom trawling date back to at least the 14th century (Engelhard, 2008), and this fishing practice has taken place in New Zealand since around 1900. 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 repeatedly productive fishing grounds, and quickly move to other grounds when catch rates decreased. A 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 benthic impact of bottom trawling have a long history, it is only in recent decades that dedicated and persistent attempts have been made worldwide 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 bottom trawling activity by space, time, and/or gear-type. It has also included efforts by fishing technologists, commercial fishers, and others to mitigate these impacts through gear modification, often with the goal of reducing the area of seabed contacted by the trawl gear, known as the trawl footprint.

## 1.3 Contents of this review

This review summarises efforts to modify bottom trawl gear, reduce the trawl footprint, and mitigate the impacts of bottom trawling on benthic habitats. To provide context, the New Zealand bottom trawl fishery is described (Chapter 2) as well as various types of bottom trawl gear used around the world, including New Zealand (Chapter 3). The trawl components responsible for seabed contact are then described (Chapter 4), followed by a description of how the seabed and habitat is impacted by trawl gear (Chapter 5). Options to reduce seabed impact by bottom trawl gear are described (Chapter 6), including gear modification (Chapter 7), focusing on modifications to trawl doors, sweeps and lower bridles, and the groundrope. Finally, the application of these modifications to New Zealand bottom trawl fisheries is discussed (Chapter 8), followed by recommendations for future remedial activity (Chapter 9). Appendices are also provided that summarise efforts in New Zealand and elsewhere to reduce the footprint of bottom trawl gear on the seabed.

# 2 The New Zealand bottom trawl fishery

## 2.1 Target species and trawl fleet

Commercial fish landings in New Zealand fisheries are dominated by trawl-caught species such as hoki (*Macruronus novazelandiae*), squid (*Notodarus gouldii* and *N. sloanii*), jack mackerel (*Trachurus* spp.), southern blue whiting (*Micromesistius australis*), barracouta (*Thyrsites atun*), orange roughy (*Hoplostethus atlanticus*), oreo (*Allocyttus niger* and *Pseudocyttus maculatus*), snapper (*Pagrus auratus*), and gurnard (*Chelidonichthys kumu*)[1] (Williams *et al*., 2017). Both bottom and midwater trawls are used to target these species and the latter is sometimes used in contact with the seabed.

There are 37 vessels (Plate 1) in the large trawl fleet (>28m), targeting middle depth species[2] such as hoki and squid and deepwater species such as orange roughy, oreo, cardinal fish (*Epigonus telescopus*) and alfonsino (*Beryx splendens*) (Morrison *et al*., 2014; Fisheries New Zealand, 2019b). Orange roughy accounts for 91% of the bottom trawl catch in the deepwater fishery (Ministry of Fisheries, 2008), often on seamounts using acoustic technology to detect and target the fish (Ministry of Fisheries, 2008). Almost 80% of known seamounts located between 500-1,000 m in New Zealand waters have previously been fished using bottom trawls (Morrison *et al*., 2014).

Occasionally these vessels may also move to inshore waters and target species such as snapper and trevally (*Pseudocaranx georgianus*), particularly around the North Island (Fisheries New Zealand, 2019b). The large trawl fleet completes approximately 25,000 tows annually and bottom time may range from less than one hour to several hours depending on target species. Between 2002-06, average tow duration while targeting orange roughy was 2.19 hours, although one third of tows were shorter than 15 minutes and 60% were shorter than 30 minutes (Ministry of Fisheries, 2008). Most of these tows extended for less than 3.7 km (2 nm).

The small vessel (Plate 2) trawl fleet (<28m in length) comprises approximately 140 vessels and usually operates in inshore waters, targeting snapper, gurnard, blue cod (*Parapecis colias*), and Tarakihi (*Nemadactylus macropterus*), although seasonally they may target hoki and other middle-depth species. This fleet typically completes between 50,000 to 60,000 tows each year (Fisheries New Zealand, 2019b). Towing duration may be as long as four hours, and towing speed is generally 2.7-3.0 knots (1.4-1.5 $ms^{-1}$) (Baird *et al*., 2015). Tows for these species typically extend for about 15 km, although some may exceed 20 km.

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[1] See https://fs.fish.govt.nz/Page.aspx?pk=6&tk=97 for the total allowable commercial catch (TACC) of each species.

[2] As a guide, middle-depth fisheries are generally considered to extend between 150-500 m (Fisheries New Zealand, 2019c). Deepwater fisheries operate in waters greater than 500 m. Inshore trawl fisheries generally operate up to the 12 nautical mile outer limit of the territorial sea, or to the 200 m depth contour. Middle depth fisheries and deepwater fisheries predominantly occur in waters beyond 12 nm from shore (Fisheries New Zealand, 2018a).


Plate 1. A typical New Zealand deepwater trawler. Source: [www.balticshipping.com](http://www.balticshipping.com) (Copyright Steve Watkins)


Plate 2. A typical New Zealand inshore bottom trawler. Source: Cris West

## 2.2 Management

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 set harvest levels to ensure sustainable fisheries resources (Day, 2004; Bodwitch, 2017). The QMS now regulates approximately 450,000 tonnes of wild fish landings annually with an export value of about NZD$1.5 billlion (Williams *et al*., 2017). Hoki, squid, mackerel, and ling (*Genypterus blacodes*) comprise around one third of seafood export revenue in New Zealand; the hoki catch limit in 2020 is 115,000 tonnes (Ministry for Primary Industries, 2020). Snapper is the dominant inshore species by landed value, representing 15% of the total value of all inshore landed species (Williams *et al*., 2017).

The QMS was introduced in the early 1980s, although 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 Act 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 bottom trawling and dredging is banned (Helson *et al*., 2010), the introduction of marine reserves, restrictions on fishing gear, minimum fish landing size limits, and protection of marine species including all mammals, all seabirds (except black backed gulls), some corals, some sharks and rays, some bony fish, and all reptiles. 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 New Zealand are now sourced from certified fisheries (Seafood New Zealand, n.d), and New Zealand fisheries have twice (in 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, 2019a).

## 2.3 Innovation

Continuing this tradition of innovation and leadership in sustainable fisheries development, a world-first approach to fish harvesting and handling has been developed by Precision Seafood Harvesting (PSH). This NZD$43.3 million research and development partnership between government, research (Plant and Food Research Ltd (Nelson)), and industry has developed a significantly different approach to bulk-harvest trawling 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), and they are now frequently being used on the new Sealord vessel; FV Tokatu, and the RMD Māori family company-owned vessel, the FV Santy Maria, which fishes mainly in inshore waters. There is also growing international interest in adopting this harvesting system. A similar industry innovation is the Better Fishing Cage, a stainless-steel cage designed by a Hawke's Bay fisher that replaces a traditional codend and allows the escape of undersized fish prior to hauling the trawl onboard (Bates, 2018).

## 2.4 Bottom trawl gear

Alfredo-style trawl nets are commonly used by the domestic trawl fleet, particulary in deep water, and are characterised by low headline height (3-5 m), a short groundrope (20-30 m), small mesh netting (100-300 mm), larger diameter twine (5mm or more) and small rubber bobbins (300-450 mm diameter) (O'Boyle *et al*., 2018). The lower wings on these trawls are either absent or significantly reduced, to minimise the risk of net damage.

In shallow waters, wing trawls or so-called 'Spanish" trawls are used. These have a similar headline height and mesh sizes compared to the Alfredo trawl but the wingends and groundrope are longer and smaller diameter bobbins are used in the groundrope, reflecting their use on smooth seabed. Sometimes these nets are used in a twin-rig arrangement, comprising two identical nets spread by a single pair of trawl doors, with a sledge or clump weight connecting the inner wings of both nets. Sweep and bridle length may reach 220 m and 30 m respectively. Midwater trawl nets are sometimes also used, at times in contact with the seabed.

High aspect ratio trawl doors are commonly used when fishing seamounts, and on large vessels they may weigh 2,000 kg or more in air with a surface area up to 8 m$^2$ (Ministry of Fisheries, 2008; Clark *et al*., 2016;). They are also designed and rigged to operate clear of the seabed or with minimal seabed contact. Trawl door spread may be as wide as 150 m. Sweeps and bridles are relatively short, often around half the length used to target hoki (Ministry of Fisheries, 2008). This improves trawl manoeuvrability and responsiveness and allows the net to be 'flown' clear of the seabed prior to encountering the aggregated fish, therefore reducing the likelihood of hookups and gear damage. A review of deep-water trawl fishing gear and fishing effort in New Zealand waters is provided by the Ministry of Fisheries (2008) - now Fisheries New Zealand - 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).

## 2.5 Trawl footprint

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.; Helson *et al*., 2010; Black & Tilney, 2015; O'Boyle *et al*., 2018;), around 24% of seabed available to bottom trawling (>1,600 m) was fished at least once since 1990, representing a total bottom trawl footprint (area swept) of around 335,000 km$^2$ (Ministry for the Environment & Stats NZ, 2019). Approximately 75% of this footprint is located in water depths <400 m and 25% located between 400-600 m. In shallow-water (<250 m), an area equivalent to almost half of the available seabed was trawled at least once between 1990-2011 (Baird *et al*., 2015; Ministry for the Environment, 2016). The annual bottom trawl footprint in this region was equivalent to about 20% of the available seabed (Baird *et al*., 2015).

Jack mackerel and squid fishing create the greatest footprint of all Tier 1[3] and 2 fish species, contacting 13.7% and 8.3% of the shallow-water (<250m) seabed respectively (Baird *et al*., 2015). Hoki fishing contributes around 80% of the total bottom trawl footprint in waters between 400-800 m (Black & Tilney, 2015; Baird & Wood, 2018), and contacts about 19% of the seabed in the 200-400 m zone, 25% in the 400-600 m zone, and 24% in the 600-800 m zone (Baird & Wood, 2018). Orange roughy fishing contacts the highest proportion of seabed in waters greater than 800 m, with highest contact (7.6%) in the 800-1,000 m zone. Overall, Tier 1 fish stocks contribute approximately 87% of the total trawl footprint (Baird & Mules, 2019). Notably, approximately 90% of the EEZ has never been bottom

[3] Tier 1 deepwater species include hake, hoki, jack mackerel spp, link, oreo species, orange roughy, southern blue whiting, scampi, and arrow squid. Tier 2 deepwater species include barracouta, alfonsino, and warehou species.

trawled, in part because most of the EEZ is deeper than 1250 m where there is little bottom trawling (Ministry for Primary Industries, 2016).

## 2.6 Habitat impact and response

New Zealand bottom trawl fisheries have operated since the early 1990s and the most serious damage to seabed habitats is likely to have already occurred (Fisheries New Zealand, 2018b), presumably during the early days of bottom trawl activity within each fishery. Bottom trawling is the greatest threat to benthic habitats between 200-2,000 m, including seamounts (MacDiarmid *et al*., 2012), and pressure is increasing to mitigate the benthic impacts of bottom trawling to the greatest extent practicable, particularly given the critical role of these habitats in marine ecosystem health and resilience. Notably, during the most recent MSC recertification of the hoki, hake, and ling trawl fisheries (O'Boyle *et al*., 2018), concern was expressed at the potential of these fisheries to expand into new areas if the distribution of these stocks changed in the future. Implicit in this concern was that such expansion could adversely impact undisturbed benthic habitats that are not currently subject to fishing pressure. Similar concerns over the impact of bottom trawling have also been expressed in the media (e.g. Vance, 2018; LegaSea, 2019; Mitchell, 2019; Scoop, 2020), some which also express distrust over the behaviour and motives of the fishing industry. This distrust is evidence that the social licence of fishers involved in bottom trawling is being questioned by some stakeholders.

To date, responses to this pressure in New Zealand have been limited and ad hoc, both by fishers and others. Some fishers have endeavoured to minimise seabed contact through gear modification, for example, by reducing sweep and bridle length while targeting orange roughy, but there is little evidence of additional efforts to modify trawl gear to reduce seabed contact. There has also been a paucity of scientific research to achieve the same outcome, although a notable exception was the testing of semi-pelagic trawl doors by Jones (2014) in the inshore trawl fishery. This research demonstrated the ability of these trawl doors to reduce seabed contact by 95% compared to conventional trawl doors. Catch rates of target speceis were almost identical between trawl doors, and fuel consumption was reduced by an average of 16%, but for reasons that are unclear, these outcomes were not embraced by fishers.

The New Zealand Government has sought to use marine spatial planning and oceans policy to address marine health overall, however, this has not yet been concluded and to date only limited protection of benthic habitat is provided. Whilst New Zealand’s BPAs protect around 30% of the EEZ, they do not meet the 2020 United Nations (UN) Sustainable Development Goal of protection for at least 10% of coastal and marine areas (Anon, 2020). This recognises that BPAs do not meet the IUCN Other Effective Area-Based Conservation (OECM) 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 whole (i.e. not a single habitat or species) (Day, *et al*., 2019).

# 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 vessels towing a trawl net (Table 1). In New Zealand, the most common trawl categories are single vessel otter trawl, twin bottom trawl (twin-rigged bottom trawl), bottom pair trawl, and single vessel midwater trawls. Increasingly, the Precision Seafood Modular Harvesting System is being used by both bottom and midwater trawlers in New Zealand. This system consists of a flexible polyvinyl chloride (PVC) liner instead of a traditional codend, with escape openings specifically designed to allow the escape of non-target species (Sanford, 2020), and has been approved for use in selected inshore and deepwater fisheries (Ministry for Primary Industries, 2019). The remaining trawl categories are not known to be used in New Zealand, but are provided here to deliver a full and complete summary of international trawl gear categories.

Table 1. International classification of trawl gear, including gear code and abbreviation, and New Zealand classification based on electronic logbook codes (Source: FAO, 2013; Fisheries New Zealand, 2018c). NEI - not enough information

| Trawl category | International classsification | NZ classification | |
|---|---|---|---|
| | Abbreviation | Gear code | Logbook code |
| **Beam trawl** | TBB | 03.11 | - |
| **Single vessel otter trawl** | OTB | 03.12 | BT |
| **Twin bottom trawl** | OTB | 03.13 | - |
| **Multiple bottom trawl** | OTP | 03.14 | - |
| **Bottom pair trawl** | PTB | 03.15 | BPT |
| **Bottom trawl (NEI)** | TB | 03.19 | - |
| **Single vessel midwater trawls** | OTM | 03.21 | MW |
| **Midwater pair trawls** | PTM | 03.22 | MPT |
| **Midwater trawls (NEI)** | TM | 03.29 | - |
| **Semi-pelagic trawl** | TSP | 03.3 | - |
| **Trawls (NEI)** | TX | 03.9 | - |
| **Precision bottom trawl** | - | - | PRB |
| **Precision midwater trawl** | - | - | PRM |

## 3.1 Beam trawls (03.11)

Beam trawls are arguably the simplest trawl gear (Figure 2), however, they are not used in the New Zealand fishing industry. 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 therefore often unnecessary, and sweeps and bridles are not usually used. Groundropes may consist of a single chain, chain mat, or rubber bobbins and discs depending on the anticipated seabed characteristics. The area of seabed swept by a beam trawl is the product of beam width and distance trawled.

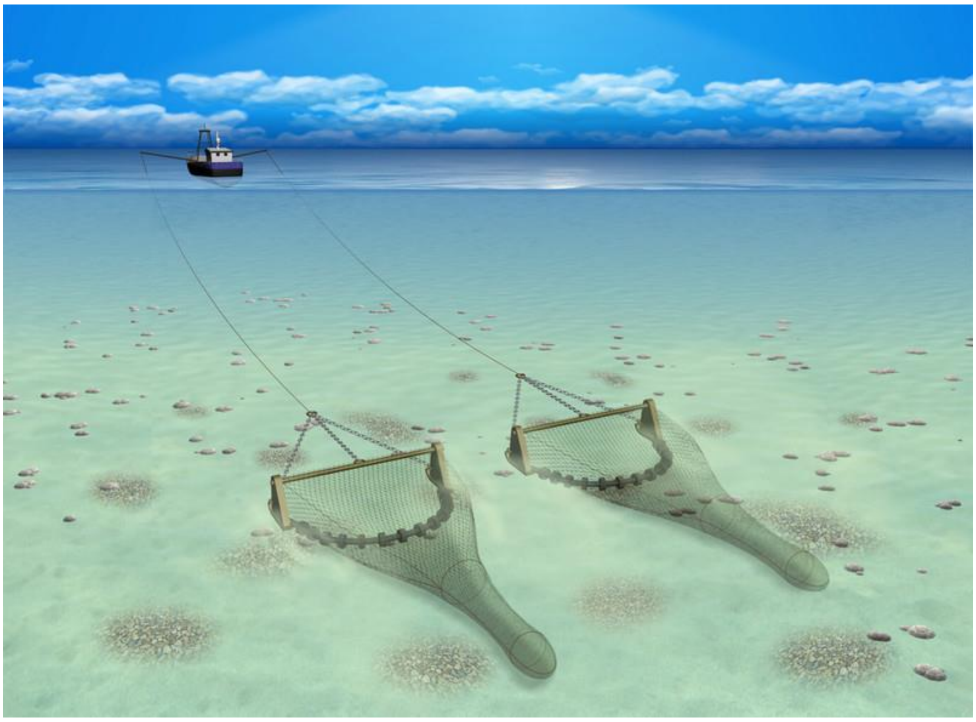

Figure 2. A beam trawl. The shoes are located at each end of the rigid beam. Image courtesy of Seafish Asset Bank

## 3.2 Single vessel 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 vessel (Figure 3), the use of trawl doors to spread the net horizontally, and sweeps and bridles to herd fish into the approaching net. Groundropes may consist of weighted rope, rubber bobbins and discs, or chain. The area of seabed swept by this trawl is the product of trawl door 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 trawl doors are used to spread the nets, attached to the outer wings of each net. The inner wings are connected to a single sledge, sled, or clump weight. Groundropes may consist of rubber bobbins and discs, or chain. This system is also sometimes known as twin rig, and the area of seabed swept by this trawl system is the product of trawl door spread and distance trawled.

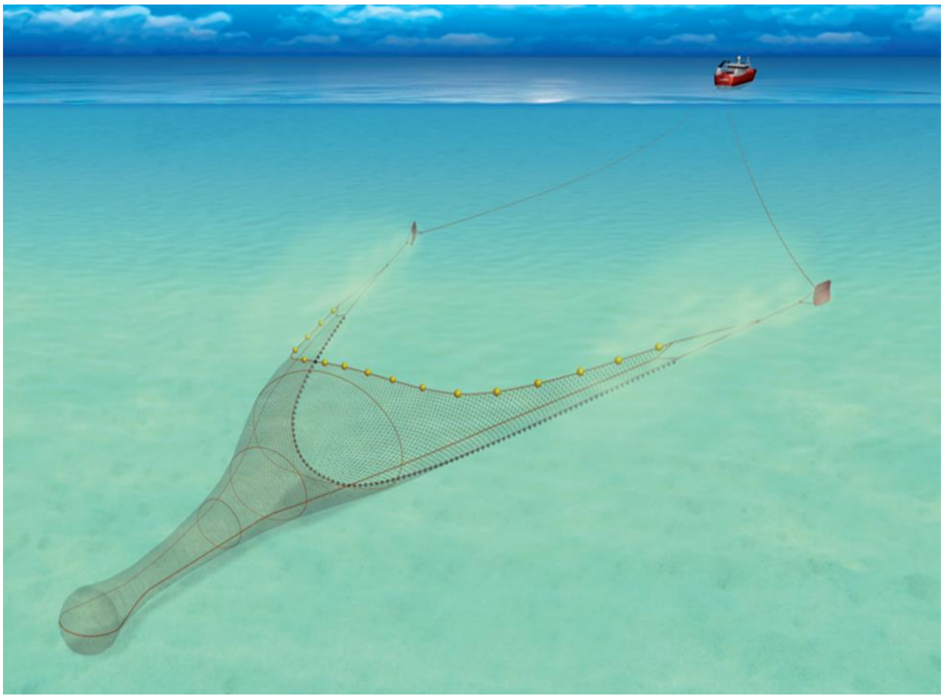

Figure 3. Single bottom trawl. Image courtesy of Seafish Asset Bank.

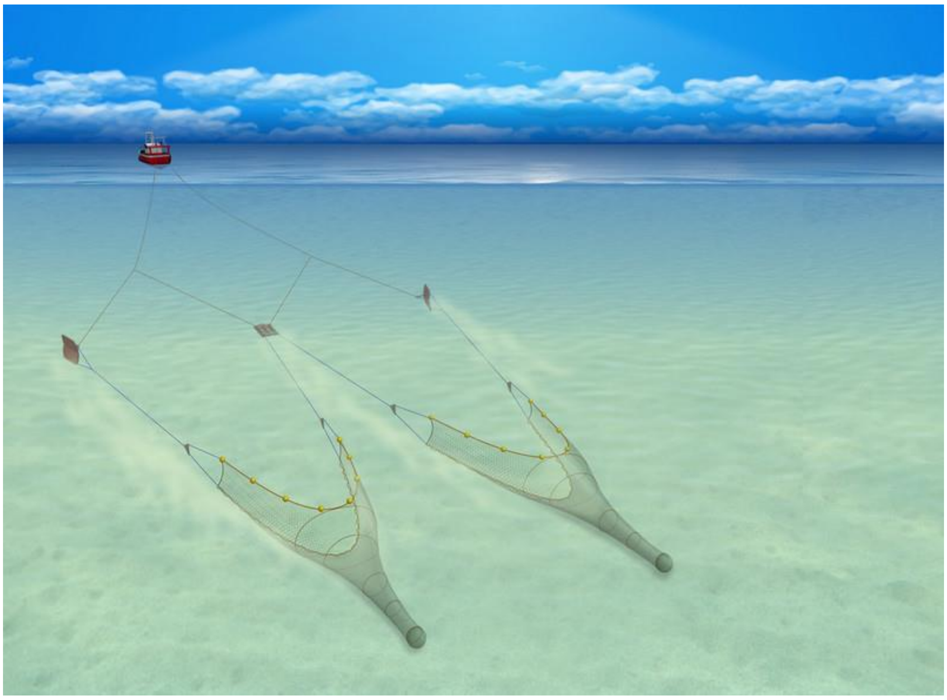

Figure 4. Twin bottom trawl. Image courtesy of Seafish Asset Bank.

A similar system includes towing two nets side by side each with their own pair of trawl doors (Figure 5). This system is sometimes called double rig and is commonly used in tropical prawn trawl fisheries in Australia and around the world.

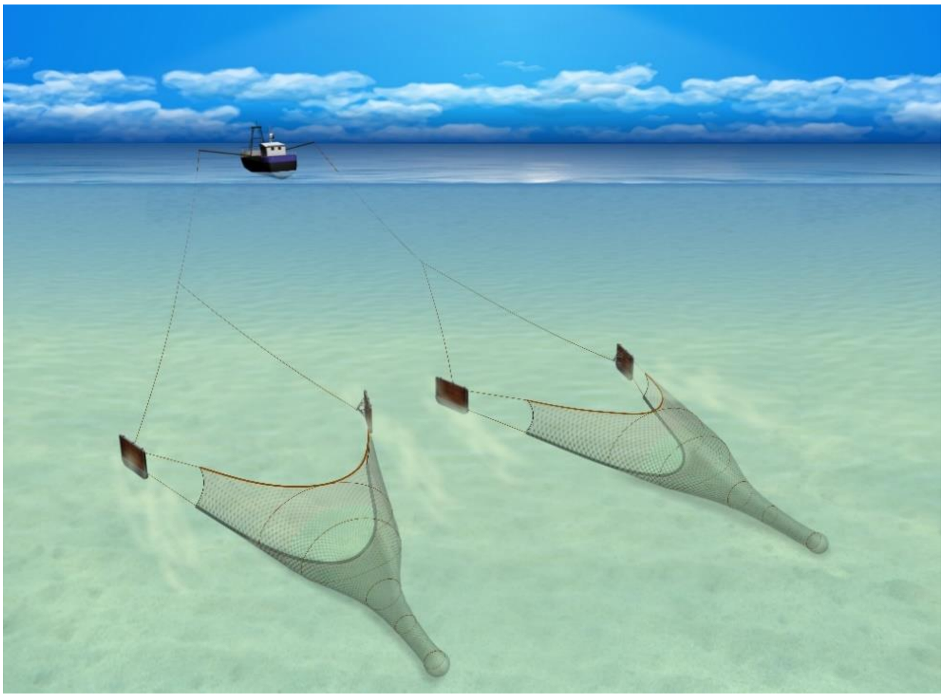

Figure 5. Alternative twin bottom trawl. Image courtesy of Seafish Asset Bank.

## 3.4 Multiple bottom trawl (03.14)

In some bottom trawl fisheries, particularly those that target prawns, scampi, or flatfish, three 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 trawl doors (Figure 6). The inner wingends of each net are attached to a sledge, sled, or clump weight. A four-net system, or quad-rig, is characterised by four connected nets spread horizontally by two trawl doors (Figure 7). The inner wingends are similarly connected using a sledge, sled, or clump weight, and the groundropes may consist of rubber bobbins and discs, or chain. A variation of this system is two twin trawls towed side by side, with each pair of trawls towed from an outrigger or boom. This arrangement is commonly used in tropical prawn trawl fisheries in Australia and around the world. The area of seabed swept by this trawl system is the product of trawl door spread and distance trawled.

## 3.5 Bottom pair trawl (03.15)

This trawl category involves the use of two vessels towing a single net (Figure 8). Trawl doors are not used because the horizontal opening of the net is the result of the horizontal separation between the two vessels. To optimise bottom contact, heavy weights are usually attached to the leading ends of the sweeps. Groundropes 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-vessel trawls, not only because two vessels are used, but because the absence of trawl doors 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.

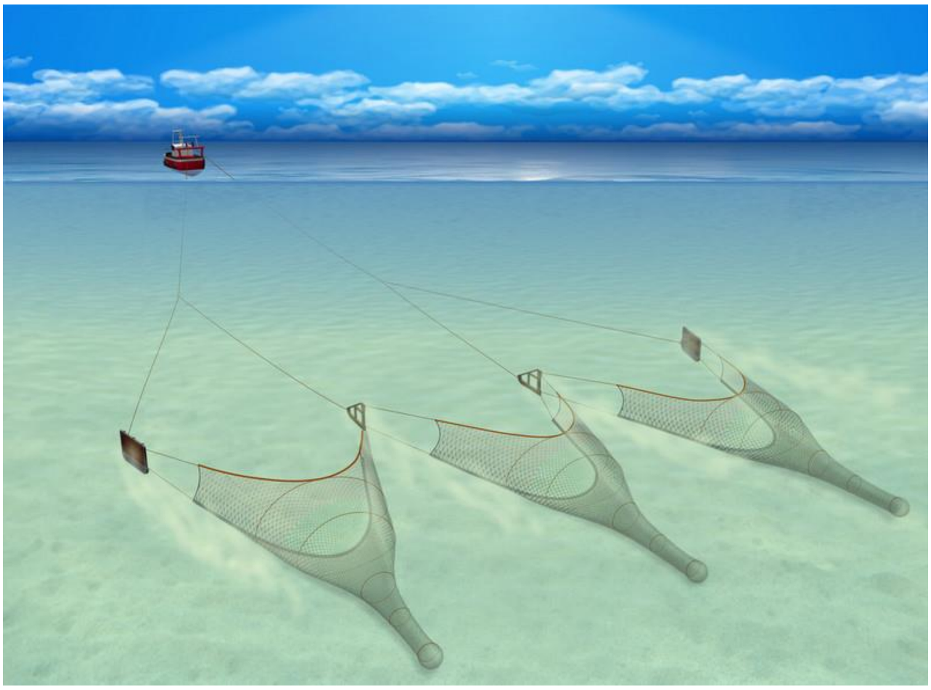

Figure 6. A triple trawl system. Image courtesy of Seafish Asset Bank

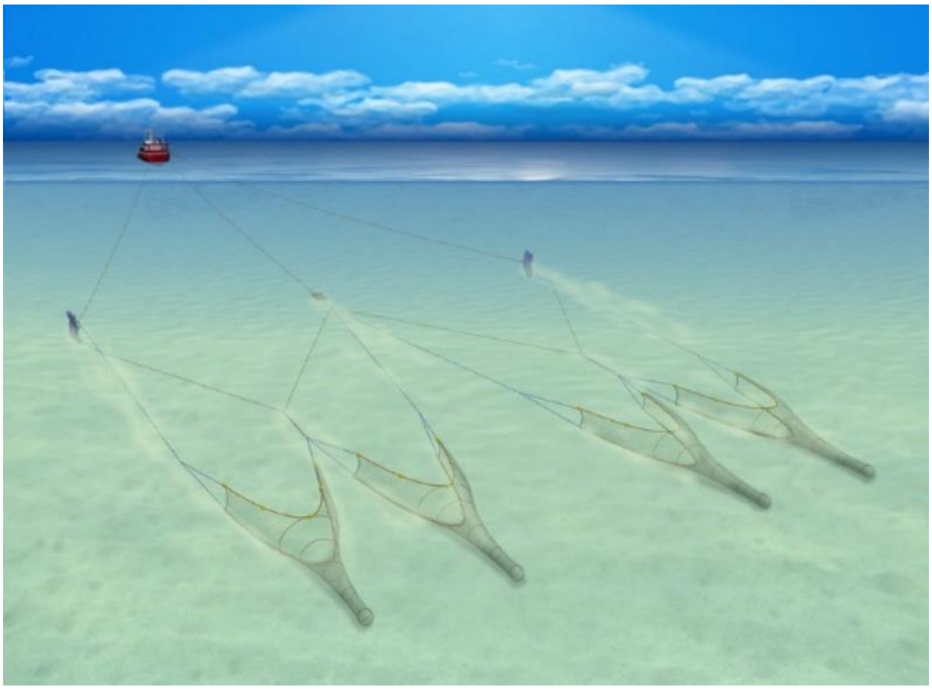

Figure 7. A quad trawl system. Image courtesy of Seafish Asset Bank.

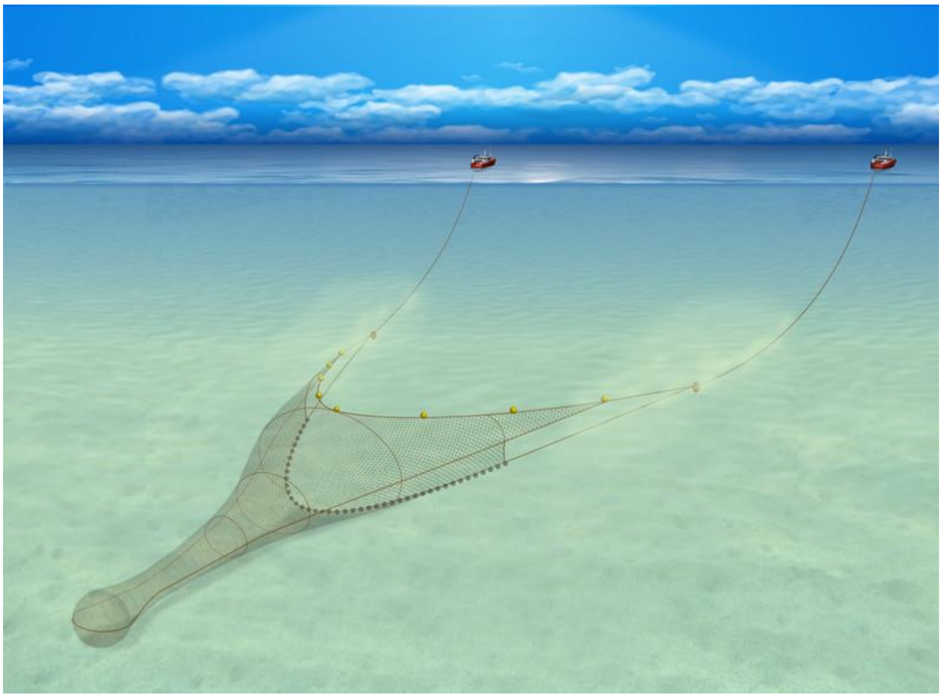

Figure 8. Bottom pair trawl. Image courtesy of Seafish Asset Bank.

## 3.6 Single vessel 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 well over 10 m long 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 trawl doors 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. Groundropes, 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 of this system is the product of the distance between the trawl doors 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.

## 3.7 Midwater pair trawls (03.22)

These are some of the largest trawl nets ever constructed. Trawl doors are not used and the horizontal opening of the trawl net is a result of the horizontal distance between two trawlers (Figure 10). Weights are attached to the lower wingends of the trawl and/or along the fishing line, 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 not usually designed for bottom contact, although in some fisheries they are operated close or in contact with the seabed. The groundrope may consist of chain along the entire length or just some of the footline, or other weights attached at intervals.

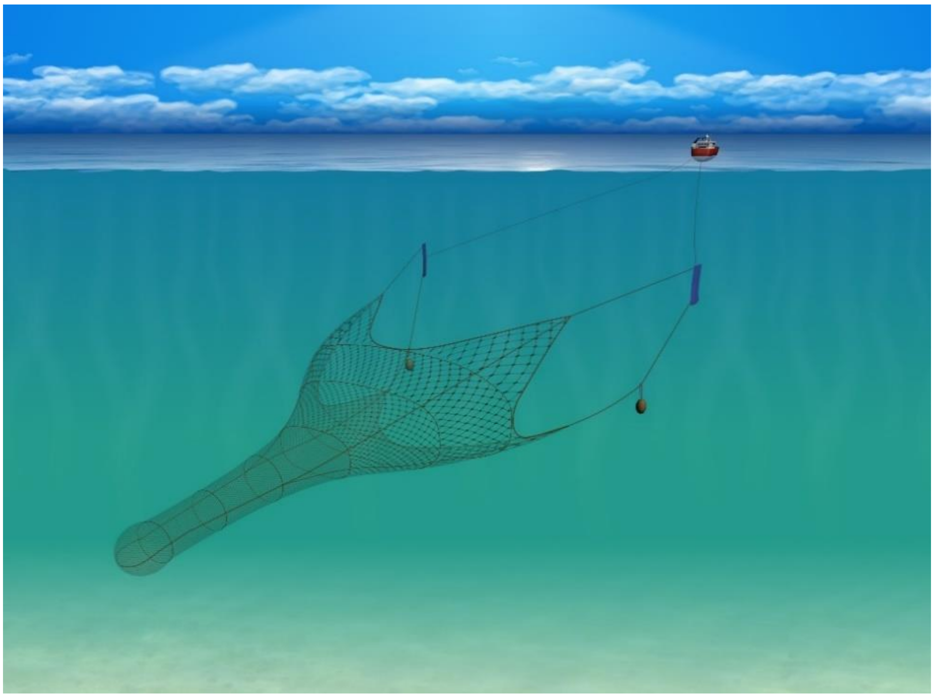

Figure 9. Single vessel midwater trawl. Image courtesy of Seafish Asset Bank.

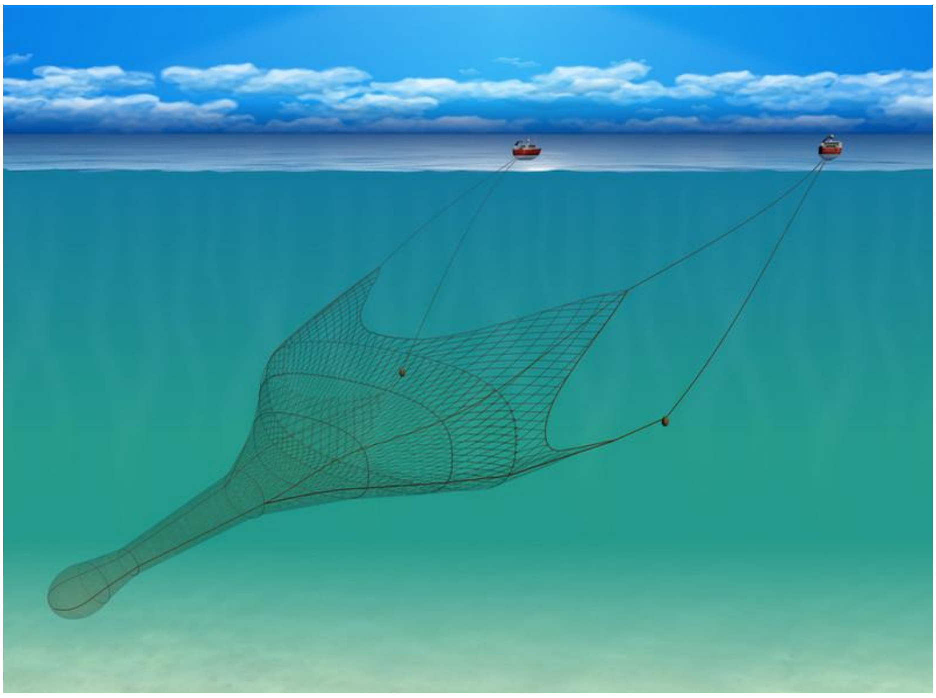

Figure 10. Midwater pair trawl. Image courtesy of Seafish Asset Bank.

## 3.8 Semi-pelagic trawls (03.3)

This system typically comprises an ordinary bottom trawl net with the trawl doors and some or all of the sweeps lifted clear of the seabed (Figure 11). An alternative in some fisheries is a trawl system with trawl doors in contact with the seabed, but not the trawl net (Larsen *et al*., 2019). Groundropes 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.

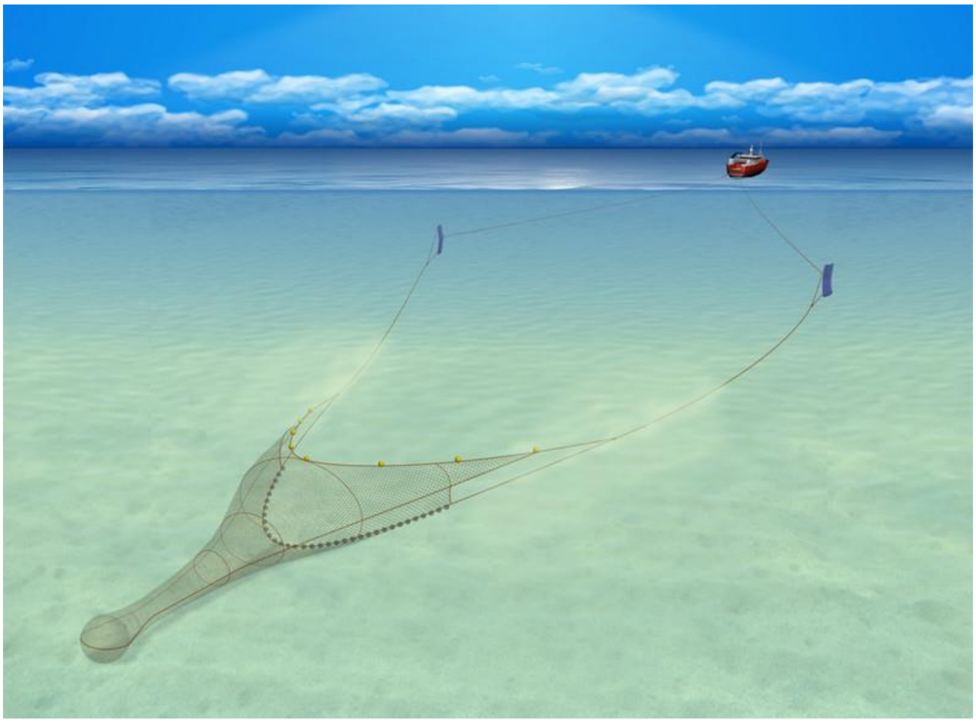

Figure 11. Semi-pelagic trawl. Image courtesy of Seafish Asset Bank.

# 4 Trawl components in contact with the seabed

The components of a bottom trawl that contact the seabed are the trawl doors, sweeps and lower bridles, and the groundrope (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 Trawl doors - design and operation

The function of the trawl doors 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 trawl doors are the first point of seabed contact, and the distance between them is colloquially referred to as trawl or door spread. This distance is important in calculating the area of seabed contacted by the trawl because in addition to the trawl doors themselves, the sweeps, lower bridles, and the groundrope are also in seabed contact (Figure 12); note that for simplicity the groundrope is often assumed to be in seabed contact along its entire length, irrespective of groundrope type.

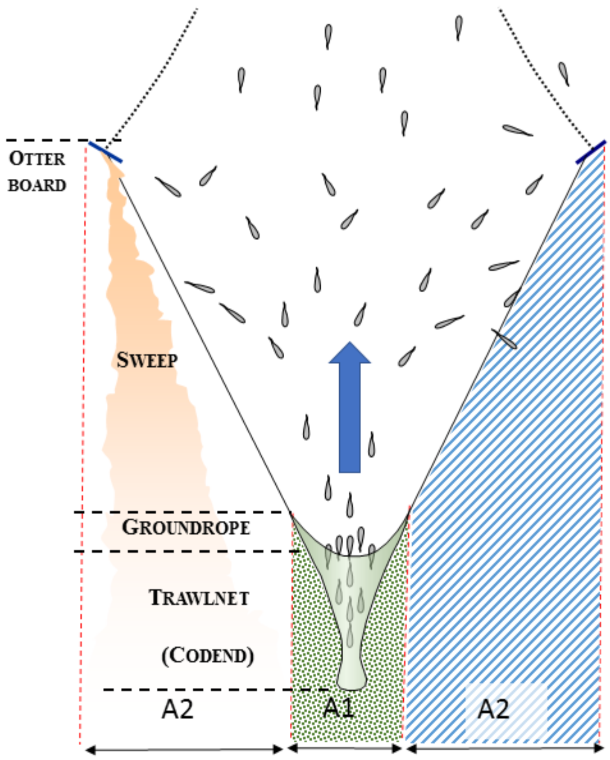


Figure 12. Schematic indicating swept width of a single-vessel bottom trawl system. This includes the width of the trawl net between wingends (A1) and width covered by the sweep and otter boards (A2). A sediment plume produced by the trawl door on the left is also indicated. Image courtesy of Seafish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

A range of trawl door designs are used in bottom trawl fisheries worldwide (Figure 13). The rectangular flat trawl door was the earliest trawl door design used in these fisheries, 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.


Figure 13. Commonly used trawl doors for bottom trawling. Image courtesy of Seafish Asset Bank.

The evolution of trawl door design includes the use of oval-shaped trawl doors with one or more cambered foils, and more recently, the use of high aspect ratio, multi-foil trawl doors. In New Zealand, rectangular multi-foil trawl doors and high aspect ratio, multi-foiled trawl doors are commonly used in bottom trawl fisheries.

Rectangular flat trawl doors are not hydrodynamically efficient. Hydrodynamic efficiency is a measure of the lift to drag ratio of the trawl door, where lift is the horizontal spreading force[4] generated by the trawl door as it is towed through the water, and drag is the penalty attempting to oppose the motion of the trawl door. With rectangular flat trawl doors the lift to drag ratio is close to 1:1, while the lift to drag ratio of a high aspect ratio, multi-foiled trawl door may be 2:1 or higher. This improvement in efficiency means that smaller, multi-foiled trawl doors can be used to produce the same spreading force as a less efficient trawl door, with an attendant reduction in drag and associated improvement in fuel efficiency. These trawl doors may also be more manoeuvrable in the water and more easily handled onboard.

Another benefit of improved hydrodynamic efficiency is to permit operation of the trawl door at lower angle of attack. This is the angle of the trawl door relative to the direction of tow, which is needed to generate the required spreading force and maintain the horizontal opening of the trawl. Inefficient trawl doors are commonly operated at around 30° or more, primarily to ensure their stability during deployment and retrieval, while more efficient designs can be operated at 20° or less. Reducing angle of attack from 30 to 20° also results in a 32% reduction in the width of the trawl door footprint on the seabed.

## 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 trawl doors to the trawl net and to a limited extent help keep the trawl net close to the seabed. The lower bridle extends between the sweep and the juncture where the groundrope and fishing line 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. The diameter of the lower bridle is sometimes larger than the upper bridle for greater breaking strain and abrasion resistance. A third or middle bridle is sometomes 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 3). Combination rope is 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

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

on the expected amount of tension (drag) generated by the trawl during the fishing operation and the expected 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.


Plate 3. 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.

The length of sweeps and bridles varies based on target fish 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 in length. The bridles may measure 25 m or more although if too long their weight may reduce headline height. Where the seabed is characterised by rocky ledges and outcrops, or other obstacles, the sweeps may be 50 m or less to increase trawl manoeuvrability and responsiveness and to reduce the risk of becoming fouled on the seabed.

## 4.3 Groundrope - design and function

The groundrope is designed explicitly to contact the seabed, protect trawl netting from damage, and help to keep the trawl net close to the seabed (Figure 14). The design of the groundrope varies significantly, from simple lengths of rope with weights attached to lengths of wire rope threaded through rubber discs of varying size.

Groundrope terminology is varied. In many fisheries around the world this part of the trawl is referred to as the groundgear, footrope, or footline. In the United States of America this part of the trawl is called the sweep, and the sweeps are called ground cables. In New Zealand, the line to which trawl netting and the groundrope is attached is called the fishing line, although in other countries this line may also be referred to as the footrope or footline.

On very smooth substrates such as sand, mud, or gravel, the groundrope may simply be comprised of chain wrapped around the fishing line or attached (scalloped) to the fishing line at equal intervals (Figure 15). These designs are commonly used in tropical prawn trawl fisheries around the world.

In other fisheries, a simple groundrope consisting of numerous small 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. In some countries this is referred to as a ‘cookie’ groundrope.

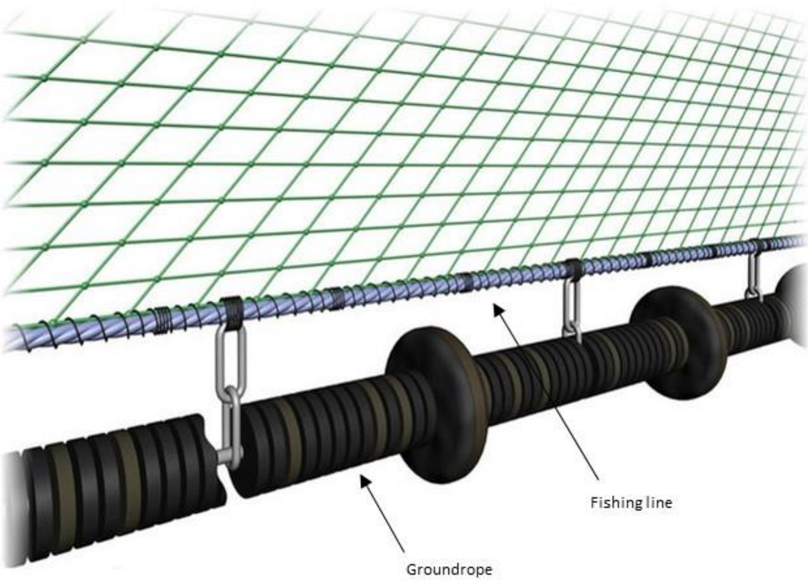


Figure 14. A typical groundrope arrangement in a fish-trawl fishery. Image courtesy of Seafish Asset Bank.

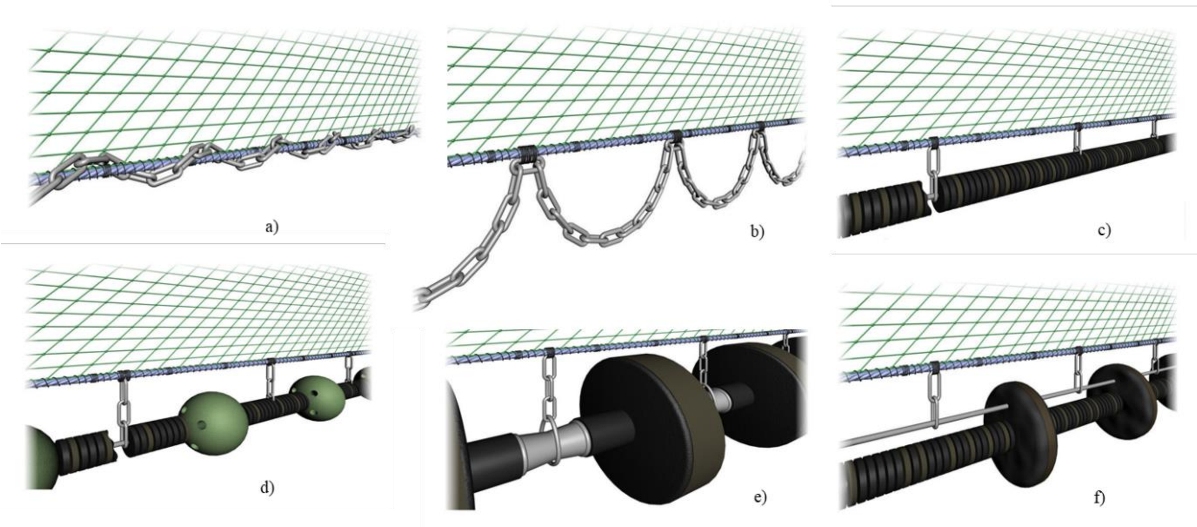


Figure 15. Some common groundrope designs: a) chain-wrapped fishing line, b) scalloped chain fishing line, c) rubber disc (‘cookie’) groundrope, d) spherical bobbin groundrope, e) large bobbin groundrope, f) rockhopper groundrope. Image courtesy of Seafish Asset Bank.

On substrates that are less smooth, or where rocks and rubble may be encountered, the groundrope may include large rubber discs or spherical bobbins made from heavy rubber or steel. The diameter of these discs or bobbins may be largest at the trawl mouth, sometimes measuring 600 mm or more, and they may be smaller towards the wingends. Smaller rubber 'cookie' discs and lead weights are typically fitted between each disc or bobbin. In the center of the groundrope the discs or bobbins may rotate as the trawl gear is towed over the seabed. This helps reduce ploughing of seabed sediments, but may result in crushing of benthic invertebrates and structure. Along the wings of the trawl the discs or bobbins are unable to rotate and are dragged laterally over the seabed. In fisheries where the risk a net damage is high, the groundrope may be fitted with spherical bobbins or rockhoppers to facilitate passage over obstacles on the seabed. Rockhopper groundropes do not rotate; this gear is designed with a wire rope threaded under tension through the large rubber discs, which helps 'spring' the groundrope over obstacles.

Many groundrope designs are used in New Zealand bottom trawl fisheries, although the most common are the cookie groundrope, spherical bobbin groundrope, bobbin groundrope, and rockhopper groundrope. The diameter of the large rubber discs in rockhopper gear ranges from 500-800 mm in the orange roughy fishery (MRAG Americas, 2016).

Dan lenos are a part of the groundrope that serve as an attachment point for the fishing line and lower bridle (Figure 16). They are either triangular or bobbin-shaped and constructed from steel or heavy rubber to protect the attachment point from impact and seabed damage. In some fisheries they are known as bumper bobbins, and they are designed to be in contact with the seabed.

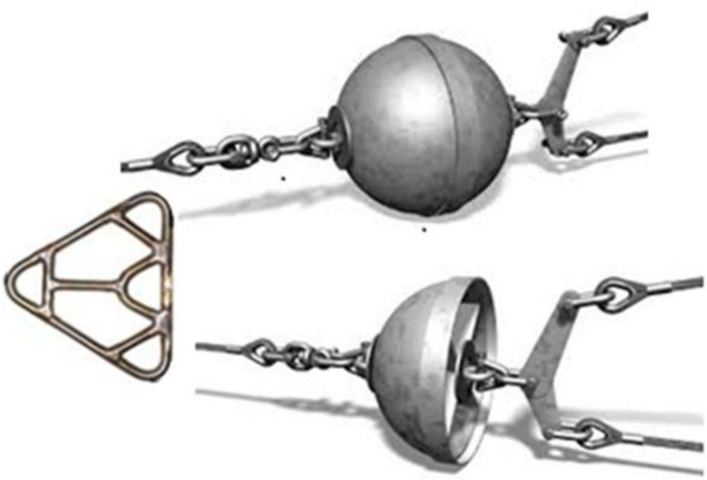

Figure 16. Triangular and bobbin-shaped dan lenos. Source: Larsen *et al*., 2019.

## 4.4 Codends

The codend is designed to retain the catch that has passed through the trawl. It is usually constructed from larger-diameter twine and sometimes from codend twine that is doubled (double braid) prior to mesh construction. In New Zealand bottom trawl fisheries the minimium codend mesh size is 100 mm (Parliamentary Counsel Office, 2017), although some fishers use 110 mm instead (O'Boyle *et al*., 2018).

Codends may contact the seabed intermittently when filled with catch or debris. 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. In some instances the entire codend is protected, particularly when catch depredation by marine mammals and elasmobranchs is a concern. In other fisheries, including those in New Zealand, 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. Little is known about the interplay between codend design and rigging, catch (volume and type), towing speed, and seabed contact.

# 5 Description of habitat impact by bottom trawl gear

Bottom trawling has both direct and indirect effects on seabed and benthic organisms. 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 organisms, 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; O'Neill & Ivanovic, 2016; Clark, *et al*., 2016; Collie *et al*., 2017). An estimated 13.7 million km$^2$ (~50%) of the continental shelf globally has been affected by bottom trawling, and much of this area is trawled multiple times each year (Oberle *et al*., 2016), although in a recent study, Amoroso *et al*. (2018) reported that 86% of a 7.8 million km$^2$ area encompassing 24 continental shelves and slopes (> 1,000 m) around the world was not trawled over a 2-6 year period.

## 5.1 Scraping and ploughing

Scraping and ploughing of the seabed by a bottom trawl is caused by trawl doors, sweeps, lower bridles, the groundrope, and in some circumstances, intermittent contact by the codend. Factors that influence the penetration depth or extent of this impact include gear design, rigging, weight, towing speed, tides and currents, and seabed characteristics. Trawl doors can plough deep furrows in unconsolidated sediment that may be up to 30 cm deep and 20 cm wide (Jones, 1992; Linnane *et al*., 2000; Humborstad *et al*., 2004; Buhl-Mortensen, *et al*., 2013) and compress sediments at the bottom of the furrow (O'Neill & Ivanovic, 2016). They may also produce a sediment berm on either side of each furrow, sometimes measuring up to 10 cm high (Humborstad *et al*., 2004). Whilst furrows may be quickly filled in by natural perturbation in shallow waters (Krost *et al*., 1990), they may also be observable for several months in sandy habitats (Lokkeborg & Fossa, 2011), for 1-2 years in muddy habitats (Ball *et al*., 2000), and in deeper waters, for five years or longer (Jones, 1992; Clark *et al*., 2010). The footprint of trawl doors on the seabed is usually equivalent to less than 10% of the swept width of the groundrope (Ball *et al*., 2002) and 5% or less of the total swept width of the entire trawl system, although they are generally considered to have the greatest impact on seabed sediments compared to other trawl components (Kaiser *et al*., 2003).

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. They are sometimes fitted with rubber discs to increase seabed contact, and while they increase sweep and bridle diameter weight by around 20% (in water), it is unclear if the impact force per unit area is increased or otherwise.

Chain groundropes typically skim or lightly scrape surface sediments, and have 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 groundropes is less than that for trawl doors (Humborstad *et al*., 2004), usually measuring several centimetres in depth (Buhl-Mortensen, *et al*., 2013).

Codend contact may be light and intermittent and thus responsible for scraping of some sediments, and although poorly studied, this impact is considered relatively minor compared to that by other trawl components.

## 5.2 Sediment resuspension

Sediment resuspension is a function of sediment grain size, degree of compaction, tides and 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. Trawl doors are a major contributor to sediment resuspension, which occurs as a result of water turbulence (eddies) behind the trawl doors as they are towed on or near the seabed. The resulting sediment plume is desirable in bottom trawl fishing because it 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 have serious negative ecological impacts, including the release of nutrients or contaminants held in the sediment, vertical redistribution of sediment layers or exposure of anoxic layers, and smothering of epibenthic fauna resulting in compromised feeding, respiration, reproductive capability, and survival rates (Jones, 1992; Kaiser *et al*., 2003; Clark, *et al*., 2016). Not all taxa are equally sensitive to sediment resuspension (Clark, *et al*., 2016), and their recovery is influenced by the extent and persistence of resuspended sediments and biological characteristics of impacted organisms. 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 six months or longer.

## 5.3 Benthic fauna and habitat

All components of a bottom trawl in contact with the seabed can have negative impacts on benthic fauna, including scattering, removal, injury, or mortality. Epibenthic fauna may suffer immediate mortality due to crushing or shearing impact from contact with trawl components, or they may suffer compromised mobility and delayed growth or reproductive capacity as they recover from injury (Clark, *et al*., 2016).

Habitat removal by trawl gear may contribute to increased rates of invertebrate predation due to their exposure and compromised ability to escape or find refuge. Some inverterbrates, such as molluscs, crustaceans, and echinoderms, may also be retained in the codend and discarded overboard as the catch is processed. Some of these individuals may survive catch and release, and in some instances ultimately colonise new areas of seabed, while others suffer depredation or subsequent mortality due to injury. Large-scale and intense removal of some species, such as those that naturally graze on, or modify benthic habitats, 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 faunal biodiversity and catch composition are changed, sometimes severely comromising onceproductive fishing grounds (Jones, 1992; Sainsbury *et al*., 1993). Examples include the removal of emergent, structurally complex habitats that provide food or shelter to target or prey species, such as coral communities, 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; Tuck *et al*., 2017). Species most sensitive to trawl activity are thought to be emergent epifauna such as sponges, bryzoans, hydriods, sea pens, and tube building ploychaetes and, in deepwater, many of these invertebrates are long lived and grow extremely slowly. The recovery of these habitats may take many decades or longer (Clark *et al*., 2016; Fisheries New Zealand, 2018b) although a detailed understanding of the consequences of trawl impact and habitat recovery is limited (Tuck *et al*., 2017). Detailed reviews of published studies and associated meta-analyses are provided in Collie *et al*. (2000), Kaiser *et al*. (2006), and Clark *et al*. (2016).

# 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: (1) reduce fishing effort, (2) establish closed areas, (3) the use of alternative fishing gear, or (4) the modification of existing fishing gear. McConnaughey *et al*. (2020) extended this number to nine, grouped into four classes: technical measures, spatial controls, impact quotas, and effort control (Table 2). All of these options should result in a reduction in habitat impact, to a greater or lesser extent, and improve the relative benthic status (RBS)[5] of the area of concern. Some, however, may result in concentrating fishing effort (intensity) to specific locations or 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 international body of research that has investigated options to modify bottom trawl gear to mitigate seabed contact and habitat impact. Many of these options are designed to reduce the footprint of the trawl by elevating trawl components clear of the seabed. These options are discussed in detail in Section 7. Key to the adoption and use of these options by fishers is that they have minimal impact on the target catch, have limited negative economic impact, and that the capital cost of conversion is quickly recovered through improved access (including security of access) to the fishery, reduced operating costs and/or increased catch value. If catching efficiency is reduced as a result of modification, an unintended consequence of this option may be increased fishing effort to offset reduced catch rates 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 may permit increased fishing time and seabed contact. This weighting of different sustainability criteria is an example of the need for coherent national policy.

Spatial controls serve to eliminate high-impact fishing 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 to mitigate seabed impact providing the target species are vulnerable to the replacement gear. 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 also preclude this as a viable option, particularly if accompanied by a need for substantial vessel modification. Finally, there is also increased risk of gear conflict in areas that remain open to trawling activity, and fishers

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

may increase fishing effort to offset reduced catch rates, thereby eroding the gains associated with replacement of the higher-impact gear.

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 impacted areas |
| | Nearshore restrictions and zoning | Reduce bottom 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 organisms |
| **Effort control** | Removal of fishing effort | Reduce impacts by reducing fishing activity |

Impact quotas serve to reduce habitat impact by placing a cap on the capture of benthic invertebrates or on access to sensitive organisms. Benthic invertebrate quota can incentivise fishers to avoid fishing grounds where high numbers of these animals may be caught by fishing gear, although this option is challenged by a need to establish sustainable levels of invertebrate quota, 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 species.

Fishing effort control is usually applied to limit fishing mortality on fish stocks, but it can also serve to reduce the frequency of bottom trawling impacts on the seabed. In some instances, these controls may result in fishers avoiding certain areas of the fishery, thus having a similar impact as spatial controls. 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 gear modification is poorly understood or unregulated by management authorities. Notably, the application of an individual QMS, such as that used in New Zealand, can similarly reduce bottom trawling impacts on the seabed. Such systems set harvest at sustainable levels and provide fishers a property right for a proportion of the total allowable catch, but an inevitable consequence is fleet rationalisation, reduced fishing effort, 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 mitigate seabed contact and subsequent habitat impact. These attempts are grouped into three categories; (1) trawl door modification, (2) sweep and bridle modification, and (3) groundrope modification. They are based on knowledge of trawl gear operation and supported by relevant scientific and grey literature. Many of these modifications are relevant to New Zealand bottom trawl fisheries and can conceivably be applied by local trawl fishers. Some, however, are not immediately applicable, requiring substantial financial investment and time to introduce and operate effectively, while several others are not considered applicable but are provided to evoke consideration of new and innovative ideas to mitigate seabed contact.

Summaries of key literature describing modification of trawl gear to mitigate seabed contact are provided in Appendix A – Trawl door modification, Appendix B – Sweep and bridle modification, and Appendix C – Groundrope modification.

## 7.1 Trawl door modification

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

- Reduced warp to depth ratio
- Increased towing speed
- Adjust trawl door heel and tilt
- Lighter trawl door materials
- Reduced angle of attack
- Semi-pelagic trawl doors
- Controllable trawl doors

### 7.1.1 Warp to depth ratio

This ratio describes the length of wire (warp) used to tow a bottom trawl in a given depth of water. It influences how closely the trawl door and other trawl components contact the seabed, trawl door stablity, 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 1,000 m of water. These ratios may differ somewhat between fishers because towing speed, tide, 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’, and this might include using a higher warp to depth ratio to ensure close and persistent seabed[6] contact. Fishers may also choose to reduce this ratio where close seabed contact 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 New Zealand fisheries where the target species cannot be herded into the path of the approaching trawl, for example prawn or scampi, this speed is generally around 2-4 knots (1.0-2.1 $ms^{-1}$). In these fisheries catch rates are proportional to trawl door 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 2-5 knots (1.0-2.6 $ms^{-1}$), and sometimes higher (Valdemarsen *et al*., 2007).

If towing speed is too slow, trawl door stability may be compromised and they may fall over, perhaps becoming bogged and difficult to dislodge from the seabed. If towing speed is too fast, the trawl doors may lose bottom contact resulting in a reduction in the sediment plume. They may also lift the anterior section of the sweeps clear of the seabed, resulting in reduced catching efficiency and fish loss from the trawl. In extreme instances, excessive towing speed can result in the entire sweep, the lower bridles, and the groundrope 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 these forces increase to such an extent that the trawl is lifted clear of the seabed.

### 7.1.3 Trawl door heel and tilt

Fishers sometimes adjust the heel and tilt of a trawl door (Figure 17) with trawl door stability, seabed contact, and catching efficiency in mind. Heel and tilt are influenced by the amount of trawl warp that is used, towing speed, and trawl door rigging (FAO, 1974; SEAFISH *et al*., 1993). Outward heel ensures that hydrodynamic forces[7] acting on the trawl door has a downward component that helps keep it in close contact with the seabed. Conversely, inward heel may result in less contact because the hydrodynamic forces are attempting to lift the door 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 attachment point where the warp is connected to the trawl door or increasing towing speed are options to help overcome inward heel.

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[6] 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 trawl doors on the seabed ($F_D$). This relationship can be expressed by, $F_D = W - F_U = W - T.\sin(\propto)$, where W = trawl door weight in water and T = warp tension.

[7] Hydrodynamic forces are produced as a result of towing a trawl door through the water. They include an outward spreading force (lift), which is needed to open the trawl net horizontally, and a drag force. The magnitude of these forces depends on towing speed, door size, weight, shape (design), heel and tilt, angle of attack, and substrate type.

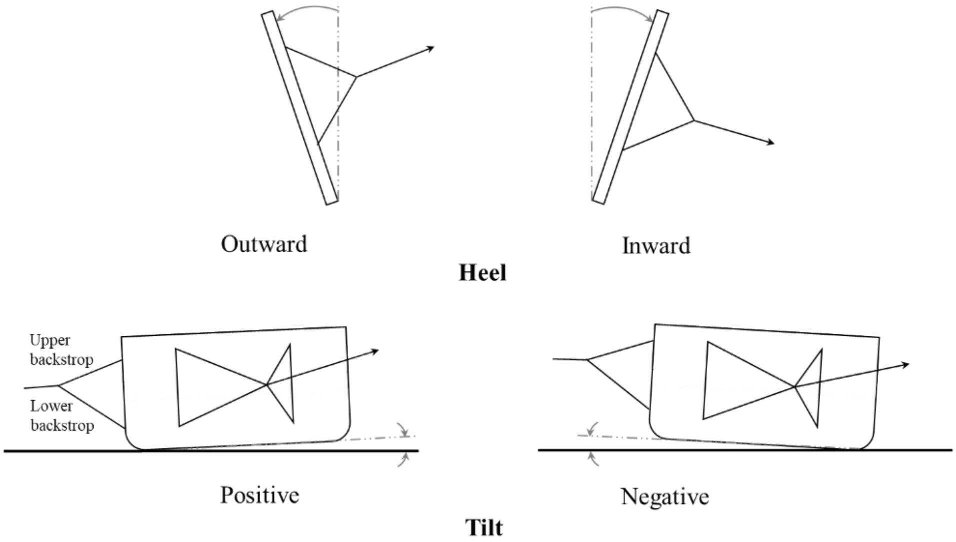


Figure 17. Trawl door heel and tilt. Source: FAO, 1974.

Trawl door tilt (or pitch) can be negative or positive. Negative tilt results in the leading edge of the trawl door digging in or "snubbing" on the seabed. This can be overcome by reducing warp length, raising the towing point on the trawl door, increasing trawl door weight, or reducing towing speed. Adjustment to backstrop chains may have limited or no impact on tilt depending on trawl door design (SEAFISH *et al*., 1993). Slight positive tilt is usually desirable as it facilitates the passage of the door over obstacles on the seabed and may result in less seabed contact. How a trawl door is contacting the seabed can at least be partially explained by inspecting the polish on the underside of the trawl door shoe.

### 7.1.4 Lighter trawl door materials

All things held equal, the use of a lighter trawl door translates to lighter seabed contact and less scraping and ploughing of seabed sediments. Reducing trawl door weight can be achieved by removing any weights attached to the shoe of the door, or by using lighter construction materials.

Fishers usually add weights to the shoe of the door to facilitate rapid sinking of the trawl, improve door stability in the water column, or on the seabed, and ensure they closely contact the seabed. These weights may weigh 50-100 kg per trawl door or more for larger doors. While these weights can easily be removed, their removal may provide little or no appreciable reduction in seabed contact given the extent and magnitude of this contact is strongly influenced by environmental factors such as tide, currents, and variation in seabed smoothness and composition. In shallow water, wind, sea, swell, and tide can affect vessel motion and contribute to intermittent loss of seabed contact. Fishers can also readily overcome the influence of lighter trawl doors by increasing warp to depth ratio, reducing towing speed, adding weight to the groundrope, or adjusting groundrope rigging.

Trawl doors are typically constructed from steel and may each weigh several hundred kilograms to several thousand kilograms depending on the engine power of the vessel. In the New Zealand deepwater fishery, some vessels tow trawl doors that weigh 2,000 kg in air with a surface area up to 8 m$^2$ (Clark *et al*., 2016; MRAG Americas, 2016). In water, however, these doors lose around 13% of their in-air weight because they are subject to an upward buoyancy force.

Further reductions in door weight 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 is to insert high density foam inside a steel shell, which reduces door weight in water by up to 83% compared to their weight in air (NET Systems, n.d.)(Plate 4). While these doors are designed for midwater (pelagic) operations, the manufacturers suggest their operation in contact with the seabed is a feasible option.


Plate 4. Lightweight trawl doors by NET Systems. Source: NET Systems (n.d.).

### 7.1.5 Angle of attack

Angle of attack can be defined as the angle of the trawl door relative to the forward direction as it is towed through the water (Figure 18). This angle is the result of all forces acting on the trawl door, including hydrodynamic forces, seabed friction, shear, and ploughing. At higher angles the width of the doors footprint is increased, all things held equal. The profile area of the door is also increased, resulting in higher fuel consumption[8]. In many bottom trawl fisheries, fishers have gravitated towards using more hydrodynamically efficient[9] trawl door designs, either to spread larger nets or reduce fuel consumption. These doors include high-aspect ratio, multi-foil designs that are operated at an angle of attack between 20-30°, where the lift to drag ratio is close to maximum[10]. Less efficient trawl doors, such as rectangular flat or vee doors, are usually operated at angles in excess of 30°, noting they are far more stable at this angle, especially when shooting, turning sharply or in strong cross currents. At 20° the trawl door footprint is equivalent to just over 1/3rd of trawl door length, and half of trawl door length when operated at 30° (Plate 5).

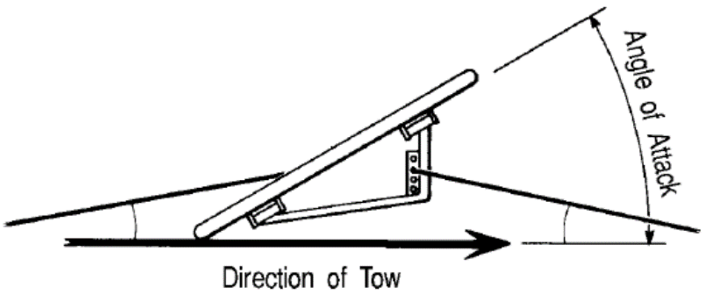


Figure 18. Trawl door angle of attack. Source: SEAFISH *et al*., 1993.

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 trawl door stability and performance. One notable exception is the batwing trawl door (Plate 5, Figure 19), designed with a flexible foil restricted to an angle of attack of around 20° (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 doors is equivalent to the width of the framework shoe. This trawl door was designed for use in a tropical prawn trawl fishery in Australia, and has not been widely adopted by prawn fishers elsewhere. This trawl door reduces bottom contact by approximately 86% compared to conventional trawl doors, and reduces drag by approximately 18%.

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[8] Fuel consumption is the penalty associated with overcoming drag forces acting on the trawl. Drag is proportional to the profile area of the trawl door, the square of towing speed, and door shape, all things held equal.

[9] A measure of the lift to drag ratio produced by a trawl door at a given angle of attack.

[10] Reviews of trawl door 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).


Plate 5. The effect of angle of attack on the swept width (footprint) of trawl doors. The flat rectangular trawl door on the left is operating at an angle of attack in excess of 30º and the 'batwing' trawl door on the left is operating at around 20º. Source: Sterling and Eayrs, 2010.

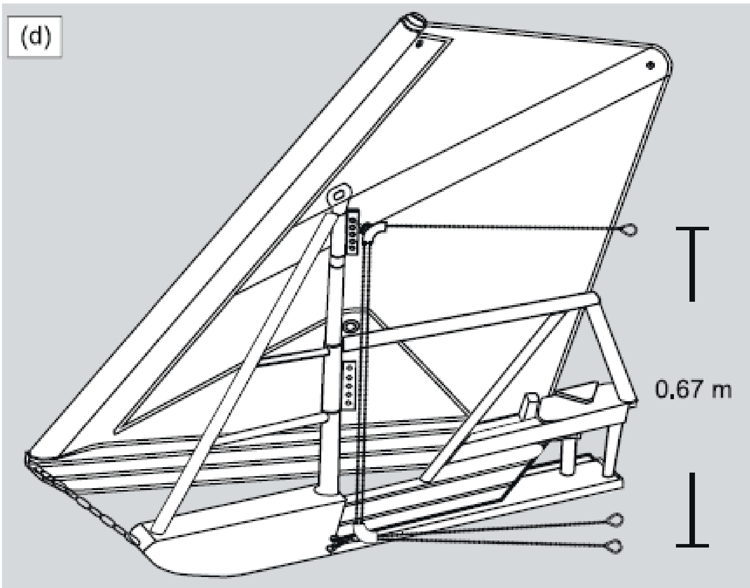


Figure 19. The batwing trawl door. The bottom of the foil is hinged to the towing frame and a chain at the leading edge restricts angle of attack. Source: McHugh *et al.*, 2015.

### 7.1.6 Semi-pelagic trawl doors

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

Several efforts have been made to evaluate the performance of trawl doors in fisheries targeting shrimp (DeLouche & Legge, 2004; He *et al*., 2006) and fish (Eayrs *et al*., 2012; Eayrs, 2014a, 2014b; He, 2014; Jones, 2014). These efforts have usually involved the replacement of conventional bottom-tending trawl doors, with little or no modification to sweeps or other gear components. Additional efforts using semi-pelagic trawl doors 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 trawl doors are clear of the seabed, less towing warp can be used compared to that when using bottom-tending trawl doors. Acoustic monitoring sensors[11] attached to each trawl door can be used to monitor their height above the seabed, and warp length adjusted to either raise or lower the trawl doors. The dynamic movement of other trawl components may result in fluctuation in trawl door height, as may movement of the vessel in a sea or swell, particularly in shallower waters. Sometimes this fluctuation may result in the trawl doors briefly rising to five metres or more above the seabed (CRISP, 2017).

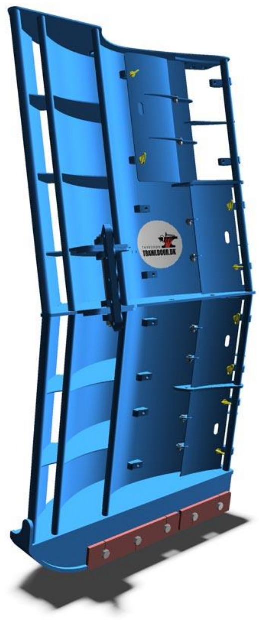

Figure 20. Semi-pelagic trawl door constructed by Thyborøn Skibssmedia A/S. Source: http://thyboron-trawldoor.dk/products/semipelagic-trawldoors/.

[11] Acoustic sensors are more commonly found on larger vessels as their cost is often prohibitive for smaller vessels. A basic suite of senors comprising trawl door distance (spread) sensors, a headline height sensor, hydrophone (transducer), and wheelhouse display can easily reach NZD$100,000, or more, particularly for vessels operating in deepwater. This is in addition to the cost of a set of trawl doors, net, warps, sweeps, bridles, groundgear, codend, and floats, which may reach NZD$50,000 or more on smaller vessels, and over NZD$100,000 on larger vessels.

In the study reported by Eayrs *et al*. (2012) and Eayrs (2014a), the fisher simply replaced bottom-tending trawl doors with semi-pelagic trawl doors, and made no changes to warp to depth ratio. While the absence of scratch marks and polish on the bottom of the trawl door shoe indicated that 95% of the shoe was clear of the seabed (Plate 6), the remainder was clearly in seabed contact. Acoustic sensors were not used by the fisher to monitor seabed clearance, as reduction of fuel consumption was the primary reason for using these trawl doors. Underwater video of these trawl doors is available at https://www.youtube.com/watch?v=NzOndGXJRiU. The fisher involved in this study was using these trawl doors for several years prior, and continues to do so to this day. In the study reported by Jones (2014), a 95% reduction in shoe contact was also recorded. An additional sweep wire and a heavy weight was attached between the conventional sweep and trawl door. Fuel consumption was reduced by an average of 16%, although catch loss was susbtantial. This was a pilot study funded by NIWA, using semi-pelagic trawl doors previously purchased by a commerical fisher. It was also the first known study of its type in New Zealand, and whilst testing was limited and catch rates were low, it serves to demonstrate the potential local application of semi-pelagic doors. Anecdotal evidence suggests there was little industry appetite at that time to build on the results and test the doors more thoroughly.

Plate 6. Shoe of a semi-pelagic trawl door indicating wear ('polish) on the bottom of the shoe. This door appears to have been heeling inward slightly, with positive tilt.

Fuel savings are often reported as a result of using these trawl doors, although this may also be accompanied by catch loss, particularly if the trawl doors lift the anterior section of sweep clear of the seabed. Some 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 trawl door drag to the total drag of all trawl components combined. Despite the risk of catch loss, these trawl doors are increasingly being used by fishers, particularly in industrial fisheries in North America and Europe to reduce fuel consumption.

### 7.1.7 Controllable trawl doors

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


Figure 21. Controllable trawl doors. By opening the upper vents and leaving the lower vents closed, trawl door height above the seabed is increased. Source: Notus electronics.

The extent of use of these trawl doors is unknown, and may be limited by the capital cost of new trawl doors and associated acoustic equipment. There are also challenges with variable acoustic communication between vessel and doors (CRISP, 2016) although some fishers have already transitioned and are regularly using these doors (Hansen, 2018). Excellent videos describing the design and operation of these doors, including underwater animation, are available at:

- https://www.youtube.com/watch?v=Mk0BlS_lalU
- https://www.youtube.com/watch?v=KNCqMLImC7Y
- Additional information and videos are available at http://mld.one/

### 7.1.8 Other trawl door options

Over the years several innovative trawl door 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 trawl door (Figure 22). Known as the Hong Kong device, one ball was located near the leading edge of the door 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 door. The leading ball measured 220 mm in diameter and the trailing ball measured 180 mm in diameter, and each cradle was suspended from 300 mm chain droppers. A horizontal buoyancy chamber was also attached to the trawl door, filled with polyurethane foam. This chamber rendered the trawl door 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 trawl door was used, and there is no evidence of it in use today.

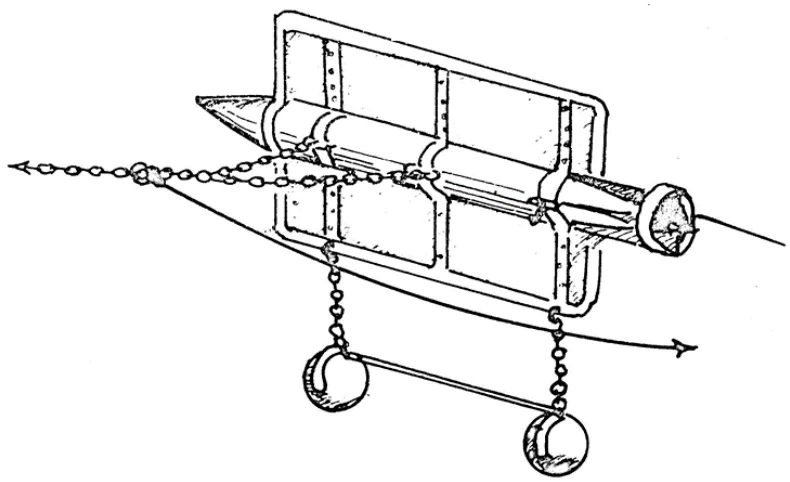

Figure 22. Floating trawl door or Hong Kong Device. Source: Garner, 1978.

A similar and more recent attempt to produce a door with components that rolled over the seabed was the Le Beon Panneau a Roue Type LBR (SEAFISH *et al*., 1993). This was designed with a large steel wheel attached to the leading edge of a foil and a small steel ball attached to the inside of the foil (Figure 23). No evidence describing the purpose of the large wheel has been found although it is likely to have been designed to roll as the trawl door was towed forward. As the small steel ball rotated around a horizontal axle, it probably served to stablise the door and prevent it falling inward. It is unknown if this door was towed at low angles of attack, although this would appear to be a logical outcome in order for the large wheel to rotate. There is no evidence to suggest this door was widely used, and it was likely to have been cumbersome and difficult to use and stow onboard.

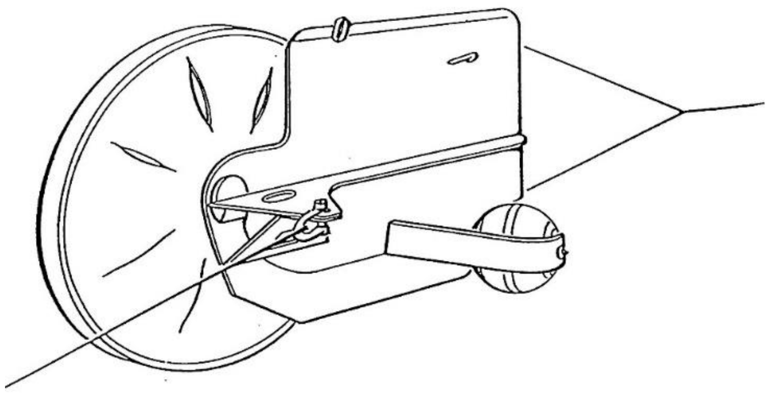

Figure 23. Le Beon Panneau a Roue Type LBR trawl door. Source: SEAFISH *et al*., 1993.

## 7.2 Sweep and bridle modification

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

1. Reduce sweep and bridle diameter and weight per unit length
2. Use shorter sweeps and bridles
3. 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 constructed from strands of steel wire rope covered with polypropylene fibre twisted together to form a rope. The diameter of sweeps and bridles may range from 25-75 mm on small vessels and up to 100 mm or more on larger vessels; sometimes they are made from the same wire used to construct towing warps. 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 ploughing or snubbing of trawl components on the seabed.

In some fisheries, including in New Zealand, sweeps and lower bridles are covered in a plastic hose to protect them from abrasion and damage. In other fisheries they are covered in small rubber discs (cookies), which also serve to increase their weight to maintain bottom contact. The diameter of these discs is typically 75-150 mm, and they may be used along the entire sweep or bridle length. It is unclear if the additional surface area and weight results in deeper penetration of the seabed or greater damage to benthic organisms. 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 than 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 an estimated 0.1-0.6 m. In a similar study, Guyonnet *et al*. (2008) replaced sweeps with lightweight ropes fitted 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.

In some fisheries, increasing the diameter of sweeps and bridles with plastic hose or rubber discs is thought to reduce their impact per unit area on the seabed and benthic fauna. No confirmation of this assertion could be found in the literature, and it remains unclear if this modification is beneficial or otherwise.

### 7.2.2 Shorter sweeps and bridles

This modification is sometimes used by fishers to improve trawl manoeuvrability and responsiveness, particularly when trawling over hard seabed, in the vicinity of reefs, or on underwater tophograhpical features (UTFs) such as seamounts. This reduces the likelihood of trawl components contacting the seabed, potential hookups, 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.

All things held equal, the use of shorter sweeps and bridles means a proportional reduction in the swept width of the sweep and bridle, e.g. if sweep length is halved then 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, or they panic and escape over the 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 trawl doors 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) 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 seagrass, sponges, and corals.

A similar option is the use of helical or helix ropes (Plate 7). These are in effect two ropes bound together, comprising a small diameter rope twisted around the surface of a 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 ropes surface. These ropes are also positively buoyant. They 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 their lift allows for the use of smaller trawl doors, headline flotation, and foot rope weights. While there is some evidence of these ropes being used in midwater trawl fisheries around the world, no evidence could be found indicating their use as replacement sweeps and lower 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 concerns over their cost, increased bulkiness, and impact on trawl handling and catch rates. There is also a lack of unequivocal evidence suggesting these ropes can adequately lift sweeps and lower bridles clear of the seabed.


Plate 7. Helical ropes. Source: Kebede *et al*. (2020).

The second option is to fit the sweeps and lower bridles with large rubber discs (Plate 8). 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 15, 20, and 25 cm in diameter, and respectively they raised the clearance of the sweep and lower bridle by 5, 7.5, and 10 cm above the seabed.

These discs reduced sweep and lowered bridle contact by 95% compared to convention sweeps and bridles, and there was no significant difference in the catch ratio (control sweeps/modified sweeps) of flatfish and Pacific cod (*Gadus macrocephalus*) using the 15 cm and 20 cm discs. The loss of flatfish using the 25 cm discs was 5-10%, and they also significantly reduced the damage and mortality of sea whips (*Halipterus* sp.) and crabs (*Chionoecetes bardi*, *C. opilio*, and *Paralithodes camtschaticus*).

Evidence suggests that the impact of this modification on the commercial catch is influenced by variation in ambient light levels, with higher escape rates of fish during the daytime (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).

Plate 8. Cluster discs attached to trawl sweeps. Source: J. Gauvin. Alaska Seafood Cooperative.

The final option is to use semi-pelagic trawl doors to lift some or all of the sweeps clear of the seabed (Figure 24). This option involves the use of high aspect ratio trawl doors and a clump weight to ensure some or all of the sweep is in contact with the seabed. Underwater animated video 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 cod catch when sweeps were partially lifted clear of the seabed. This is to be expected given the ability of the doors and sweeps to herd fish towards the approaching trawl is now compromised, and while not reported, the heavy clump weights presumably resulted in ploughing of seabed sediments and significant impact on the seabed.

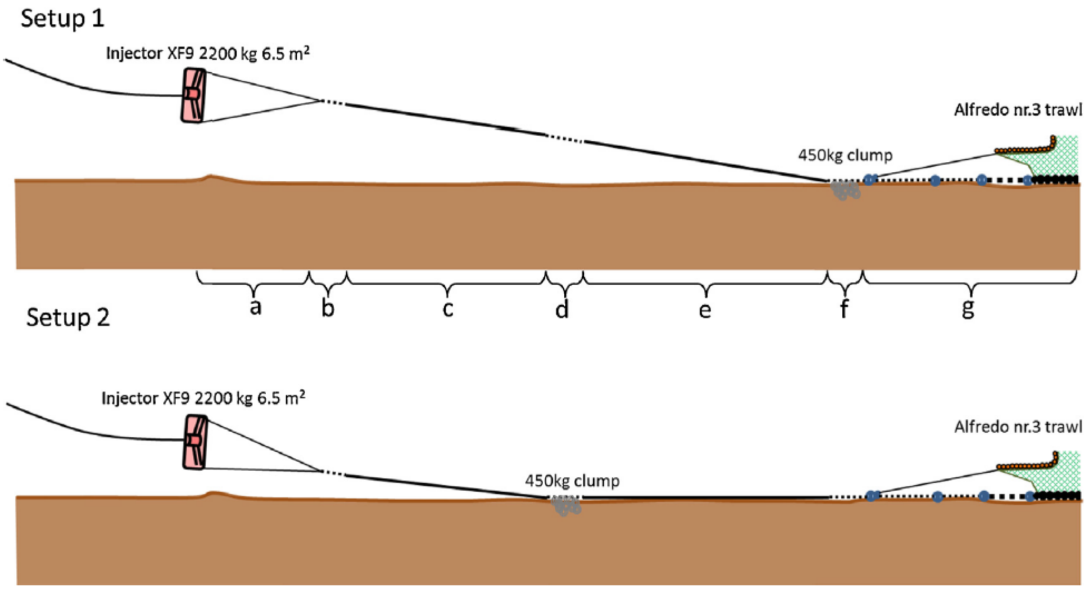


Figure 24. Experimental trawl gear (Setup 1 and 2). (a) 15.9 m backstrop, (b) 3 m backstrop extension, (c) 30 m of 30 mm sweep, (d) 4 m of 19 mm chain (attaching position for the clumps), (e) 45 m of 30 mm sweeps, (f) 4 m of 19 mm chain (attaching position for the clumps), (g) 45 m of groundrope composed of 19 mm chain (32 mm chain closest to the rockhopper), and the rockhopper. Source: Sistiaga *et al*., 2015.

## 7.3 Groundrope modifications

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

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

### 7.3.1 Reduce groundrope weight

Reducing the weight of the groundrope seems like an obvious option to reduce seabed contact and penetration of substrates. In New Zealand deepwater fisheries the groudrope may weigh several tonnes (Clark *et al*., 2016), although this weight is often necessary to keep the groundrope in contact with the seabed (Valdemarsen *et al*., 2007; He & Winger, 2010) and to minimise the escape of fish underneath the groundrope and trawl net. In shallow waters, this can be a significant issue as the motion of the vessel in heavy seas can result in lost bottom contact and significant catch loss.

Relatively few efforts appear to have been made to replace heavy with lighter groundropes without making other changes to the trawl, such as rigging changes to operate the trawl semi-pelagically (see

7.3.5 and 7.3.6 below for details). In a notable exception, He (2001) reduced the weight of the groundrope in a pandalid shrimp trawl by 56%, and measured a 69% reduction in seabed contact without loss of catch. In heavy weather, however, an identified issue was loss of seabed contact and gear damage using the lighter groundrope.

### 7.3.2 Distance between rubber bobbins

Increasing the distance between bobbins serves to reduce the number of bobbins in contact with the seabed, but it will also reduce the overall weight of the groundrope. It is likely however, to result in loss of catch because the space 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 those aligned with the direction of tow, or to use steel rollers (Plate 9). The use of aligned bobbins is an attempt to overcome the scouring action of conventional bobbins as they are dragged laterally over the seabed. Scouring action results in signficant 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 groundrope spread. It is also unknown how sensitive this gear is to variations in groundrope spread that can be expected during each tow and over the range of normal operating conditions.

Air-filled steel rollers or bobbins are designed to roll over the seabed and reduce the scouring action of rubber discs and associated sediment resuspension. They also lose up to 85% of their weight in air (Larsen *et al*., 2019) and have been found to reduce fuel consumption by as much as 12% (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 comprises of nylon brushes that are cylindrical in shape (Plate 10). They are located between the rubber discs in a groundrope to ensure the fishing line remains clear of the seabed. Apparently this gear also eliminates the scouring action of rubber discs and significantly reduces sediment resuspension. Concerns over increased catching efficiency and the escape of small fish and other non-target species has resulted in this gear being banned in the United States, despite claims of reduced seabed impact (Cascorbi & Stevens, 2004).

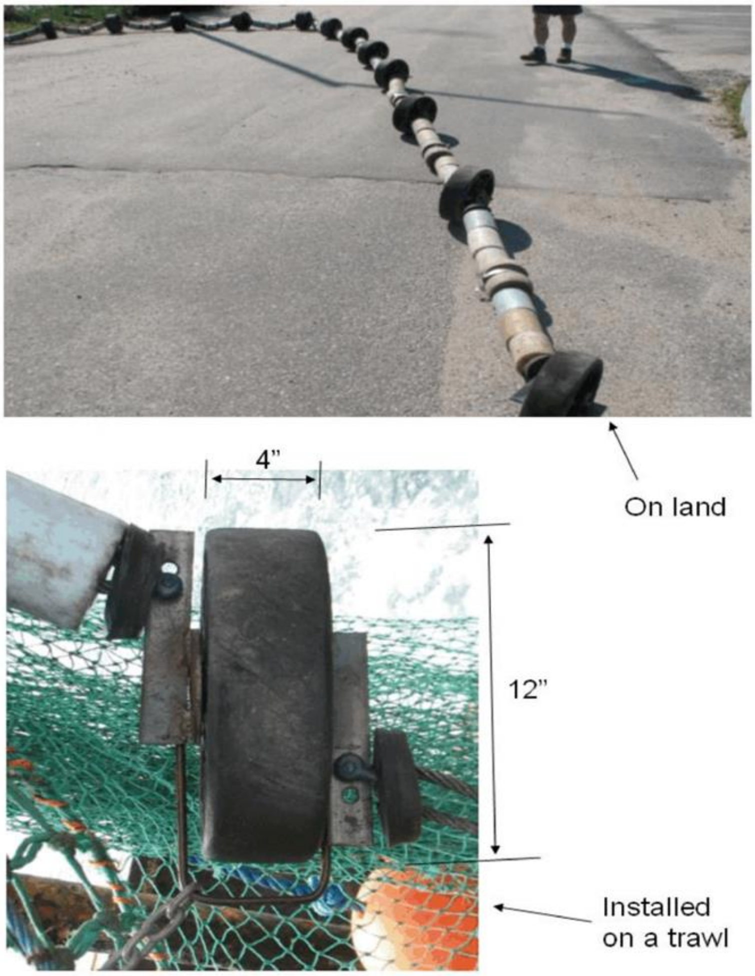


Plate 9. Aligned groundrope. Source: He & Balzano, 2010.

Plate 10. Street sweeper gear. Source: Mike Pol, Massachusetts DMF.

### 7.3.4 Plate gear

This is a novel concept consisting of a series of 50 cm x 50 cm rubber or plastic plates (Plate 11) that replace the conventional groundrope along the quarters and wings of the net (Valdemarsen & Hansen, 2004). The aim of this gear is to reduce trawl drag and seabed contact, reduce catch loss under the trawl, and improve the handling ability of the trawl net.

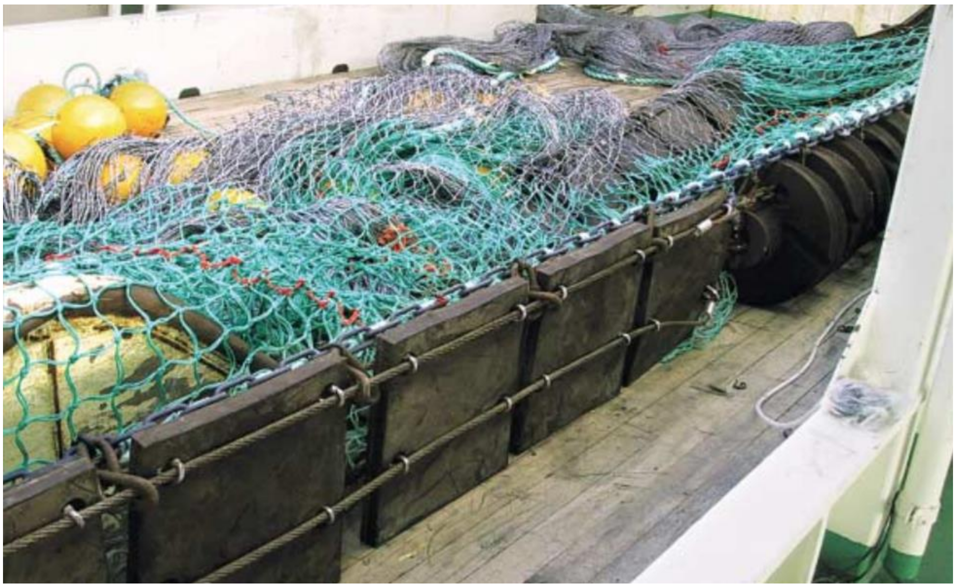

Plate 11. Plate gear. Source: Valdemarsen & Hansen, 2004.

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 groundrope reduced drag by 4% and increased wingend spread by 13% compared to a conventional groundrope (Valdemarsen & Hansen, 2004). 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 a net drum.

Conceivably, plate groundropes simply glide 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 groundrope in seabed contact is possibly higher than that for conventional groundropes using rubber discs, although the anticipated increase in wingend spread conceivably means smaller trawl doors are required to spread open the trawl, with a concomitant reduction in door weight and substate penetration.

A similar modification is the use of semi-circular plates (Plate 12) to replace conventional groundropes. These plates were initially used by Grimaldo *et al*. (2013) to reduce fuel consumption and environmental emissions, and subsequently tested by Brinkhof *et al*. (2017) to evaluate catch loss underneath the foot rope and 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 groundrope was 30% lighter in water compared to the conventional gear, and underwater observations indicated substantially smaller sand clouds, indicative of less seabed disturbance. This groundrope also returned sooner to the seabed following encounter with large obstacles. Trawl door spread was increased by an average of 7% (Grimaldo *et al*., 2013) and the catching efficiency of Atlantic cod above 56 cm was increased by up to 22% (Brinkhof *et al*., 2017).

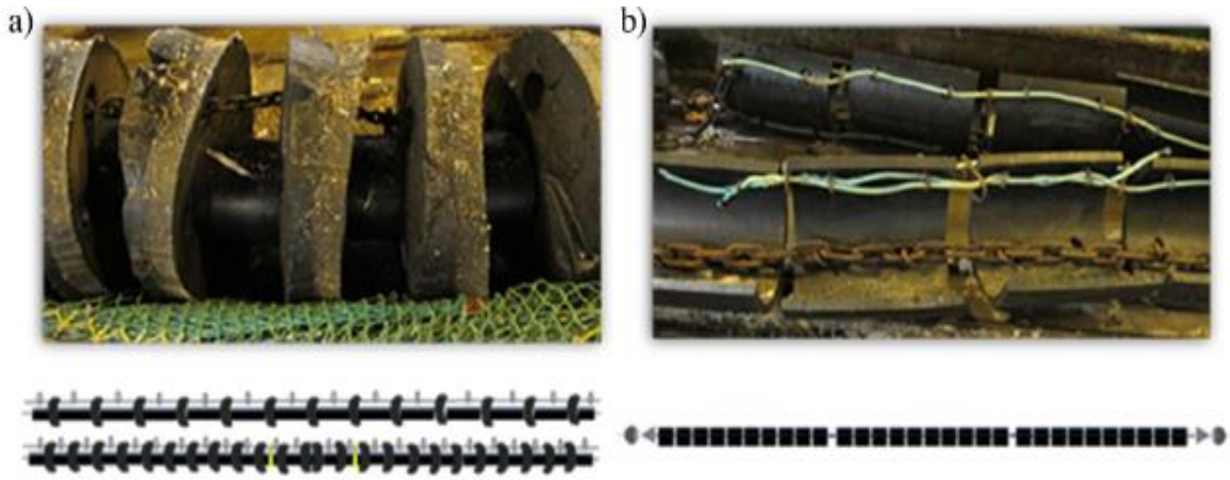


Plate 12. a) Conventional rock hopper groundrope and b) semi-circular spreading gear. Source: Brinkhof *et al*., 2017.

### 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. Groundropes, if used with this trawl, are typically very light. Heavy weights may be attached to the lower wingends, and sometimes a small number of additional weights are attached along the fishing line. In contrast to bottom trawls, the upper bridle (or fly wire) is lengthened and attached directly to the towing warp (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.

It is thought this style of trawl was designed to land fish located a short distance above the seabed, particularly on 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 is little evidence of widespread commercial use of this trawl.

However, in recent years some interest has been shown in this trawl to reduce seabed contact (He & Winger, 2010). This trawl has been tested successfully in an inshore groundfish fishery off the South West English coast, with the trawl fishing line 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 Anne' trawl, was tested in a fishery targeting mainly *Lutjanus* spp. in Northern Australia (Ramm *et al*., 1993). This was a four-seam trawl with equal headline and fishing line 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 fishingline. The fly wire was attached to the warp wires 37 m ahead of the trawl doors. 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 trawl were similar but catches of benthic invertebrates were significantly reduced. Underwater video indicated trawl wingends were approximately 1 m clear of the seabed and 0.3 m in the center of the fishing line. 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.

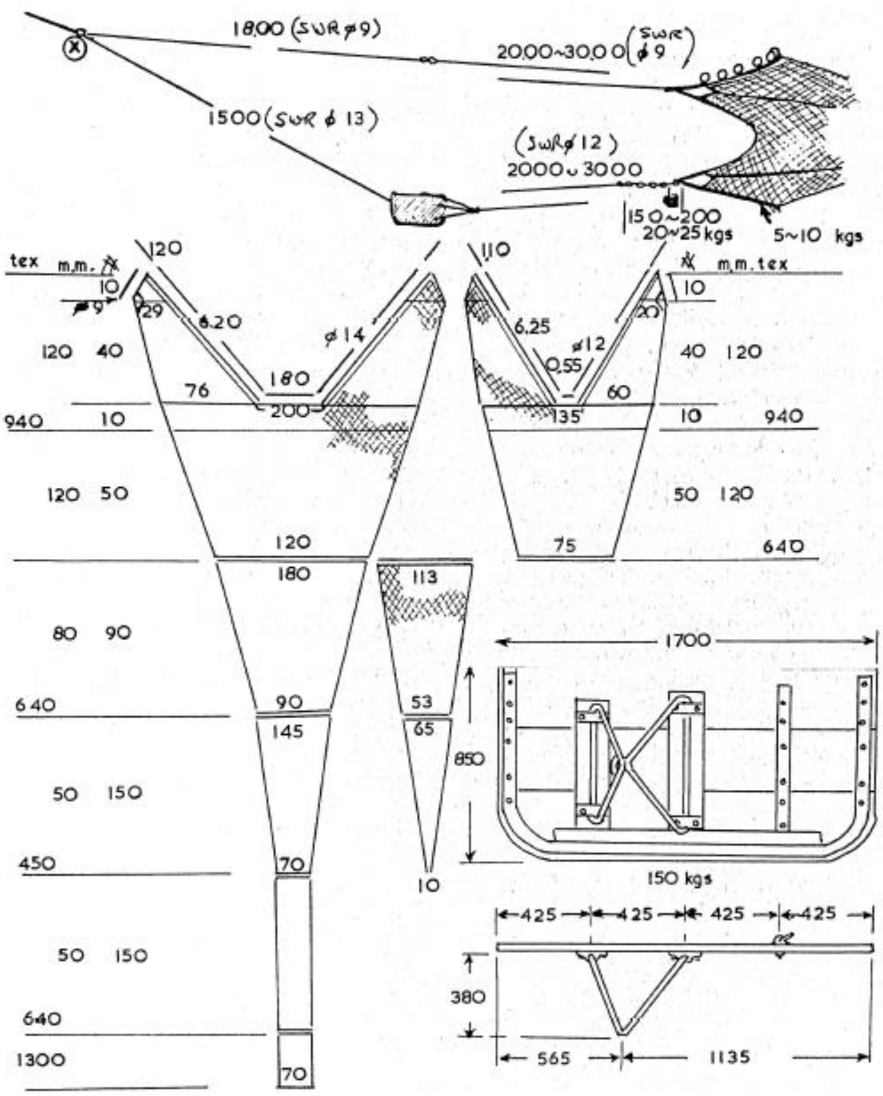


Figure 25. A detailed net and rigging plan for a semi-pelagic trawl. Note the upper bridle is lengthened and attached directly to the towing warp. Source: Garner, 1978.

### 7.3.6 Raised fishing lines and drop chains

Several attempts have been made to remove the groundrope and elevate the fishing line clear of the seabed. In the North Eastern United States, a raised fishing line trawl and a so-called 'sweepless'[12] trawl have been tested in the whiting (*Merluccius bilinearis*) fishery in the Gulf of Maine (Figure 26). The raised fishing line trawl replaces the groundrope with a long horizontal chain connected to the fishing line via 1 m long drop chains (Shepard *et al*., 2004). The sweepless trawl is similar to the raised fishing line trawl with the exception that the horizontal chain is removed. In the absence of the groundrope, numerous 1 m long drop chains were attached to the fishing line, and the desired fishing line 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 has confirmed retention of whiting while reducing catches of non-target flatfish (Shepard *et al*., 2004). Fishing line height was 30-60 cm above the seabed. The 'sweepless' trawl is now mandated for use in the whiting fishery, based on a demonstrable reduction in non-target fish.

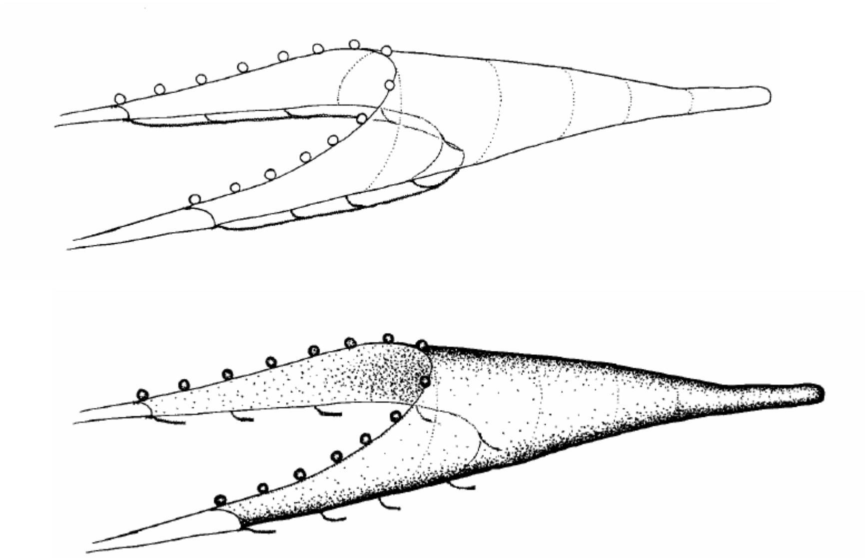

Figure 26. The raised footrope trawl (upper) and the 'sweepless' trawl (lower). Source: Shepard *et al*., 2004.

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 (see 7.3.5) and to simplify rigging and handling. The conventional groundrope was replaced with five dropper chains with weights attached (Figure 27). Bridles and sweeps were kept short to improve manoeuvrability and control, and trawl doors were selected 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 the

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

target species. This trawl is currently not being used in the fishery, and in fisheries where flatfish are the target species, or comprise a significant proportion of total catch landings, these trawls are not an option due to the escape of these species beneath the fishing line.

Drop chains have also been tested in an Australian prawn trawl fishery. Known as a soft-brush groundrope, the traditional 'Texas' drop ground chain arrangement (Plate 13) was replaced with a 6 mm diameter high performance polyethylene rope threaded through 74 oval floats measuring 90 mm long with a 60 mm diameter (Broadhurst *et al*., 2015). The 'Texas' drop ground chain is usually a few chain links shorter than the fishing line in order to stimulate prawns from the seabed and into the trawl.

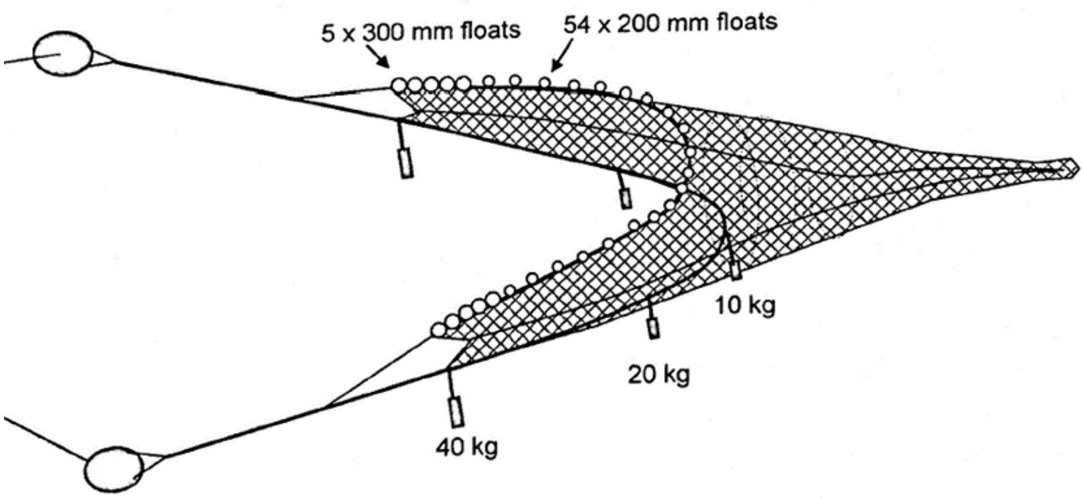


Figure 27. Semi-pelagic trawl with groundrope replaced with weights. Source: Brewer *et a*l., 1996.

Plate 13. Typical 'Texas' drop ground chain arrangement. Source: Sterling, 2008.

The polyethylene rope was approximately 4% shorter than the fishing line, 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 28. Soft-brush groundrope. Source: Broadhurst et al., 2015. & Plate 14). An identical dropper chain was attached to the center of each float using plastic zip-ties. Four out of five floats were drilled to achieve neutral buoyancy, and the groundrope attached to the shoes of a beam trawl 100 mm above the seabed. These modifications resulted in the rope floating suspended above the seabed and approximately 160 mm of each chain dropper in contact with the seabed. This groundrope reduced seabed contact by 63% compared to a conventional groundrope, 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.

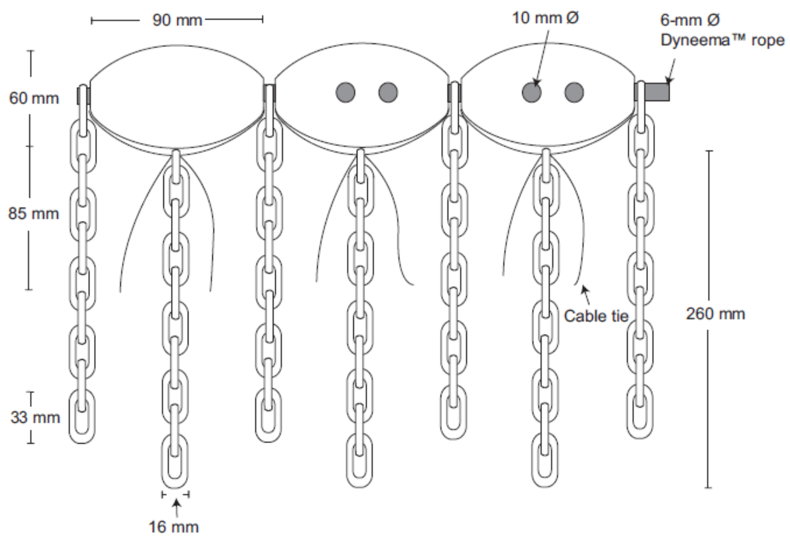


Figure 28. Soft-brush groundrope. Source: Broadhurst et al., 2015.

Plate 14. Soft-brush groundrope 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 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 New Zealand 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; *Trawl door*, *Sweeps and bridles*, and the *Groundrope*, compared relative to conventional bottom 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.

## 8.1 Relative merits of each gear modification

The most effective modifications to mitigate seabed contact by trawl doors are semi-pelagic trawl doors or controllable trawl doors. Both options have the potential to reduce seabed contact by at least 95% compared to coventional trawl doors. Their impact on the catch should also be low, unless they also lift the forward section of sweeps clear of the seabed. They are inherently fuel efficient, and when used clear of the seabed, further fuel savings are realised due to eliminating seabed friction and ploughing. The cost of semi-pelagic trawl doors can reach NZD$20,000 or more depending on size, although there is evidence that the amortization (pay back) period for these doors may be less than one year in some circumstances.

Controllable trawl doors have the potential to allow full control over their position in the water column, and to readily adjust headline height and wingend spread. These doors have only recently been developed in Europe and there is not yet evidence of their widespread use by fishers. There is evidence of ongoing issues with the acoustic connection between vessel and doors and their cost is likely to be significantly higher than that for semi-pelagic trawl doors. Their complexity also challenges immediacy of application and ease of use. Many of the remaining trawl door options can be readily applied by fishers and do not require significant financial outlay. However, there is no evidence to suggest that the application of these modifications consistently and persistently reduces seabed contact, and their fuel saving potential is modest at best.

The use of buoyant materials to increase flotation, cluster discs, or the use of semi-pelagic trawl doors appear to be the most effective options in reducing seabed contact by sweeps and lower bridles. Increasing 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, with no recorded concerns over handling and operation of these modifications.

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

| GEAR CATEGORY & PROPOSED MODIFICATION | OPERATIONAL CONSIDERATION | | | | | |
|---|---|---|---|---|---|---|
| | Reduction in Seabed Contact | Impact on Catch | Fuel Saving | Capital Cost | Immediacy of application[1] | Ease of use[2] |
| *Trawl doors* | | | | | | |
| Reduced warp to depth ratio | L | L | L | L | H | H |
| Increased towing speed | L | M | L | L | H | H |
| Adjusted trawl door 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 trawl doors | H | L | H | H | L | M |
| Use of controllable trawl doors | 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 trawl doors | H | M | H | H | L | L |
| *Groundropes* | | | | | | |
| Reduced groundrope 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 groundropes | M | L | M | M | L | M |
| Semi-pelagic trawl | H | H | H | H | L | L |
| Raised fishing line 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.

At least one fishery in the USA has now mandated the use of cluster discs. A significant reduction in seabed contact will be achieved using semi-pelagic trawl doors to deliberately lift the forward section of sweeps clear of the seabed. Whilst this is an improvement in terms of seabed contact, it is likely to result in significant catch loss. There is only anecdotal evidence supporting the use of shorter sweeps and bridles to reduce seabed contact, although intuitively there is not reason to doubt its efficacy compared to conventional sweeps and bridles. With the exeption of cluster discs and anecdotal reports regarding shorter sweeps and bridles, there is limited evidence to suggest that the remaining options significantly reduce the impact of sweeps and bridles on the seabed.

The most effective groundrope options appears to be the use of a semi-pelagic trawl with French- or fork-rigging, and trawls with raised fishing lines. Both options involve removal of the groundrope and elevation of the fishing line to clear the seabed. Fuel saving potential is high with these options because seabed ploughing and friction are substantially reduced or eliminated, although immediacy of application and ease of use is relatively low. The risk of reduced catch is also high, particularly when targeting flatfish species, although less so when targeting aggregated species or towing at higher trawl speed.

## 8.2 Application in New Zealand bottom trawl fisheries

Based on primary author knowledge and experience there appears 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 already been tested successfully in multiple fisheries around the world, usually with little or no modification to the vessel and handling by crew. For example, semi-pelagic trawl doors have been tested in New Zealand, Australia, Europe, and the United States, on both small inshore trawlers and large deepwater trawlers. Providing that door size is matched to vessel engine power and the net, there is no evidence suggesting they cannot be used on bottom trawlers of all sizes and designs. Any difference in the deployment and retrieval of these doors is minor and does not seem to require any significant change in deck layout, winches, or hauling gear. In some countries, fishers have been voluntarily using these trawl doors for several years, primarily because they have found them simple to operate and an opportunity to reduce fuel costs.

Sweeps fitted with cluster discs are now a required trawl modification on the west coast of the USA. They have also been tested on the east coast of the USA as well as in Newfoundland and Labrador with encouraging results. Providing this modification does not result in substantial catch loss, there seems little reason why they cannot be used by fishers in New Zealand, although there is a possibility that flanges on net drums will need to be enlarged to accommodate the bulky cluster discs. This modification is also unlikely to result in any substantial handling issues, and the operation of the trawl should be little changed by the addition of these discs.

Raised fishing line trawls have been tested in Australia and the USA and are now required in some fisheries in both countries. These modifications can eliminate seabed contact by the groundrope and provide a substantial fuel saving, although they are unsuitable for target species such as flounder and other benthic habitat species. It can also be a challenge maintaining seabed clearance using these trawls, particularly in heavy weather when vessel movement is transmitted via the warp wires to the trawl, resulting in rapid vertical movement of the doors and net. These modifications are therefore probably only suitable for use in sheltered, inshore waters targeting schools of fish.

Most of the remaining modifications can also conceivably be applied in New Zealand, many immediately and easily, although there are fishing locations where some are less suited than others, and some that will require adjustment to suit different target species and different sized fishing gear and vessels. Understanding which of these gears can and cannot be used, and where and when, will rely heavily on the knowledge, skill, and expertise of local bottom trawl fishers.

## 8.3 Skill and expertise

There is little doubt that New Zealand trawl fishers have the skill and expertise to apply and use most if not all of these modifications. Many of these modifications are simple adjustments to existing gear and practice and can be applied quickly and easily. Some are very expensive, particularly if acoustic sensors are required to monitor trawl peformance, and some are complicated and may necessitate provision of technical advice, particularly when attempting more revolutionary changes such as semi-pelagic or controllable trawl doors. This advice can be provided by trawl door manufacturers, net makers, fishing technologists, researchers, or fishers that have prior experience.

# 9 Discussion and recommendations

This report has described numerous efforts worldwide to modify bottom 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 trawl components 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 and damage.

There is little evidence to suggest the adoption of any modification described in this report is limited by vessel size, design, or engine power, and in fact some modifications can reduce engine demand through drag reduction. Perhaps the only instance where deck modification may be required is when using cluster discs, because the flanges on the net drum may need to be enlarged to accommodate their bulk. The need for modification, however, will depend on a case-by-case basis.

Whilst all modifications described in this report have the potential to reduce seabed contact, to a greater or lesser extent, it is important to also recognise their potential to negatively impact the catch and the day-to-day operation and handling of the trawl gear. For this reason any attempts in New Zealand to evaluate their efficacy must 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 evaluate 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 fishers will be essential at this time, including working closely with them to test and evaluate these modifications and widely sharing relevant news and information. Failure to adopt this holistic approach risks challenging the level of commitment by the New Zealand trawl fleet and their level of interest in investing in options to reduce seabed contact.

Based on this report, it is recommended that consideration is given to prioritising the testing of semi-pelagic trawl doors and cluster discs attached to sweeps and lower bridles, particularly in the New Zealand inshore bottom trawl fishery. Both modifications have a proven, albeit limited, track record of reducing seabed contact with little or no impact on target species. Semi-pelagic doors also reduce fuel consumption, thus providing an immediate incentive and benefit to fishers.

Furthermore, on the basis that this report serves as an important early step toward reducing seabed contact by the New Zealand bottom trawl fleet, the following additional recommendations are provided for consideration:

1. Share this report 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 mitigating impact through gear modification. This includes seeking feedback about the gear options recommended in this report, including where they may be suitable and otherwise, and any perceived operational, economic, regulatory, or other challenges.

2. Consider interviewing fishers that operate in the inshore and deepwater fisheries, 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.

3. Review the 2020 audit of New Zealand trawl gear completed by NIWA and Fisheries New Zealand. This will help identify and quantify variation in trawl doors, sweeps and bridles, and groundropes across the trawl fleet, provide an understanding of the size and weight of these components, and help to further understand how they are being used. This information could then help refine estimates of swept area, and highlight additional information needs to refine these estimates, for example, data on bottom contact time by each vessel. Importantly, the audit would also provide information about historical efforts by fishers to mitigate seabed contact through gear modification, allow estimation of the potential reduction in trawl footprint through future gear modification, and help prioritise and focus future efforts to modify trawl components and mitigate seabed impact caused by bottom trawls.

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 trawl doors 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 allow them access to a suite of modified gears of different sizes. For example, a range of semi-pelagic trawl doors 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 trawl doors 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 trawl doors, 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

introduction of sustainability linked loans could also be considered to incentivise this activity 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, by contributing to the development of a strategic, long-term plan to facilitate modernisation of the trawl fleet, and by agreeing to objectives and methods related to mitigating seabed contact. 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 vessel modernisation can reduce fishing time and environmental impacts even further, as old, less efficient, and environmentally unfriendly vessels are removed from the fleet.

   Associated with this, it is important to be cognisant that very little understanding exists both within and outside of the fishing industry regarding how spatial access adjustments would affect seafood production, quota values and Annual Catch Entitlement (ACE) pricing, and profitability. These are critical to model through, and to understand the industry's need to do so, so 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 favour 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, consider a seafood sector, Government process to agree collaboration principles for protecting benthic habitat, the livelihoods of the catching sector and subsequent supply chain, and which respect Treaty of Waitangi obligations and the importance of the dividends to Māori. (in the case of Moana New Zealand). This also should include agreeing to required short, medium, and long-term actions to reduce seabed impacts, and exploring the potential to regenerate marine ecosystems and underpin quota rights.

   A novel research and analysis framework to achieve these outcomes has been proposed in Appendix D.

# 10 Glossary of terms

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| Aspect Ratio | In trawl door parlance, aspect ratio refers to the ratio between trawl door height and length. The aspect ratio of a rectangular flat trawl door is typically around 0.5 i.e. trawl door length is twice trawl door height. Contemporary trawl doors are usually constructed using one or more cambered foils with an aspect ratio of 2-3:1 or higher. |
| Bosom/Bosum | 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 that live on or in the seabed or bottom of a body of water. |
| Bridle | A length of wire that extends from the upper or lower wingend of the trawl to the sweep. Most bottom trawls are designed with both a lower and upper bridle attached to each wingend. |
| 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. |
| Deepwater | Generally considered to be waters greater than 500 m deep. |
| 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. |
| Emergent epifauna | Marine organisms that settle on hard surfaces on the seabed or organisms with part of the body emerging from seabed sediments. |
| Epifauna | Marine organisms living on the surface of the seabed. |
| Fishing line | The line to which netting in the bottom panel is attached. Sometimes known as the foot rope or footline. The groundrope is usually attached directly to the fishing line using chain droppers or other means. Sometimes a secondary line, called a bolsh line, serves as an attachment point for the groundrope. This line is similar in length to the fishing line and groundrope. It is also attached to the fishing line, and protects the fishing line from abrasion and damage caused by the groundrope and seabed contact. |

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| Footprint | The area of seabed contacted by a bottom trawl. It serves as a proxy for seabed impact. |
| Groundrope | That part of the trawl gear attached to the bottom of the trawl net. It usually comprises a combination of chains, rubber discs, lead weights, and bobbins. In many parts of the world it is called ground gear, because it is comprised of multiple components fitted together, and not just a simple 'rope'. In the North Eastern United States it is called a sweep, while in other places it may be referred to as foot gear or a foot rope. |
| Hook up | A term to described fouling or snagging of the trawl on the seabed, both temporary or otherwise. |
| Inshore waters | Generally considered to be waters less than 200 m deep, although this term also refers to waters 0-12 nautical miles off shore within the NZ Exclusive Economic Zone. |
| Middle waters | Generally considered to be waters between 150-500 m deep. |
| Quarters | That part of the trawl headline or footline between the bosom and wings of the net. Sometimes referred to as shoulders or gussets. |
| Rugosity | A measure of surface roughness or the variation in the height of the seabed. |
| Seamount | Prominent feature on the seabed that typically provides a wide variety of habitat types for a wide diversity of species. They may rise hundreds or thousands of metres above the seabed, are often volcanic in origin, and are cone-shaped. |
| Shoes | That part of a beam trawl or trawl door in contact with the seabed. The shoe is usually constructed from steel and extends along the length of the trawl door. Heavy weights are sometimes added to the shoe to keep the trawl door upright, particularly in the water column, and ensure bottom contact. The leading edge of the shoe is often curved to help the trawl door pass over rocks and other obstacles on the seabed. |
| Sweep | A length of wire extending from the bridles to the trawl doors. |
| Swept area | The area of seabed swept by the trawl gear. Nominal swept area is a function of the distance between the trawl doors and the distance trawled per unit time. It serves as a proxy for the footprint of a bottom trawl because it is assumed that trawl doors, sweeps, lower bridles, and groundrope are fully in contact with the seabed. Measurement of swept area requires measurement of trawl door spread using acoustic distance sensors and GPS measurement of distance trawled. |
| Warp | The towing wire connecting the trawl gear to the vessel |
| Wingends | The anterior sections of the trawl net to which the bridles are attached. |

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# 12 Appendix A - Trawl door 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 trawl doors. 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 trawl doors were replaced with Poly-Ice Elcazador trawl doors. These trawl doors weighed 550 kg and surface area was 2.8 $m^2$. In the second trip a different trawler was used. On this trawler larger trawl doors 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 seven tows; data from the control and experimental gear was collected from four and three tows respectively. Tow duration was 2.5-4.0 hours. In the second trip data was collected from nine tows; data from the control and experimental gear was collected from three and five 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 trawl door spread and a depth sensor used to measure trawl door 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 trawl doors, although no specific detail was provided.

**Impact on fuel consumption:** No detail provided.

**Ease of use:** Replacing bottom-tending trawl doors with semi-pelagic trawl doors only required them to be changed over and less trawl warp to be used. Trawl door spread was around 17% higher using the semi-pelagic trawl doors despite reducing warp length by up to 33%. For many tows seabed contact was minimal (Plate A 1). The heavier semi-pelagic trawl doors 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 trawl doors with lighter trawl doors, 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 trawl door indicating limited seabed contact.

**Consultant notes**

- Excessive trawl door weight can present challenges elevating them clear of the seabed. Reducing warp length is an option, although the author's noted that low catches may have been a result of using too little warp. This suggests that catch loss underneath the sweeps and/or trawl net may have occurred.
- Based on this study it seems that replacing bottom-tending trawl doors with semi-pelagic trawl doors can be a relatively straight forward exercise, only requiring them to be changed over and reducing the trawl warp. This however, assumes that acoustic sensors are available to monitor trawl door height above the seabed. These sensors may be cost-prohibitive for smaller operators**.**

**Reference:** He *et al*., 2006.

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

**Objectives:** 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 trawl doors 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 trawl doors clear of the seabed. The new trawl doors 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 trawl doors 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 groundrope was attached to a lower sweep. The upper sweep was attached to the top of the trawl door and the lower to the bottom of the trawl door.

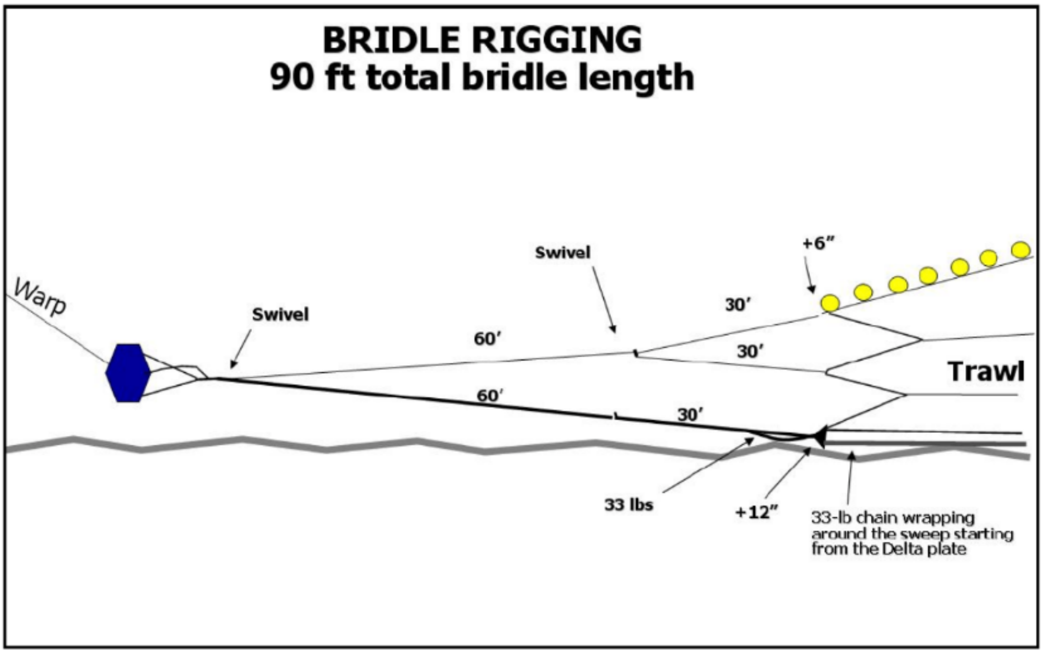


Figure A 1. The rigging arrangement used in 2004. Source: He *et al*., 2006.

**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 2-2.5 knots (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 groundrope was attached to a lower sweep. The two sweeps were attached to a single point behind the trawl door.

**Key findings/outcomes**

**Impact on benthos and habitat:** To ensure the trawl doors 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 trawl doors were easy to use during deployment and retrieval. Trawl door spread reasonably steady during operation and wingend spread was relatively constant. Trawl door clearance, measured using acoustic sensors, was steady while the trawl was towed in a straight line, although while turning, the inside trawl door contacted the seabed. The aft 30% of the trawl door 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 trawl door 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 trawl doors 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 three or four months each year. Fishers are usually engaged in other fisheries at other times, including ground-fish trawling and/or gill-netting, 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 trawl doors 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 trawl doors in a shrimp fishery, however the challenge of achieving and maintaining a desired trawl door clearance above the seabed apply irrespective of target species.

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

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

**Objectives:** Evaluate the ability of semi-pelagic trawl doors to i) maintain the catch of commercially important species, ii) reduce the consumption of diesel fuel during the trawl operation, and iii) reduce or eliminate trawl door contact with the seabed, in comparison to contemporary bottom-tending trawl doors.

**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 trawl doors were evaluated using an alternate haul experimental design on a typical bottom trawler (Plate A 1). The same trawl net was attached to both sets of trawl doors. Over a 5-day period each trawl door 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 trawl doors were a typical multi-foil design with a surface area of 2.25 $m^2$ and a weight of 485 kg (Plate A 2).

**Experimental gear:** The semi-pelagic trawl doors were similarly constructed with multi-foils but with a higher aspect ratio (height to length ratio). They were Type 14 trawl doors purchased from Thyboron Skibssmedie A/S in Denmark. The surface area of the semi-pelagic trawl doors were only 1.75 $m^2$ and they weighed 440 kg, a reduction of 22% and 9% respectively compared to the bottom-tending trawl doors.

**No. of tows/tow duration:** Data was collected from 16 2-hour tows (n = eight tows for each type of trawl door).

**Towing speed:** Towing speed was 2.9 kn (1.5 $ms^{-1}$).

**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 vessels fuel consumption when each trawl door was being used, and a Notus acoustic trawl mensuration system was used to measure and record the distance between the trawl doors during each tow. To monitor trawl door contact with the seabed, the trawl doors were visually inspected at the completion of each tow for signs of bottom contact, including scratch marks or polish on the shoe.

**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 or 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.


Plate A 1. The F/V Lisa Ann II used in the sea trials. Image courtesy of S. Eayrs.

Plate A 2. The traditional trawl door (outside) and the semi-pelagic trawl door (inside). Note the difference sizes of each trawl door. Image courtesy of S. Eayrs.

**Impact on target catch:** A total of 827 cod were landed and measured using the semi-pelagic trawl doors 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 trawl doors with a mean length of 64.8 ± 8.47 cm. The mean weight of cod caught using the bottom-tending trawl doors exceeded the semi-pelagic trawl doors 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 trawl door type. SP = Semi-pelagic trawl doors, BT = Bottom-tending trawl doors. F = Frequency of occurrence (tows). Note that an otter board is also called a trawl door.

| Species | Otter board type | Kept $\bar{x}$ +/- sd | Kept F | Discard $\bar{x}$ +/- sd | Discard 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 trawl doors was 8.4 gph ± 0.63 and 9.5 gph ± 0.63 respectively. Overall, the fuel consumption was reduced by 12% when the semi-pelagic doors were used.

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

**Cost:** The cost of a pair of small semi-pelagic trawl doors is around USD$10,000 depending on trawl door 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 trawl doors is a viable alternative to traditional bottom-tending trawl doors. 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 trawl doors for many years, which is a telling development. Several other fishers in the region have now also transitioned to these trawl doors.
- Mean spread of the semi-pelagic trawl doors were approximately 5% less than the bottom-tending trawl doors. 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 trawl door types is the same, and that he simply replaced the bottom-tending trawl doors with the semi-pelagic trawl doors without additional modification.

**Reference:** Eayrs, 2014b.

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

**Objectives:** 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.

**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 trawl doors were evaluated during separate fishing trips due to an inability to change trawl doors 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 trawl doors 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 five 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 to 1.65 $ms^{-1}$).

**Other study details:** The F/V Nobska was used in this study, measuring 30 m in length. Fuel data was logged automatically by computer at one-minute intervals. Trawl door 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 trawl doors 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.

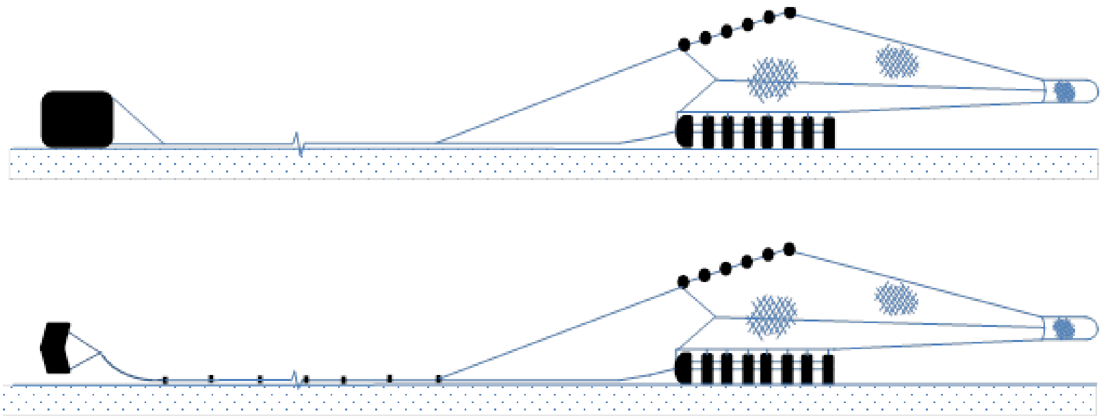

Figure A 2. The standard, bottom tending trawl system (top) and the trawl with semi-pelagic trawl doors and raised sweeps (bottom). Note the use of small rubber bobbins to life the sweeps clear of the seabed. Image courtesy of S. Eayrs.

**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 significantly less (19%) than that for trip 1. In trip 2, there was also a 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 trawl doors] nearly as fast as the traditional setup; trawl doors seemed to wallow behind the vessel. Had to slow down and let them “catch” before deploying as “normal.”
- Traditional trawl doors would easily be at a spread of 320 [97 m] or 330 feet [100 m] with this setup. Traditional trawl doors were spreading at 268 ft [81 m]**.**
- The trawl doors are too small and light for their net and the vessel, if you try to steam at all with them the doors “taken off”.

- We were catching a lot more fish right here last week...the catch composition is not much different.
- The trawl doors 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 trawl door 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 trawl doors 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 trawl doors and raised sweeps was an attempt to explore the impact of this gear combination 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 trawl doors 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 trawl doors 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.

**Objectives:** Evaluate the ability of semi-pelagic trawl doors to i) replace bottom-tending trawl doors 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 trawl doors were evaluated during separate fishing trips due to an inability to change trawl doors 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 trawl doors were used as a control, each weighing 640 kg with a surface area of 3.5 $m^2$ (Plate A 3).

**Experimental gear:** This study used NETS Gull Wing semi-pelagic trawl doors (Plate A 4) weighing 400 kg each with a surface area of 3 $m^2$ similarly constructed with multi-foils but with a higher aspect ratio (height to length ratio). The surface area of the semi-pelagic trawl doors were only 1.75 $m^2$ and they weighed 440 kg, a reduction of 22% and 9% respectively compared to the bottom-tending trawl doors.

**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 to 1.65 $ms^{-1}$).

**Other study details:** The F/V Apollo was used in this study measuring 23 m in length. Floscan fuel flow meter was fitted to the vessel prior to the experiment to measure the vessels fuel consumption when each trawl door 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/h, respectively.

**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.

Plate A 3. The Gull wing trawl door. Image courtesy of P. He.

Plate A 4. The Hi-Lift trawl door. Image courtesy of P. He.

**Impact on fuel consumption:** The mean fuel consumption for the semi-pelagic and bottom-tending trawl doors was 24.3 gph ± 3.00 and 33.9 gph ± 4.4 respectively; a 28% reduction. Overall, the fuel consumption was reduced by 12% when the semi-pelagic doors were used.

**Ease of use:** There was no difference in the handling ability of either trawl door type; the fisher had been voluntarily using the semi-pelagic trawl doors 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 trawl doors were exclusively used in trip 1 and the semi-pelagic trawl doors in trip 2. Subsequently care is required interpreting the results of this study.
- The skipper was very positive about the performance of semi-pelagic trawl doors, noting ease of use and spreading ability.

**Reference:** Jones, 2015.

**Title:** Trials of semi-pelagic trawl doors.

**Objectives:** 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 trawl doors were evaluated during separate fishing trips due to an inability to change trawl doors at sea. The same trawl net was used during both fishing trips, a 33 m albatross bottom trawl.

**Control gear:** Price engineering conventional trawl doors 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 trawl doors, 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 trawl doors and the weight.

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

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

**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 vessels fuel consumption when each trawl door was being used. Trawl door 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 trawl doors were used. Trawl mensuration data, towing speed, engine revolutions and fuel consumption were recorded manually every five minutes during each tow.

**Key findings/outcomes**

**Impact on benthos and habitat:** It was estimated that approximately 95% of the door shoe did not contact the seabed at any time during any tow, although 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 trawl doors and the semi-pelagic trawl doors in bottom contact averaged 92.6 ± 21.3 kg/$km^2$ and 83.7 ± 9.1 kg/$km^2$ respectively.

The mean standardised catch (excluding nuisance species) of the semi-pelagic trawl doors when clear of the bottom was 69.0 ± 17.5 kg/km$^2$.

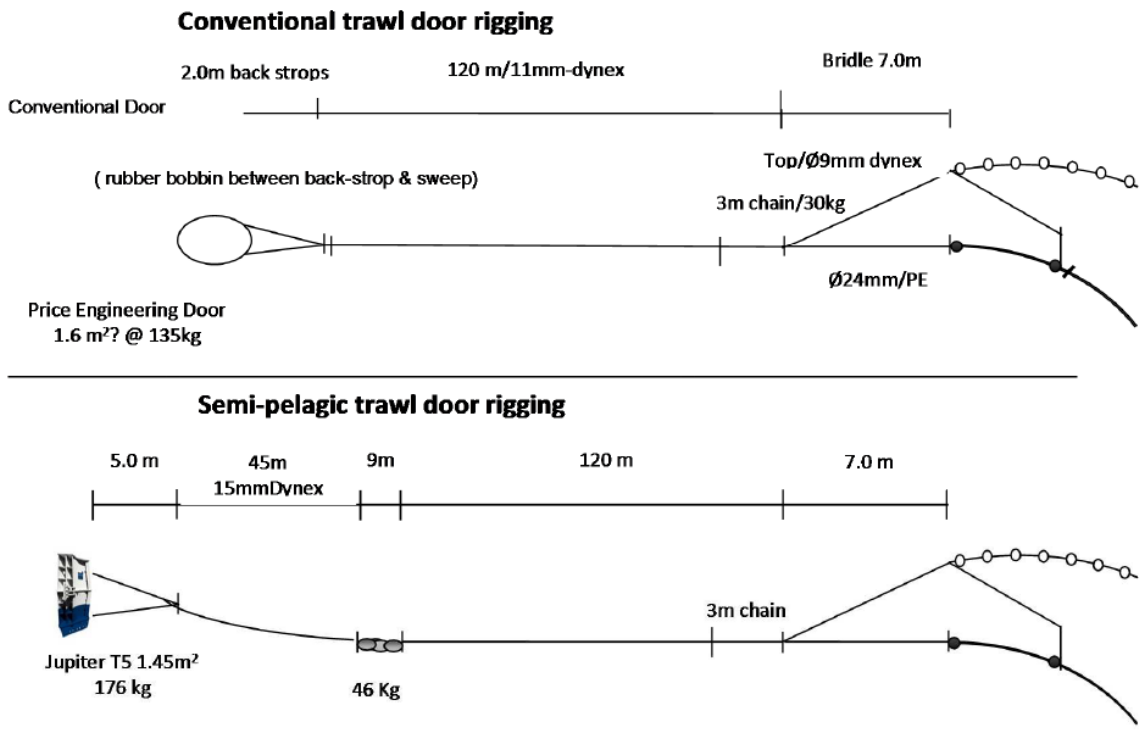


Figure A 3. The control (conventional) bottom trawl and the semi-pelagic trawl.

**Impact on bycatch:** No detail provided.

**Impact on fuel consumption:** The mean fuel consumption for the conventional trawl doors and the semi-pelagic trawl doors in bottom contact averaged 18.8 ± 0.34 litres/hr and 18.3 ± 0.33 litres/h respectively. The average fuel consumption of the semi-pelagic trawl doors when clear of the bottom was 15.8 ± 0.44 litres/h, an average reduction of 16% compared to the conventional trawl doors.

**Ease of use:** The spread of the semi-pelagic trawl doors was highly variable when fished clear of the seabed, ranging from 58-91 m. Headline height was 3.4-4.3 m. When these trawl doors were in seabed contact, spread ranged from 86-100 m and height was 2.5-3.1 m. The spread using the conventional trawl doors 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 trawl doors 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 trawl doors was frequently in excess of 15°. The optimum tilt angle for these trawl doors 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 trawl doors were in seabed contact, due to ground shear, the measured reduction when not in seabed contact was substantial.
- It is possible that the semi-pelagic trawl doors used in this study were too large. They were 30% heavier than the conventional trawl doors, and when used in seabed contact, they produced substantially more spread. Assuming the conventional trawl doors were optimally spread, higher spread may result in loss of seabed contact and escape of fish underneath the groundrope. Headline height should also be decreased, as was evident when using these trawl doors in seabed contact.
- The results of this study should be treated as indicative only, given the relatively few tows that were completed, although they are encouraging and an ideal foundation for further testing in New Zealand.

# 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:** 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 minutes.

**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.

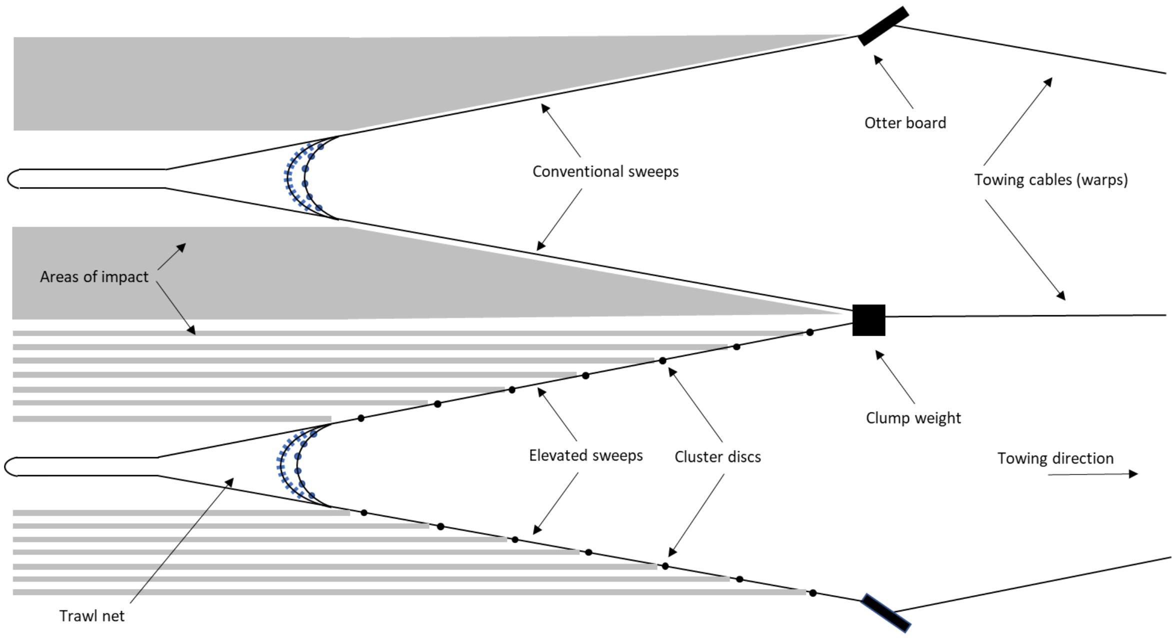


Figure B 1. Comparison of seabed area impacted (shaded) by each sweep. Adapted from Rose *et al.*, 2010a.

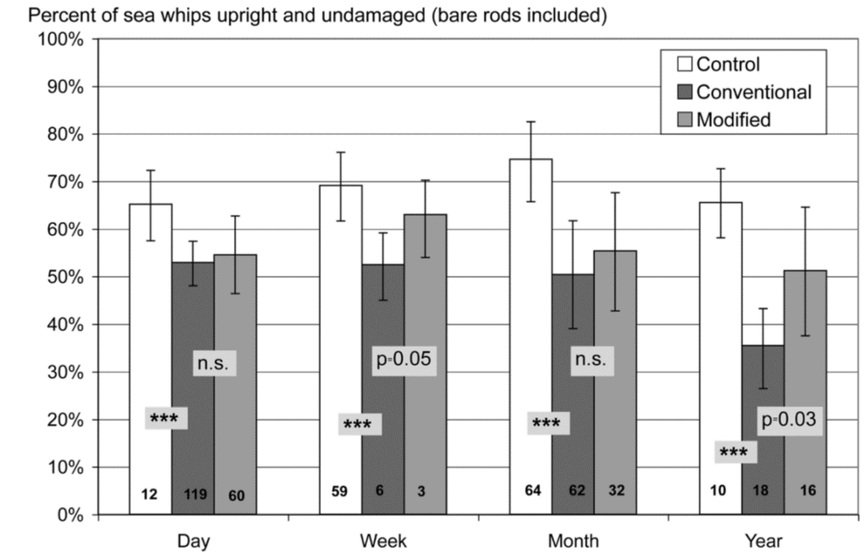


Figure B 2. Proportion of undamaged sea whips using conventional and 20 cm elevated (modified) sweeps, compared to control observations. Sample sizes are indicated in each column. Source: Rose *et al*., 2010b

**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.

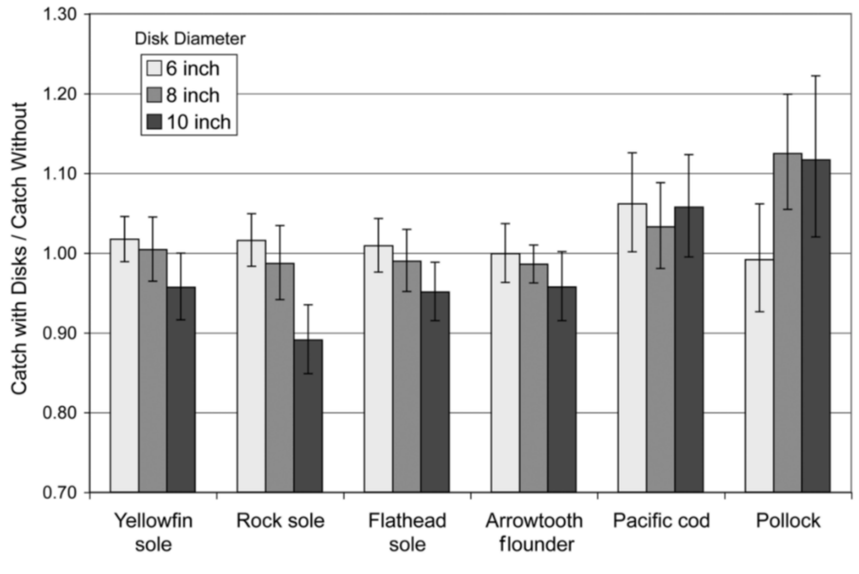


Figure B 3. Catch ratios of major species with 15 cm (6 inch), 20 cm (8 inch), and 25 cm (10 inch) cluster discs. Source: Rose *et al*., 2010a.

**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.

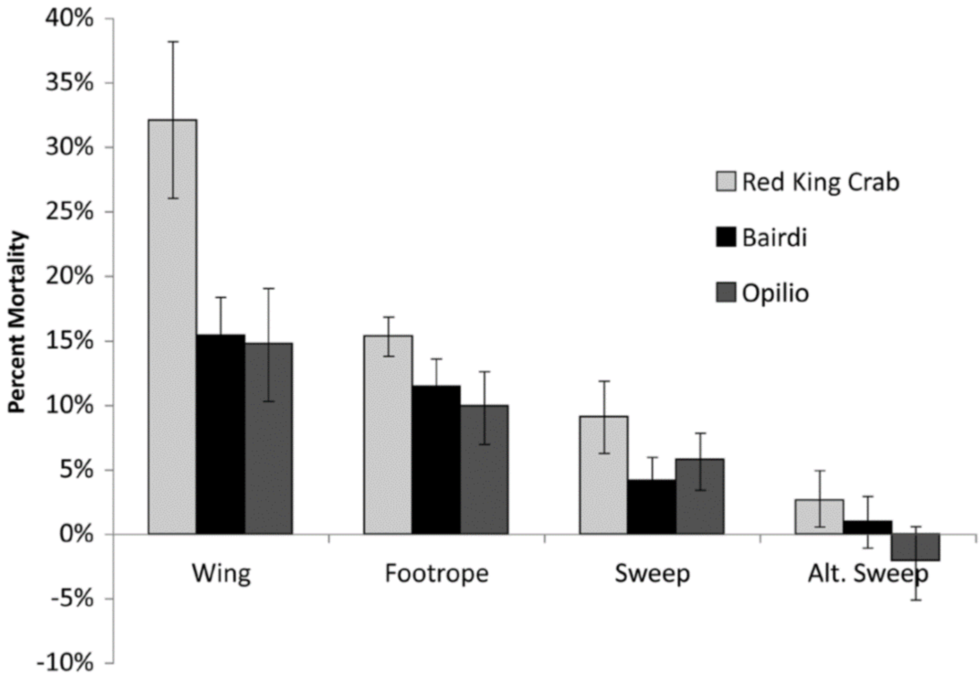


Figure B 4. Mortality rate of major crab species with 15 (light grey), 20 (black), and 25 cm (dark grey) cluster discs. Source: Rose *et al*., 2010b.

**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, trawl doors, and trawl netting (SEAFISH, IFREMER, & DIFTA, 1993) so any fuel saving due to the experimental sweeps will be minor. Furthermore, any fuel saving due to reduced seabed ploughing and friction will be minor.
- This gear modification has potential to reduce seabed contact in New Zealand bottom-trawl fisheries where the substrate is characterised by sand, mud, or gravel sediments. It is a relatively cheap modification that can be used in any single-vessel 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 centre 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 or a net maker.

**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 minutes.

**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 vessel 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 the groundrope 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 groundrope 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[13].

**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 in length.

**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.

[13] 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 groundrope clear of the seabed while trawling. The wingend weights provide a means of regulating to some extent the height of the groundrope 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 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 minutes for each haul.

**Towing speed:** 3.3 knots (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. Multi-dimensional 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 New Zealand bottom-trawl fisheries where the substrate 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 trawl doors 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.

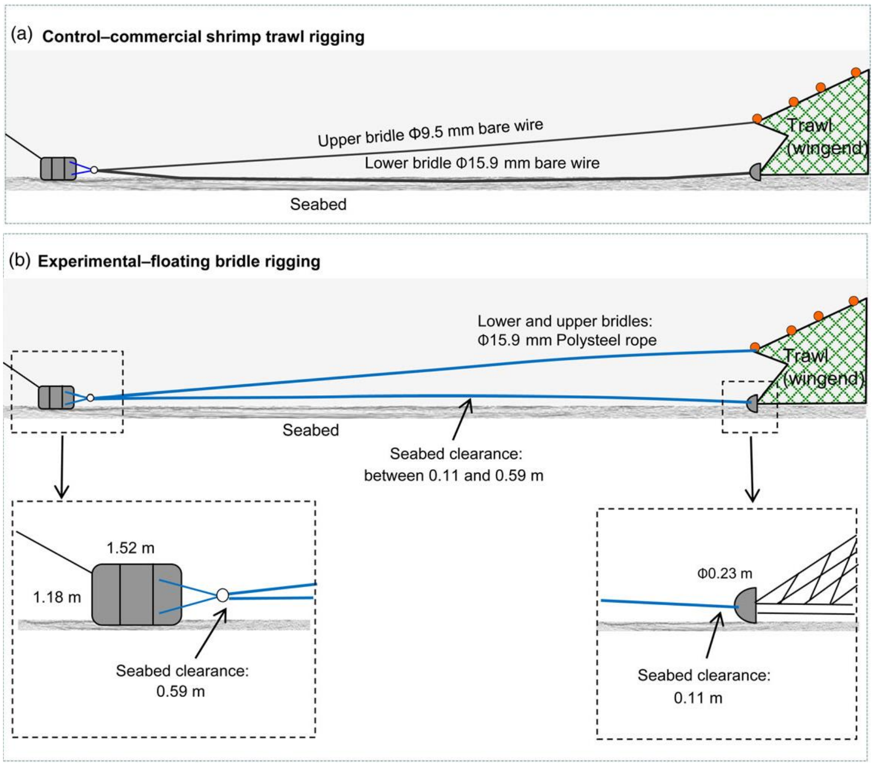


Figure B 5. Rigging of the control and experimental trawl. Source: He *et al*., 2015.

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

**Towing speed:** 2.1-2.3 knots (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 trawl door and upper wingend spread were virtually identical between control and experimental gear. It was inferred that lower wingend spread was 39-43% of trawl door 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 minor 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 lightweight 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 trawl doors 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).

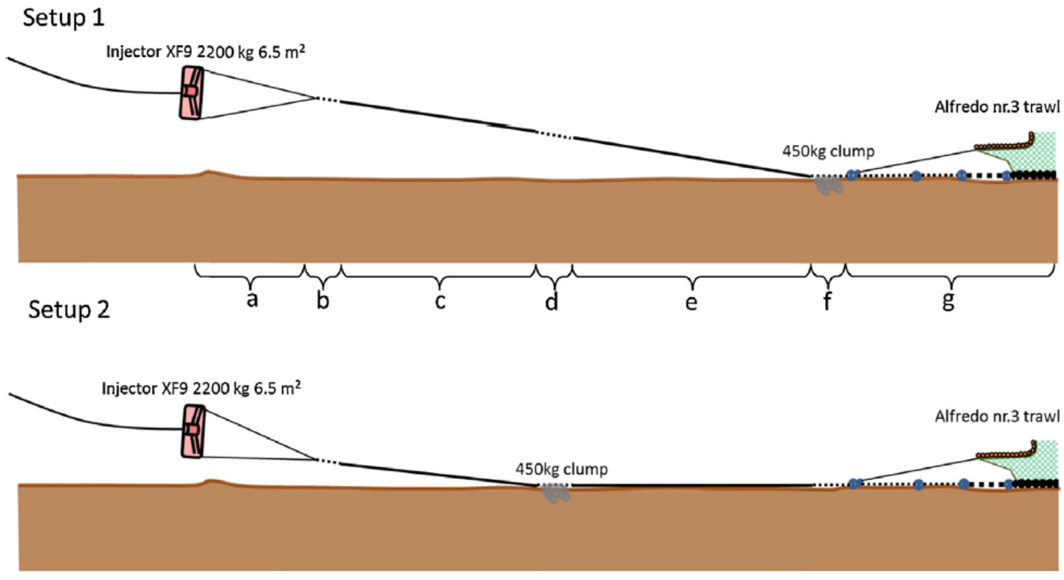


Figure B 6. Experimental trawl gear. (a) 15.9 m backstrop, (b) 3 m backstrop extension, (c) 30 m of 30 mm sweep, (d) 4 m of 19 mm chain (attaching position for the clumps), (e) 45 m of 30 mm sweeps, (f) 4 m of 19 mm chain (attaching position for the clumps), (g) 445 m of groundrope composed of 19 mm 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 minutes for each haul. All tows were completed during the day-time, although in near total darkness at high latitudes in November.

**Towing speed:** 3.5 knots (1.8 $ms^{-1}$)

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

**Key findings/outcomes**

Trawl door spread, wingend spread, and headline height were almost identical between experimental gears (setups). Experimental gear 1 (Setup 1) trawl door 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 trawl door position and ensure the clump weights were the first component in seabed contact.
- While not stated by the author's, 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 trawl doors 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 author’s, 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.

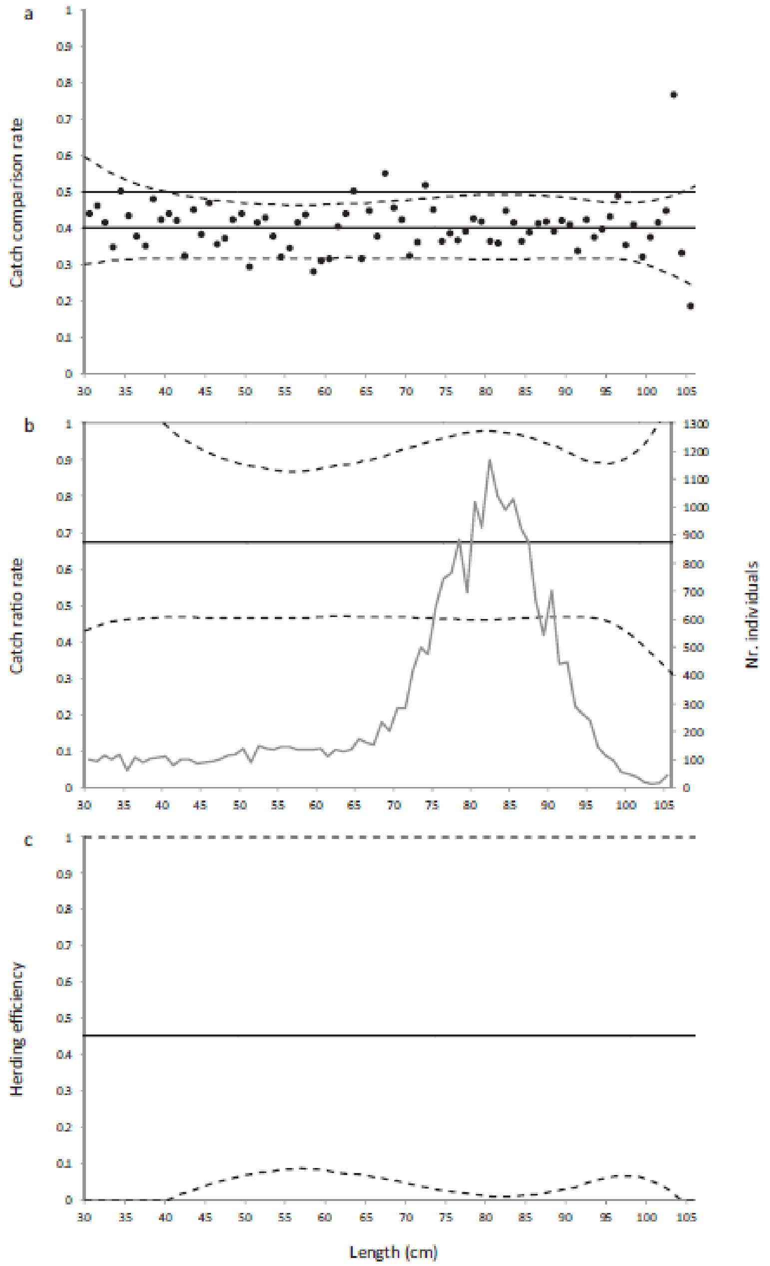


Figure B 7. Experimental gear 1 compared to 2. (a) Average catch rate (full line) and confidence intervals (dashed lines). The line at 0.5 represents equal catching efficiency between gears; (b) average catch ratio (full line) and confidence intervals (dashed lines), and size distribution (grey line) 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 – Groundrope 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 groundrope 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 four 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 groundrope. There was no difference in engine power requirements to tow this or conventional groundrope.

**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 groundrope 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.

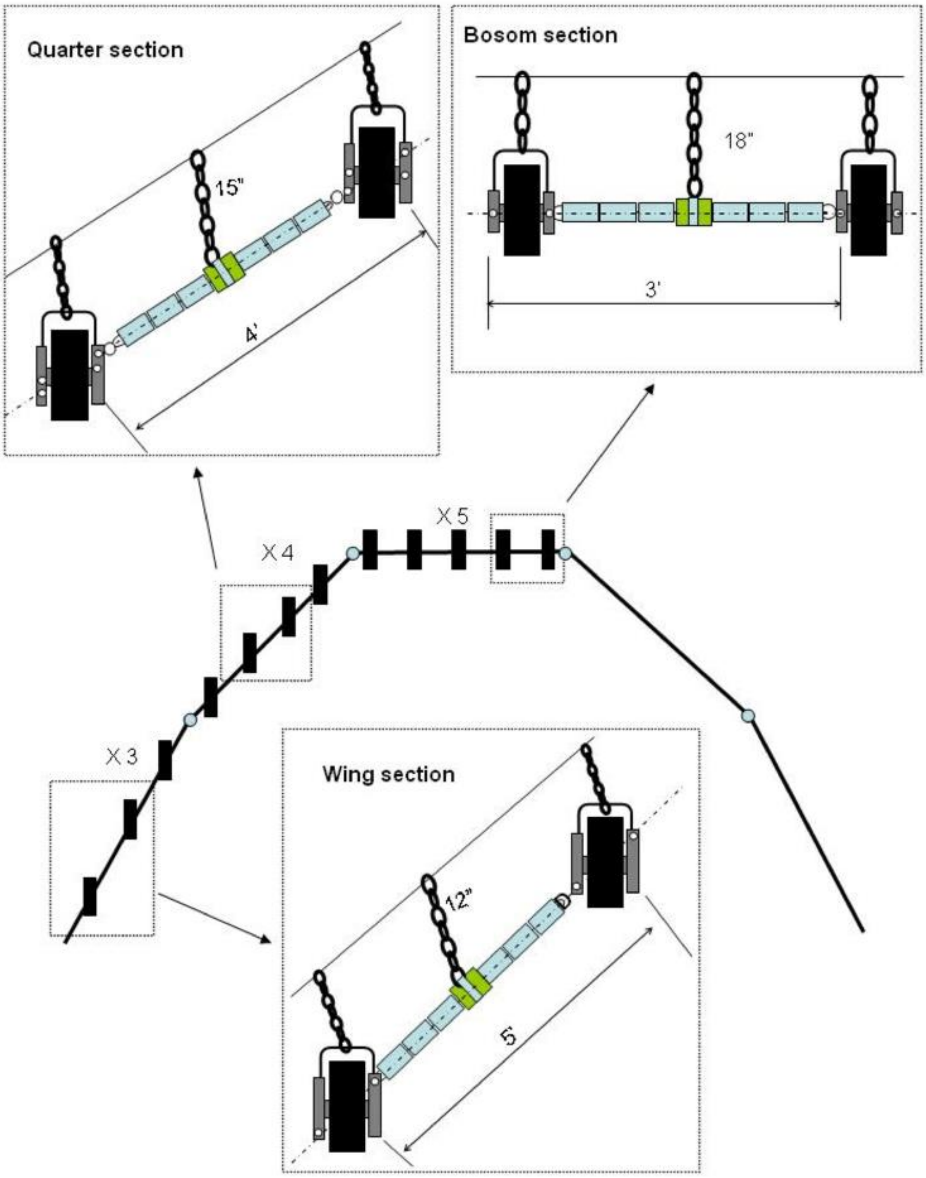


Figure C 1. Wheeled groundgear with important dimensions indicated Source: He & Balzano, 2010.

**Consultant notes**

- This groundrope 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 author's of the report. The successful development of this groundrope may reduce its footprint by an estimated 20-30%.

- As the author's 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 groundrope.

- 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 groundrope 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 trawl doors, so any change may be negligible.

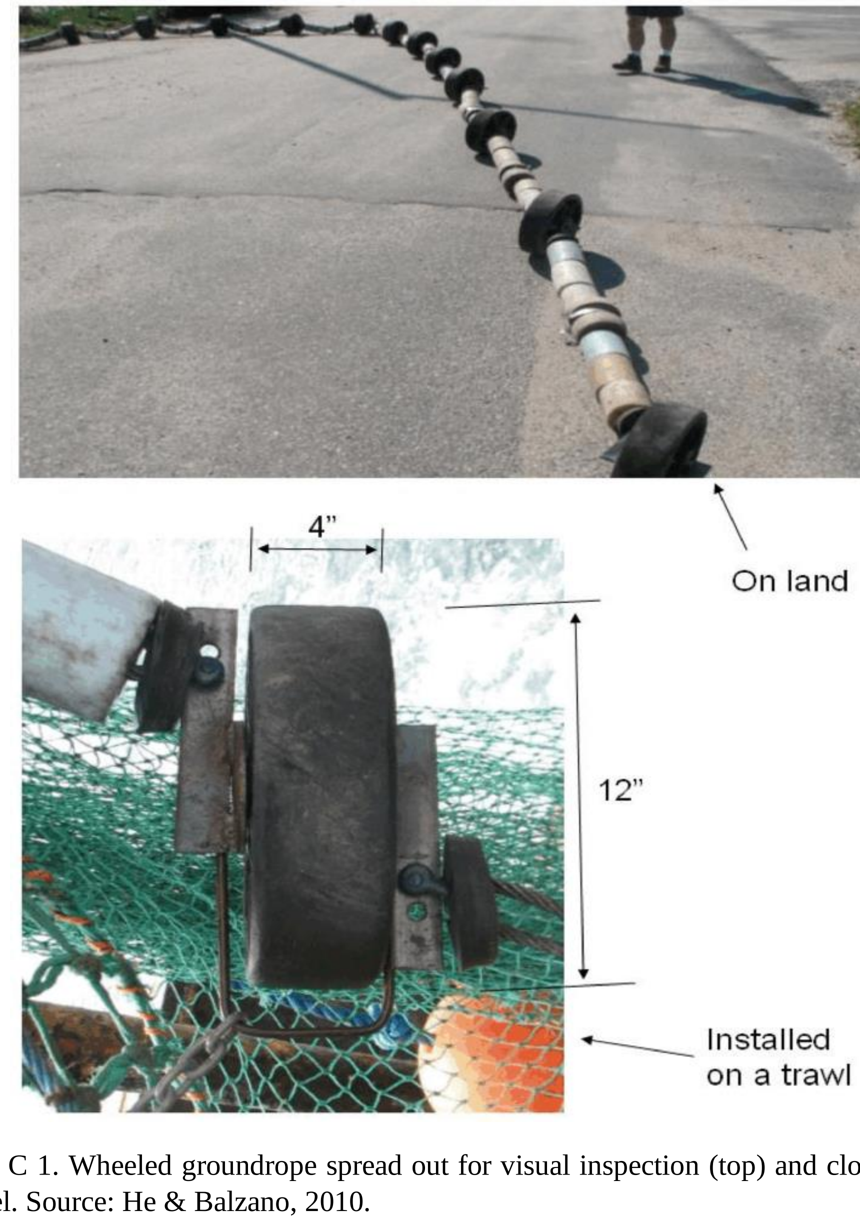


Plate C 1. Wheeled groundrope spread out for visual inspection (top) and close-up of a wheel. Source: He & Balzano, 2010.

**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 five to each of the upper selvedges (seams).

**Control gear:** A conventional 32.9 m rockhopper groundrope 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 groundrope.

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

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

**Towing speed:** 2.3 knots (1.2 $ms^{-1}$)

**Other study details:** Scale models of both groundropes were tested in a flume tank prior to sea trials. E-Sonar and Netmind acoustic sensors were used to measure trawl door 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 groundrope but only 27% was contacted with the aligned groundrope. This represents a 61% reduction in trawl footprint (Figure C 3).

At sea, the mean trawl door spread using the experimental groundrope increased by a statistically significant 2 m (~4%) compared to the conventional groundrope. 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 groundrope reduced seabed friction gear (shearing) and an associated reduction in trawl drag. This outcome was not measured in the flume tank and is believed to have negligible effect on the degree of seabed contact.

**Impact on target catch:** The trawl with the experimental groundrope 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 groundrope 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 groundrope caught significantly more of both species compared to the conventional trawl with conventional groundrope.

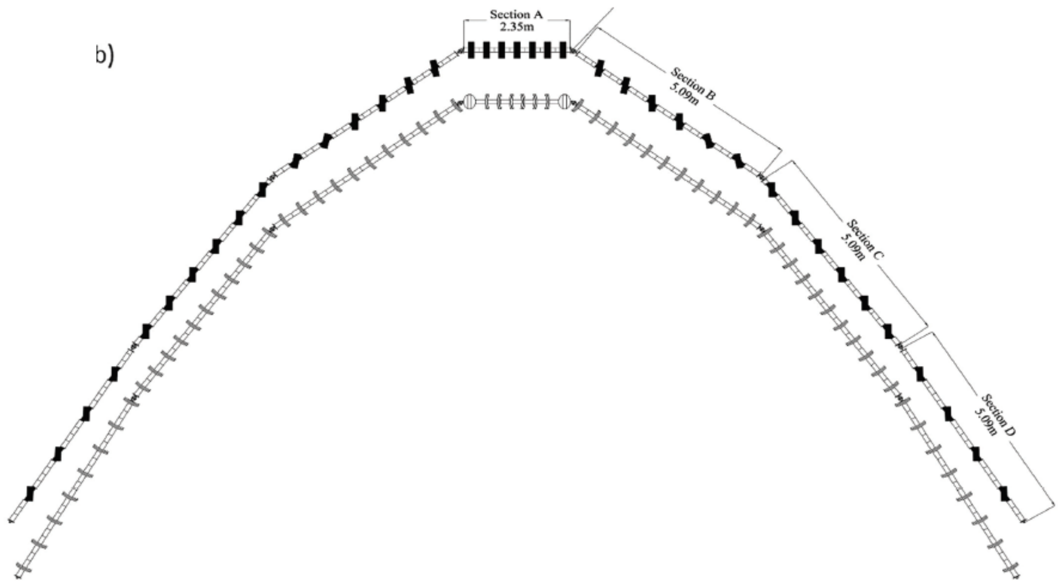


Figure C 2. Schematic of the experimental (upper) and conventional groundrope. Section A - bosom; Section B - bunt wing section; Section C - wing section; Section 4 - Wingtip sections. The bobbins in the wingtip sections of the conventional groundrope could be as much as 70° out of alignment with the 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.

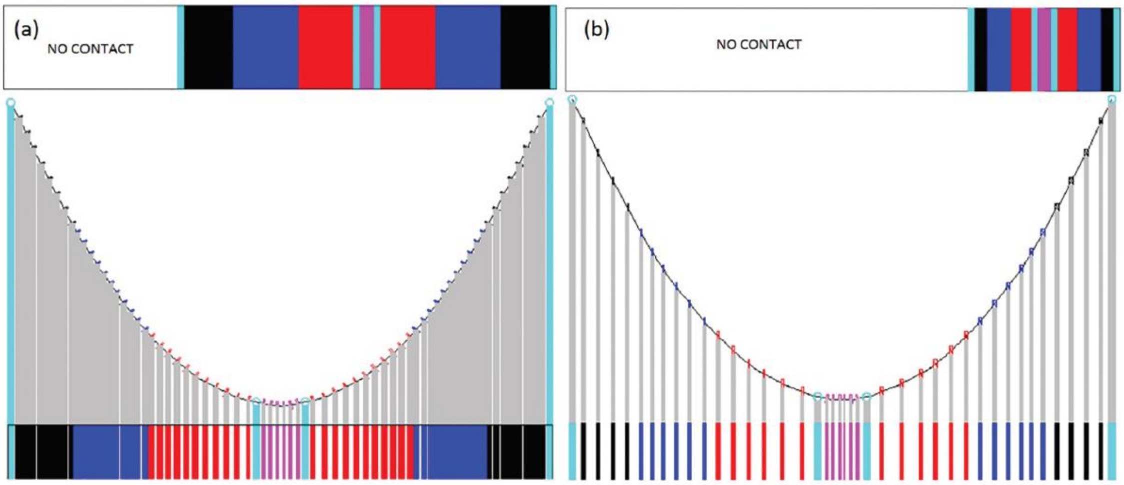


Figure C 3. The estimated proportion of seabed contact by the conventional groundrope (left) and the aligned groundrope (right). Colour coding represents the different footgear components or sections in seabed contact: Bobbins (green), wingtip sections (black), wing sections (blue), bunt wing sections (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 groundrope, given its complexity and need to visually estimate the angle of each section of groundrope relative to the direction of two.
- It would be useful to know the relative cost of this groundrope, and any handling challenges. A modest increase in cost is not an unreasonable expectation.
- Any drag reduction and associated fuel saving using the aligned groundrope is likely to be modest at best. There are two reasons for this: 1. drag associated with conventional groundrope 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 in this study was likely 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 160 kg. The groundrope comprised multiple rubber discs measuring 150 mm in diameter. Total groundrope 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 attached to each lower wingend. Attached to the centre of the footrope was 7 x 0.5 m dropper chains, each weighing 10 kg. Fly wires were attached to the upper wingends. They measured 92 m and were attached to the towing warps 37 m ahead of the trawl doors. The lower bridles were 65 m long and were attached to the trawl doors.

**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 centre of the footrope. The two wingend weights and seven 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 trawl doors. In contrast, the groundrope, 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.

**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 centre of the footrope. The two wingend weights and seven 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 trawl doors. In contrast, the groundrope, 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.

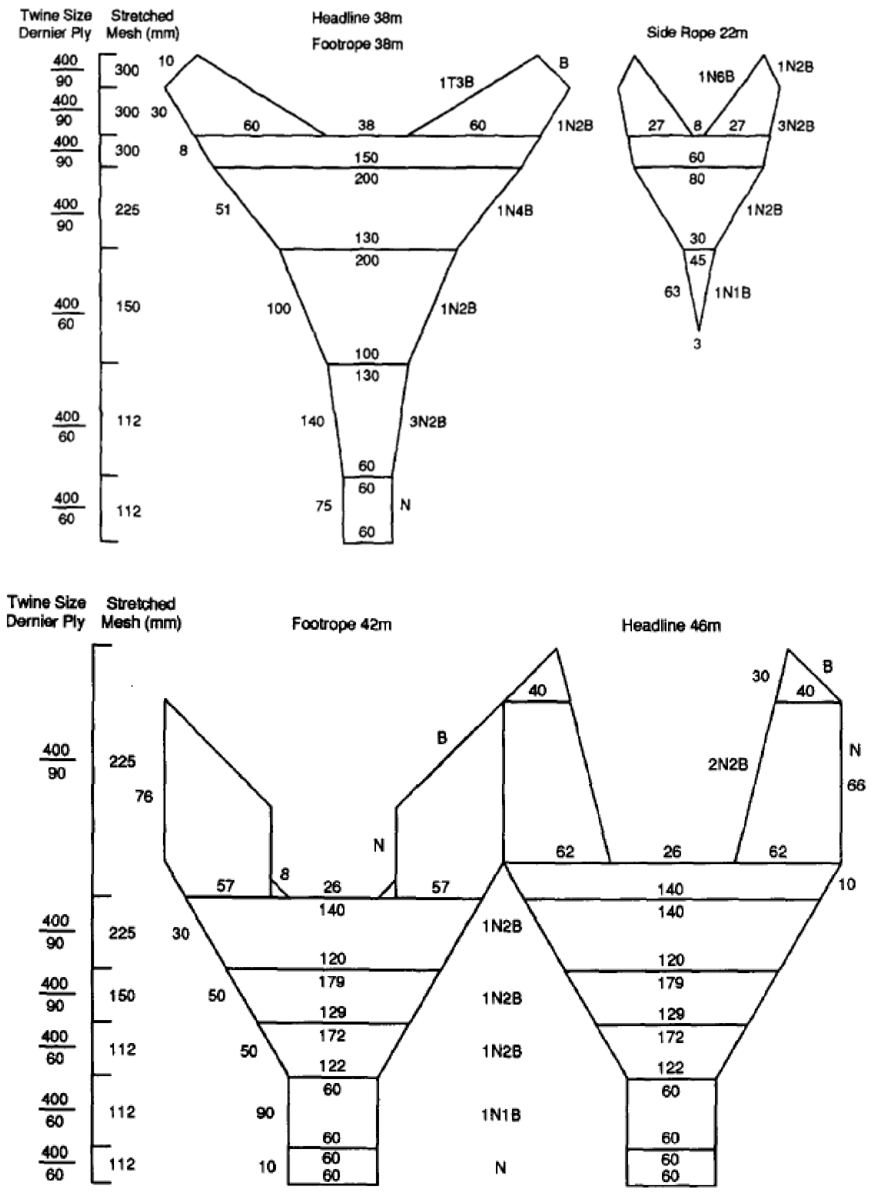


Figure C 4. Net plan of the Julie Anne trawl (upper) and the Paulegro trawl (lower). Source: Ramm *et al.*, 1993.

**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.

**Impact on fuel consumption:** No detail provided.

**Ease of use:** No detail provided.

**Cost:** No detail provided.

**Safety risk:** No detail provided.

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 |

**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 the use of this style of trawl was subsequently 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 extent 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 cause of 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 seabed.

**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 trawl doors were used weighing 1000 kg each with a surface area of 3.8 $m^2$.

**Control gear:** One trawl was fitted with conventional groundrope (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 groundrope. Two treatments of this groundrope 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 groundrope 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.

To estimate footrope clearance, a specialised beam trawl was first tested in a flume tank with the end of multiple 2.5 m long 10 mm dropper chains 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:** 3.5 knots (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. Trawl door and wingend spread was measured using Scanmar acoustic sensors.

**Key findings/outcomes**

**Impact on trawl geometry:** Compared to the conventional trawl, both treatments increased trawl door 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.

**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.

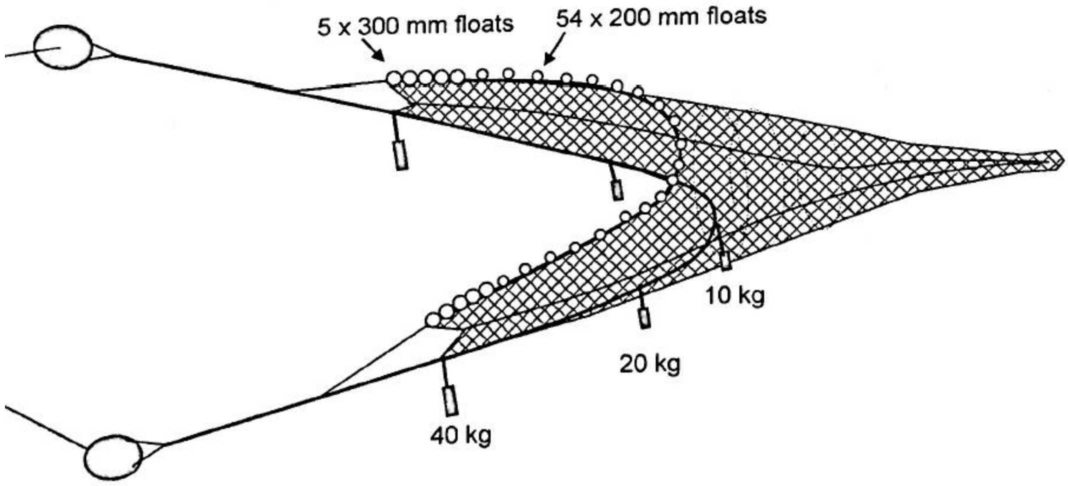


Figure C 5. The trawl rigged to fish semi-pelagically with a nominal footrope height of 0.4-0.5 m above the seabed. Source: Brewer *et al*., 1996.

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

| Trawl | Trawl door 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 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 habitat use.

**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 trawl doors 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 trawl doors 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-trawl doors 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 groundrope 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 (four tows) and 120 mins (eight tows) and for the control trawl it was 240 mins (four tows) and 120 mins (seven tows).

**Towing speed:** 2.5 knots (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 species of 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.

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

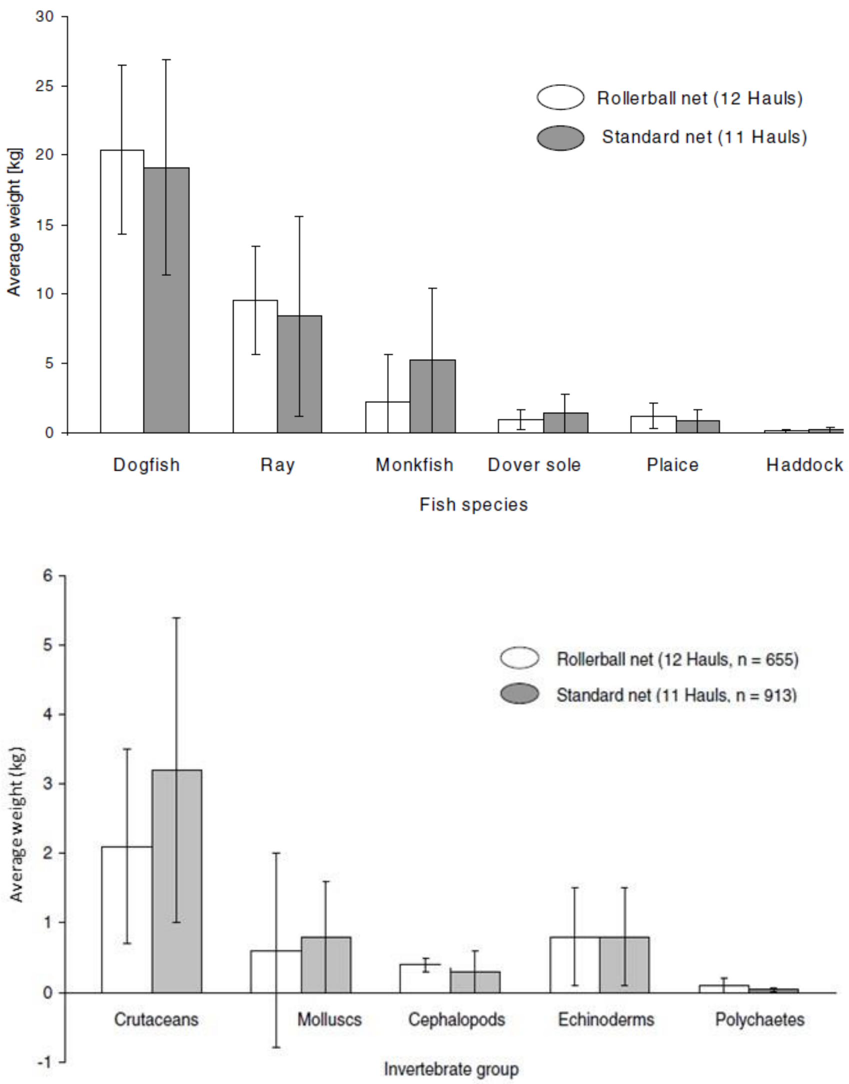


Figure C 6. Impact of Roller ball net on catches of commercial fish (upper) and invertebrates (lower). Source: Ball *et al*. (2002).

**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 trawl doors 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 trawl doors 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.

# 15 Appendix D – Reconciling ocean health

This framework (Terra Moana, 2019) is based on the central importance of the Treaty of Waitangi, grounded in respecting worldviews, and draws on the reconciliation processes developed by the National Centre for Ecological Analysis and Synthesis, and includes:

1. **Mātauranga Informed Design** – using kaupapa Māori methodology to develop and test Mauri-based designs of systematic marine protection for the EEZ (possibly e.g. dynamic) and whether using the IUCN Indigenous Protected Areas criteria has potential for a national system.
2. **Western Science Informed Design -** to do the same as above through standard modern marine science to design a comprehensive, adequate and representative network of marine protected areas. Co-designed, these would be structured for cross-discipline and cross-cultural learning i.e. using the Waka Taurua model (Maxwell *et al*., 2020)). The mapping would inform option co-design for systematic marine protection, which respects Māori fisheries rights.
3. **An Economic Implications Analysis -** model the design choice finance and economics implications to address the potential habitat changes and expected productivity improvements for key species and fisheries of different spatial management choices and the effects on quota value.
4. **A Legal, Policy and Regulatory Implications -** Analysis of different legal, policy, and management scenarios.

The proposed outcomes of this approach include:

- Quota holders and agencies co-develop area/habitats/harvest footprint and quota implications model(s) in relation to various protection regimes.
- Cross-cultural understanding on marine ecosystems and habitats.
- Enable the nature and extent to first be considered through a “Te Ao Māori lens” i.e. not driven by international pressures e.g the potential (or not) of the IUCN Indigenous Protected Areas criteria as a framework for New Zealand marine protection design.
- Compliment other efforts to clarify the nature and extent of the role for ecosystem-based management (EBM) and different forms of marine protection in New Zealand fisheries management, and help ensure EBM complements the QMS.
- On, weave and feed into other relevant programmes and projects in New Zealand (Sustainable Seas Science Challenge, government agency work, NGO recommendations etc).