# Choosing best practices for managing impacts of trawl fishing on seabed habitats and biota

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**Choosing best practices for managing impacts of trawl fishing on seabed habitats and biota**

**Running title:** Best practices for trawling impacts

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# ABSTRACT

Bottom trawling accounts for almost one quarter of global fish landings but may also have significant and unwanted impacts on seabed habitats and biota. Management measures and voluntary industry actions can reduce these impacts, help to meet sustainability objectives for fisheries, conservation and environmental management, and ultimately improve trade-offs between food production and environmental protection. These may include technical measures, input controls, and output controls, such as gear prohibitions, changes in gear design and operations, freezing the footprint, nearshore restrictions, prohibitions by habitat type, multipurpose habitat management, impact quotas (habitat or invertebrate bycatch), and effort limitation (with indirect effects on the intensity and distribution of trawling). We review the effectiveness of these measures and actions and use published studies and a simple conceptual model to evaluate and compare their performance. The risks and benefits of measures to reduce trawling impacts on the seabed depend on the extent to which the fishery is already achieving management objectives for target stocks and the characteristics of the management system that is already in place. We offer guidance on identifying best practices for trawl-fisheries management, and show that best practices and their likelihood of reducing trawling impacts depend on local, national and regional management objectives and priorities, societal values, and resources for implementation. As such, there is not a universal best practice and no single management measure or industry action is likely to be sufficient. Typically a suite of practices will be needed, in part to offset the potentially negative consequences of some measures.

**Commented [JGH1]:** I'm not sure what input and output controls are. The way it is phrased sounds as if a gear prohibition is an output control.

**Commented [JGH2]:** Too vague what this is to be useful in an abstract.

**Keywords:** benthos, dredging, ecosystem-based fishery management, impact-yield model, trade-offs, trawling

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## 1. Introduction

Fish and shellfish caught with bottom otter trawls, beam trawls and shellfish dredges (hereafter 'bottom trawls') account for around one quarter of the global capture-fisheries landings (Amoroso *et. al*. 2018). However, bottom trawling is often one of the most significant forms of physical disturbance on the seabed (Eastwood et al. 2007, Foden et al. 2011). The extent of this disturbance is highly variable and the proportion of seabed area exposed to bottom trawling ranges from <1% to >80% in different regions of the world (Amoroso *et. al*. 2018). Bottom trawls are designed to contact or penetrate the seabed to capture bottom-dwelling fish and shellfish, can be adapted for use in diverse habitats, and are readily scaled to a wide range of vessels, target species, fishing conditions, and geographical settings (Løkkeborg 2005; Valdemarsen et al. 2007; Suuronen et al. 2012). Trawling may modify sediment texture (grain size), the presence and nature of bedforms, and chemical exchange processes (Simpson and Watling 2006; Oberle et al. 2016). Trawling can also have direct and indirect impacts on populations and communities of benthic invertebrates, with significant reductions in abundance, biomass, species diversity, body size, and productivity reported in many studies (Collie et al. 2000; McConnaughey et al. 2005; Kaiser et al. 2006; Hiddink et al. 2017; Sciberras et al. 2018).

The impacts of bottom trawling at a particular location are determined by the design of the gear and its operation, the distribution and intensity of trawling, the susceptibilities of biota (which influence depletion), and the life histories of the biota (which influence recovery). Environments exposed to different physical regimes have different sensitivities to bottom trawling, reflecting characteristics of the benthic fauna (e.g. Snelgrove et al. 1994; Kaiser et al. 2018; Hiddink et al. 2019) and the background level of natural disturbance (e.g. McConnaughey and Syrjala 2014). The footprint of trawling (the geographical area that is directly contacted by trawls at least once in a specified time period) is determined by multiple factors including the distribution and catchability of fish or shellfish, technical capacity of the fleet, production costs and market prices, ruggedness of the seabed, environmental conditions (e.g. prevailing weather patterns), the state of fishery development, and changes in management measures. Each of these factors varies in space and time such that the footprint may move, contract or grow from year to year (e.g. Kaiser 2005; Jennings et al. 2012), although at broad scales, the distributions of bottom trawling tend to be consistent from year to year (Amoroso et al. 2018).

The impacts of trawling on the environment and biodiversity are the focus of societal debates about the benefits and costs of seafood production, and an increasing focus of fisheries and environmental-management regulation and certification processes. This is especially the case when trawling occurs on or close to vulnerable marine ecosystems (VMEs) or ecologically and biologically significant areas (EBSAs), but also for other types of habitat (Garcia et al. 2014). A range of ~~management measures and voluntary industry actions~~measures have been adopted to reduce or prevent trawling impacts on seabed habitats. However, the knowledge-base to evaluate the effectiveness of these measures or combinations of measures, and the extent to which they represent best practices, is fragmented.

We review and evaluate the effectiveness of management measures and industry actions ('measures' from here onwards) that are intended to minimize the impacts of trawling on seabed habitats and biota. These include changes in gear design and operation, spatial controls, impact quotas, and effort controls. Brief examples and performance-based analyses are used to develop guidance on best practices for a wide range of fisheries and associated management systems. ~~Building on results from precursory studies by the authors (Collie et al. 2017; Hiddink et al. 2017, 2019; Sciberras et al. 2018; Pitcher et al. 2017), we address multiple knowledge gaps identified in a prioritization exercise concerned with reducing the environmental impacts of trawling (Kaiser et al. 2016).~~ The resulting guidance on best practices is intended to help managers minimize environmental impacts of trawling ~~per unit weight or value of landed fish~~, while achieving a sustainable level of fish production.

## 2. Management Objectives and Trade-offs

Managers of trawl fisheries are frequently faced with the need to reconcile multiple and often conflicting societal, environmental, and economic objectives. Foremost among the management objectives is usually the need for sustainable exploitation of the targeted stocks resulting in employment, income, and food security. In most countries and regions there are also stated objectives to accomplish this with minimal habitat impacts or losses of ecosystem services, and to ensure the unintended bycatch is minimized~~, particularly for structure-forming benthic invertebrates and the juvenile stages of commercially valuable species.~~. ~~The resulting benefits from employment, income, and food security are other objectives, although h~~Habitat-protection measures may therefore limit ~~these~~ exploitation benefits due to conflicting policy-based trade-offs. ~~There may also be high short-term (perhaps continuing) economic and social costs of moving from the status quo to a situation where impacts on seabed habitat are reduced. For example, closures to protect sensitive habitats, spawning grounds or juvenile fish might ultimately improve the status of stocks (cf. Kenchington et al. 2018), but could also reduce yields and increase costs over the short-term (Steele and Beet 2003; Suuronen et al. 2010).~~ Resolving the fundamental conundrum between biological and socio-economic objectives remains one of the major challenges of fishery management.

## 3. Management Measures and Industry Actions

Four classes of ~~management measures and voluntary industry actions~~measures can be used to meet objectives for managing trawling effects on seabed habitats and to reduce these impacts per unit weight or value of landed fish (Table 1). *Changes in gear design and operation* of trawls can be regarded as technical measures. *Spatial controls* ~~are also technical measures and~~ include

**Commented [bm4]:** Could embellish relationships to previous works. This seems unnecessary and cumbersome?

**Commented [JGH5R4]:** Not needed in my opinion

**Commented [JGH6]:**

**Commented [bm7]:** Our target audience, especially in developing areas.

**Commented [JGH8]:** Phrase was saying the same thing twice.

**Commented [JGH9]:** Just trying to cut words here by deleting some text that I don't think is essential (although it is useful obviously) gear-specific prohibitions, freezing the footprint of fishing, nearshore restrictions and coastal zoning, prohibitions by habitat type including real-time (i.e. 'move-on rules'), and multipurpose habitat management (e.g. marine protected areas, MPAs). *Impact quotas* are output controls and include habitat- or invertebrate-bycatch quotas. *Effort controls* affect the overall amount and distribution of trawling. Several of these ~~management measures and actions~~measures ~~-~~can be used simultaneously, where their relative effects depend on characteristics of the fishery, environment, and management system in which they are applied.

**Commented [JGH10]:** Too vague a term

~~Management measures and industry actions~~Measures can be evaluated using both qualitative and quantitative performance metrics, recognizing that the preferred metrics will depend on the local, national or regional context. Our proposed metrics include the positive and negative effects of trawling on: (1) benthic biota, ~~(2) sustainable fish populations and food production,~~ (~~3~~2) ecosystems and ecosystem services, (3) fish populations and food production, and (4) economic performance of the fishery. In the following sections, we consider the efficacy of selected ~~management measures and industry actions~~measures using one or a combination of these four performance metrics and predictions from a simple impact-yield model.

**Commented [JGH11]:** We could lose about 50 words by just calling this measures throughout

### 3.1 Prohibitions by gear type

An absolute prohibition of bottom trawling in a given region provides the most comprehensive protection of seabed habitats from the effects of trawling and may improve harvests ~~associated with~~by competing gears. The primary objective of gear-specific prohibitions is to shift ~~demersal~~ fishing to other gears that have lower benthic impacts, such as static nets, pots and longlines~~, thereby reducing benthic impacts~~ (Suuronen et al. 2012; Pham et al. 2014). For example, Venezuela prohibited trawling less than six miles from the mainland or less than 10 miles from islands ~~shores~~ in 2001, subsequently ~~amended~~ extended in 2009 to ~~include~~ all waters (Mendoza 2015). The ban was intended to protect coastal biodiversity and increase ~~production~~ catches by small-scale fishermen who supplied 70% of annual fisheries production (compared to ~~only~~ 6%~~, or 70,000 t,~~ by trawlers~~ in 2007~~). The ban directly affected 263 Venezuelan trawlers, as well as Italian and Spanish vessels operating in the area. Approximately 6500 workers in the industry were displaced, and as many as 26,000 jobs were affected indirectly; supplies of the cheapest fish in the domestic market were also reduced as a result of the ban (Marquez 2009). In other cases the prohibition of trawlers has shifted employment towards other gear types~~,~~. In ~~such as~~ Qatar's after the closure of its bottom trawl fishery in 1993 the number of ~~, including a trend toward~~ larger artisanal-class vessels and artisanal fishers (+52%) and the artisanal catch (+159%) increased ~~and a 52% increase in the number of artisanal fishers as of 2001, and a 159% increase in the artisanal catch as of 2010~~ (El Sayed 1996; FAO 2003; Al-Abdulrazzak 2013; Walton et al. 2018). Similarly, bottom trawling was banned in favor of longlines around Madeira, the Azores, and Canary Islands in 2005 to protect coral reefs, where it has been estimated that one deep-sea bottom trawl will have an impact similar to 296–1719 longlines~~, depending on the morphological complexity of the impacted taxa~~ (Pham et al. 2014). Other examples of total and partial trawl bans exist in Palau (RPPL 7-17 2006), Belize (Statutory Instrument no. 10 of 2011),

**Commented [JGH12]:** Lost their jobs?

Hong Kong (Morton 2011), Costa Rica (Sala Constitucional, SC-CP-30), the Solomon Islands (2002; Fisheries Trawling or Dredging Prohibition Regulation 2002, Legal Notice no. 73) and Malaysia (1967; Ooi 1990) and Namibia (2002; Ministry of Fisheries and Marine Resources, Government Notice no. 241).

**Commented [JGH13]:** This is a very long list of examples, I don't think it is needed.

~~Palau banned all bottom trawling within its jurisdiction and by any Palauan or Palauan corporation anywhere in the world in 2006 (RPPL 7-17 2006). Belize instituted a complete and permanent ban in all its waters in 2011 (Statutory Instrument no. 10 of 2011). Hong Kong banned all bottom and pelagic trawling activities in its waters in 2012 (Morton 2011). A follow-up study suggested possible recovery of the stomatopod assemblage 3.5 y later, but highlighted the experimental complexity of detecting biological changes following a total trawl ban (Tao et al. 2018). Costa Rica declared shrimp trawling unconstitutional in 2013 (Sala Constitucional, SC-CP-30) and is planning to phase out these trawlers unless the industry is able to demonstrate that the fishery is sustainable. At the same time, the Costa Rican Government is examining potential alternative livelihoods for fishers who have been affected by the shrimp-trawl ban. Both dredging and bottom trawling are prohibited in the Solomon Islands (2002; Fisheries Trawling or Dredging Prohibition Regulation 2002, Legal Notice no. 73). The use of beam trawls has been banned in both Malaysia (1967; Ooi 1990) and Namibia (2002; Ministry of Fisheries and Marine Resources, Government Notice no. 241).~~

**Commented [JGH14]:** This is a very long list of examples.

The ecological benefits of total trawl bans are very sparsely documented in the scientific literature, but given enough time a full recovery of the seabed from trawling can be expected. On the other hand, ~~whereas t~~the societal challenges associated with trawling prohibitions are well illustrated by the experience in Indonesia (Bailey 1997; Chong et al. 1987; NCRITSTFAS 2001; Af-idati & Lee 2009; Fougères 2009; Anon. 2010; Endroyono 2017). A phased prohibition of trawling was first implemented in 1980 (Presidential Decree Number 39; Phase 1), in response to protests by small-scale traditional fishers who were impacted by shrimp trawlers operating in coastal waters~~ ()~~. Subsequent decrees extended the ban to the entire EEZ in 1982 (Presidential Letter of Instruction Number 11), but then exempted certain shrimp trawling (Arafura Sea) to offset decreased shrimp exports (1982; Presidential Decree Number 85). Despite strong community support, the trawling prohibition was relatively ineffective because of weak enforcement and because fishers renamed trawl-fishing gears so that they could be used legally (e.g. jaring arad, lampara dasar, cantrang; Anon. 2010). The Indonesian ban, however, is remarkable because trawling was the nation's most important fishing method at the time, both in terms of landings and export revenue (Bailey 1997). A subsequent decree phased out all trawl and seine fishing in Indonesian waters (2015; Phase 2; Ministerial Decree No. 2/PERMEN-KP/2015). What is clear from the Indonesian experience is that an immediate ban on trawling will cause considerable societal hardship in the short-term with potential positive outcomes only realized over a longer time period (Chong et al. 1987). For example, close to 25,000 trawl fishermen were immediately unemployed and shrimp exports dropped by 22% during the first year of the ban (1983), representing ~19% of the total value of fisheries exports. ~~In the medium term (3-5 y), the ban eliminated the supply of trawl-caught so-called "trash fish" to 13 fishmeal~~

**Commented [JGH15]:** A summary of these positive effects is missing.

~~factories; production dropped from 4,000 mt in 1980 to 6 mt in 1983, [illegible]~~ [illegible] shrimp per unit of effort by small-scale fisheries ~~at reduced distances~~closer to port and by the few remaining trawl vessels prior to expiration of their licenses (Chong et al. 1987; Endroyono 2017). The government of Indonesia is currently exploring alternative fish-capture technologies to exploit their shrimp resources (Endroyono 2017).

**Commented [JGH16]:** Ambiguous. Metric tons? Mega tons?

**Commented [bm17]:** **Petri:**
RP comment Nov 2018
Positive in the long term? See Petri's email.

Comprehensive trawling bans may be implemented for several reasons that are not mutually exclusive, one of which may be the reduction of impacts on the seabed. While this management measure protects sensitive as well as resilient habitats, it may also have severe consequences for direct and down-stream livelihoods. ~~Even seasonal prohibitions can cause significant socio-economic disruptions if alternative employment or fishing strategies are not available (Salim et al. 2010).~~ Availability and access to alternative gears, their relative efficiency, any new environmental effects (e.g. increasing entanglement of other species in static gear), and effects on catch levels and product quality are other considerations.

## 3.2 Gear design and operations

The design and operation of trawls may be modified to reduce impacts on the benthos, while maintaining an acceptable level of performance (Fig. 1; Valdemarsen and Suuronen 2003; Jennings and Revill 2007; Valdemarsen et al. 2007). Bottom trawls require some level of seabed contact to ensure that targeted species living on or within the seabed enter the net. Higher levels of bottom contact can improve capture efficiency, but may also increase net abrasion and fuel use. As such, the overall goal of fishers is to ensure adequate protection of the trawl itself (from abrasion and other sources of damage), with minimal ~~bottom contact/pressure and~~ escapement of target species under the trawl. Reductions in bottom contact also reduce trawling impacts, as the mortality of benthic invertebrates caused by trawl gears is correlated with the penetration of the gear into the seabed (Hiddink et al. 2017). ~~It is now possible to model the outcome of changing gear design without conducting gear-specific experiments using the strong relationship between the penetration depths of fishing gears and depletion of benthic biota (Hiddink et al. 2017; Szostek et al. 2017).~~

Many gear modifications are ~~adopted or mandated~~implemented to influence bottom contact and performance of trawls. For example, large-diameter rubber bobbins separated by sections of small-diameter discs create openings under the footrope that reduce unobserved mortality of commercially valuable crab species (Rose *et al*. 2010; Hammond et al. 2013), and are now required in the Bering Sea and central Gulf of Alaska flatfish fisheries (50 CFR § 679.24), resulting in an estimated 24% reduction in habitat disturbance through 2017 (Smeltz et al. 2019). Fly-wires attached to the warps (fork-rigged trawl), shortening of the warp-length-to-depth ratio, and lighter/high-aspect-ratio/maneuverable semi-pelagic trawl doors also reduce the contact area of otter trawls (Ramm et al. 1993; Brewer et al. 1996; Valdemarsen et al. 2007; Broadhurst et al. 2015). A wing that skims just above the bottom on a sumwing beam trawl reduces penetration depth by 50% and is lighter and towed slower than usual, which also reduces fuel consumption (van Marlen et al. 2009).

Electrical stimulation (pulse trawls) can be used to reduce the direct impacts of bottom trawling on benthos by reducing physical contact with the seabed. Pulse trawls are more selective for the primary target species (*Solea solea*, Soleidae) than conventional beam trawls rigged with multiple tickler chains used in the North Sea, and catch 40% less benthos and undersized fishes (van Marlen et al. 2014). In addition, pulse trawls are towed at a lower speed, around 5 knots as compared to 6-7 knots with beam trawls, and the electrodes penetrate less deeply into the seabed (Depestele et al. 2016, 2018). However, concerns still remain about limited knowledge of the effects of electricity on marine organisms and the benthic ecosystem (Soetaert et al. 2015). An unforeseen negative aspect of the use of electrical stimulation (and perhaps other groundgear modifications) is that the reduction in bottom contact enabled fishers to access new trawling grounds in areas of soft sediment (ICES 2018). As a consequence, electrical beam trawling may cause conflict with other fisheries such as the static-gear fleet that previously had almost exclusive access to areas with soft sediment. This highlights the importance of considering the societal consequences of modifying fishing gear, which may nullify environmental benefits of reduced seafloor impact due to the displacement of fishing activity into areas that were not previously exploitable. ~~In this case, a paired spatial-allocation scheme may have reduced the sector interaction.~~

~~Management measures~~ Measures that limit the weight and durability of gear may influence the trawling footprint by discouraging use in rough areas of the seabed that commonly support sensitive benthic species and habitats. For example, it has been proposed that “rockhopper” gear, which uses large tires on the footrope and a separate tension line to lift the net off the seabed and prevent gear damage after contact with a large boulder, should be banned (Norse 2005). Pelagic trawls, on the other hand, are frequently fished in smooth-bottom areas where they make occasional contact with the seafloor, particularly when targeted species are in close proximity to the seabed. Although it is common practice, bottom contact of pelagic trawls is discouraged in the Gulf of Alaska by prohibiting devices that protect the footrope. Furthermore, the proportion of time on bottom for any tow is limited to 10% by regulation (50 CFR § 679.24), which is a 75% reduction on previous estimates of unregulated bottom-contact time (NMFS 2005). Industry-sponsored studies have shown that alternative designs and materials for the scraper bar and chainmail net on Isle of Man scallop dredges can reduce the penetration depth and overall weight of scallop dredges, thereby reducing gear wear, fuel consumption, bycatch, and seabed impacts, with improved catch efficiency (Abram 2009; Humphrey 2009; Hinz et al. 2012).

Voluntary operational changes by fishers combined with innovative technology can further reduce the impacts of bottom trawls, due to efficiency gains that reduce the level of effort required to catch the quota. For example, ‘smart capture systems’ that improve control of the gear can eliminate the need for excessive weight used to stabilize gear (CRISP 2014). ~~Technologies such as the use of acoustic and video imaging for pre-catch identification and catch monitoring could potentially increase catch rates of target species, while preventing~~

~~excessively large catches that exceed the vessel's production capacity and reduce product quality (e.g. Barents Sea cod).~~

Commented [JGH18]: Interesting but not that relevant for benthic impacts I think.

~~Gear modifications that reduce bottom contact will usually reduce impacts on benthic species and habitats, relative to more localized reductions achieved with spatial controls alone.~~ However, there may be offsetting effects that are difficult to quantify. For example, elevated footropes that reduce the number of contact points on the seafloor may concentrate pressure forces over a smaller area of the seabed, which could potentially increase unobserved mortality and injury (Mensink et al. 2000; Hammond et al. 2013). Although potentially advantageous, modifying existing gear (or substituting other gears) is often problematic because their effectiveness often relies on close contact with the seabed due to the behavior of many target species (Creutzberg *et al*. 1987; Eigaard et al. 2016). Reduced catch rates, however, may be acceptable when offset by lower operating costs and less wear of the gear, once the capital costs for new lower-impact and/or energy-efficient gear are recovered. To assess such costs, the UK Sea Fish Industry Authority has produced a tool to evaluate the economic performance of gear designs and thus their commercial viability before fishers embark on costly investments in innovation (Witteveen et al. 2017).

## 3.3 Freeze fishing footprint

The impacts of trawling can be limited by ~~confined by regulation to~~confining activity to previously trawled areas. The spatial pattern of trawling is related to the distribution of fish, as well as various constraints of the fleet such as distance to port and operating costs (e.g. Hutton et al. 2004). High-resolution studies of vessel-monitoring-system (VMS) data show that trawl effort and catch are often highly concentrated in a small proportion of the available area (Amoroso et. al. 2018), especially at the level of individual fleets (Jennings & Lee 2012). Setting the boundary within which to allow fishing requires good historical information on the spatial distribution of trawling activity, as well as public consensus on the appropriate reference point(s) in time. For example, all untrawled and 'low-effort' areas in the Great Barrier Reef region of Australia were closed in 1999/2000 to prevent expansion of the trawl footprint (Pitcher et al. 2016). The state of Alaska instituted a series of measures in 2006-2009 to confine future bottom trawling to previously fished areas (50 CFR §679.22). The trawl footprint in the Northwest Atlantic Fishery Commission management region has been frozen since 2015 and exploratory fishing is only permitted after an expert assessment of the known and anticipated impacts of the proposed bottom fishing activity (NAFO 2016). In 2016, the Norwegian cod fleet voluntarily froze the trawl footprint in the Barents Sea and committed to mapping sensitive habitats as part of a fishery recertification effort (https://fiskerforum.com/trawl-footprint-frozen/).

Commented [bm19]: RP comment Nov 2018
We reported this in Pitcher et al 2016
Not sure if there is a more official source.
I don't recall there being any public consensus about the reference timeframe. BTW, that paper evaluated the benthos benefits for 5 management measures, including that particular closure.

An advantage of freezing the footprint over other forms of spatial management is that it avoids the potentially large negative effects on seabed habitats and biota that are associated with displacement of fishing effort to previously untrawled areas (Dinmore et al. 2003; Hiddink et al. 2006; Abbott and Haynie 2012). The resulting concentration of effort in the defined ground may be consistent with the choices of fishers who increasingly focus on core areas as competition for space and resources is otherwise reduced (Gillis et al. 1993; Kaiser 2005). This usually occurs without reductions in yield at least in the short term, and the potential benefits are especially significant for biogenic and deeper-water habitats with long recovery times (e.g. Clark et al. 2016). ~~However, it is important that this measure is coupled with limited or regulated fishing effort and/or quota controls so as to ensure that populations are not fished unsustainably.~~ Nevertheless, historical data show that the most heavily trawled areas can vary over time as stock abundance changes or fleet costs and preferences for target species change (Jennings et al. 2012). In these cases, freezing the footprint may prevent full and efficient exploitation of an expanding or redistributing stock, with implications for catch volumes and the economic viability of the fleet. For example, if the distribution of target species changed due to climate- or abundance-related effects (e.g. McConnaughey 1995), the fleet may be unable to follow the fish if the trawl footprint has been frozen. Other potential risks involve reducing the adaptive capacity of fleets in response to changes in fuel prices, landings sites or inclement weather, and increasing competition for space and resources (e.g. Abernethy et al 2010; Sainsbury et al. 2018).

### 3.4 Nearshore restrictions and zoning

Fisheries management areas within an EEZ may be based on fishery characteristics (e.g. artisanal versus industrial, trawl versus trap) but more often are based on administrative units (Funge-Smith et al. 2013). Creating fishing zones defined by depth or distance from the shore is a common practice within this framework. The partitioning of effort may be based on vessel size or gross tonnage, which in some cases effectively segregates different fishing gears.

Croatia is a good example of coastal zoning for a relatively small but nationally significant trawl fishery. Eleven fishing zones have been established within the Croatian EEZ, which consists of an inner fishing sea that begins at the shoreline, the territorial sea, and the offshore Protected Environmental Fishing Zone where fishing by foreign vessels is allowed (Mackelworth et al. 2011; Bitunjac et al 2016; Mikuš et al 2018). All trawl fishing is permanently prohibited within 1 nm of the mainland and island coasts. Most of the annual catch is taken just beyond in the inner fishing sea by small, old, and poorly equipped trawl vessels that have limited range and seaworthiness. As a result, a combination of fleet characteristics and regulations limit trawling to a relatively narrow band away from immature fish and shallow-water habitats. This management system has evolved to balance exploitation needs with protection of demersal resources and their essential habitats. Similarly, many countries in South and Southeast Asia have designated three or four fishery zones defined by depth or distance from shore, including specific regulations that limit bottom trawling in shallow water (Funge-Smith et al. 2013).

Coastal zoning is often intended to minimize gear conflicts between artisanal and industrial fishing fleets and reduce the incidence of gear-related impacts on sensitive nearshore (nursery) habitats such as eelgrass beds that support biodiversity and functional processes. With the imposition of a nearshore trawling restriction, fishery production from the nearshore is likely to decline until a possible compensatory increase in catches by substitute (artisanal) fishing methods and recovery of habitats and associated fish populations occurs. A regional or national system of spatial zoning by vessel class would be more formally allocative; it could be used to preferentially benefit local economies dependent on nearshore and recreational activities including small-scale and recreational fishing and eco-tourism. If zoning is introduced, the wholesale displacement of nearshore trawlers to the offshore zones is probably unlikely due to offshore management restrictions or the unsuitability of many inshore vessels for offshore fishing. However, offshore effort (and impacts) could increase over time if capital investments are made to upgrade or replace vessels for trawling on deeper, more distant, and potentially sensitive fishing grounds. Overall, nearshore restrictions to limit trawling impacts could be particularly effective when technology or resources (e.g. VMS or onboard observers) are not available to monitor and enforce the fine-scale distribution of trawling activity. In such cases, distinct wheelhouse colors assigned to different harbors combined with self-enforcement could be used as a simple control mechanism among the fishers, as practiced in SE Asia (e.g. 'sasi', Endroyono 2017).

**Commented [bm20]:** Need references?

### 3.5 Prohibitions by habitat type

Bottom trawling is commonly prohibited over habitat types that are both easily disturbed and slow to recover, such as seagrasses, sponges, corals, and other endemic or rare types of seabed communities (Freese 2001; Neckles et al. 2005; Clark et al. 2016; Kaiser et al. 2018). The size of areas designated for protection can be small or large depending on the specific management objectives and enforcement capabilities. In Australia, for example, many seagrass habitats are permanently closed to prawn trawling both as a habitat protection measure and to preserve nursery functions (Commonwealth of Australia 2013). Furthermore, numerous seamounts are closed to trawling (e.g. the Seamounts Marine Reserve off southern Tasmania), and sizable closures have been implemented to protect large sponges and other sessile epifauna (Environment Protection and Biodiversity Conservation Act 1999; Koslow et al. 2001). Other examples include prohibitions that prevent trawling over seagrass areas in Italy, France, Spain, Malta and Croatia (where coralligenous and maerl habitats also occur), over *Modiolus* reefs and sand volcanos capped with cold-water corals (Darwin Mounds) in Scotland, and on glass-sponge reefs at Hecate Strait and Queen Charlotte Sound in western Canada.

Permanent prohibitions by habitat type provide effective protection when locations of sensitive habitats can be identified and prohibitions can be introduced prior to significant physical disturbance (Howell et al. 2010). The designated areas are usually small so the benefits to overall ecosystem function and food production are limited, but they may confer economic benefits to local economies that rely on artisanal fisheries or eco-tourism (Gell and Roberts 2002). Fleets targeting species that are strongly associated with sensitive habitats may suffer reduced yields or increased competition as effort concentrates in the remaining areas (Poos & Rijnsdorp 2007). Overall, rare and sensitive habitats that are vulnerable to towed bottom-fishing gears can be effectively protected with long-term site-specific prohibitions, assuming adequate enforcement capabilities exist or voluntary compliance is effective.

Real-time closures are a variation of this management measure, whereby encounter-and-move-on rules substitute for strict avoidance of encounters. These regulations typically require a particular vessel to move a minimum distance away from the position of their last tow when the catch from that tow meets or exceeds a threshold weight or volume for a particular taxon. In practice, they do not necessarily minimize or eliminate further adverse effects on VMEs (Auster et al. 2011; Dunn et al. 2014; cf. Wallace et al. 2015). Moreover, fishing effort is likely to be displaced into similar (but less preferred) fishing grounds, which expands the trawling footprint and may increase total effort due to lower catch rates of target species (Kenchington 2011), thereby increasing overall impacts to seabed habitats and biota.   Compulsory but only temporary move-on rules thus produce unpredictable changes in effort and impacts overall, and may be better considered as secondary to other measures for reducing trawling impacts on sensitive biota.

### 3.6 Multipurpose habitat management

**Commented [JGH21]:** I'm not keen on this term. We're just discussing MPAs and spatial closures.

Trawling is commonly prohibited in designated areas, as part of a multipurpose habitat-conservation program with much broader objectives than preventing local trawling impacts (Gell and Roberts 2002). The terms marine reserve or MPA are commonly used to represent the wide range of closures of this type. In practice, most MPAs are small (median 4.6 km$^2$; Wood et al. 2008), although in 2018 70% of the total MPA coverage of 26.9 million km$^2$ was attributable to the twenty largest MPAs (https://www.protectedplanet.net/marine). Total MPA coverage is a small proportion of the world's ocean (7.4%) compared to the area of shelves and slopes to a depth of 1000 m that is not trawled for other reasons (mean 86%, Amoroso et al. 2018).

MPAs have been designated in locations that span a wide range of geographic, environmental, and socio-economic conditions. In the Asia-Pacific region alone, there are at least 726 MPAs at national, regional, and local levels (Funge-Smith 2013). Since 2006, the U.S. has protected nearly 1.8 million km$^2$ of benthic habitat from bottom trawling within MPAs, mostly in the Pacific (Hourigan 2009). In Australia, a 3.3 million km$^2$ network of national- and state-level MPAs protects representative examples of different marine ecosystems and generally avoids existing fishing grounds (CAPAD 2016; Mazor et al. 2017). A voluntary ban to protect benthic habitat in 11 deep-sea areas (309,150 km$^2$) of the southern Indian Ocean was enacted by four fishing companies (Southern Indian Ocean Deepwater Fishers Association; Anon. 2006).  Another initiative by the New Zealand fishing industry (Deepwater Group 2015) resulted in 17 Benthic Protection Areas that are off-limits to bottom trawling and dredging, contain ten major seamounts and ten active hydrothermal vents, and together comprise 30% (1.1 million km$^2$) of New Zealand's EEZ. Most of these areas are beyond 1000 m depth and so have little or no previous trawling history (Rieser et al. 2013).

Environmental effects of MPAs depend on location, biological and ecological traits of species, size and age of the MPA, the ecological connectivity among MPAs within a network, and the level of regulatory protection, ranging from no access to allowances for multiple-use (Hilborn et al. 2004; FAO 2011; Sciberras et al. 2015). In general, MPAs that are permanently closed to trawling or include zones that are closed to trawling are often designated to protect habitats that support relatively large, diverse, and productive populations of sensitive biota and associated fish species (e.g. Murawski et al. 2000, cf. Rieser et al. 2013), thus serving as useful ecological references for trawled areas. Maximum conservation benefits are expected for sessile/habitat-forming species and when aggregations of slow-growing species with moderate dispersal rates are protected from trawling (Fulton et al. 2015; Kaiser et al. 2018). However, MPAs that are not located in areas of high benthos abundance or diversity may have little impact on the state of benthic ecosystems, and can displace trawling to more sensitive areas (Hiddink et al. 2006; Sciberras et al. 2013). Fish production may be enhanced by larval export and spillover of juveniles and adults from MPAs into adjacent fisheries, but the benefits may be reduced if significant areas become unavailable to fishing, and by human behavior such as poaching and trawling along the boundary (Murawski et al. 2005). However, effort control in areas outside the MPA could prevent overexploitation of areas immediately outside protected areas and possibly allow for more fishers to benefit from spillover effects at increasing distance from the MPA boundary. The overall effectiveness of multipurpose habitat ~~management measures~~ measures to protect sensitive habitats ultimately depends on the resources available to locate candidate areas (e.g. habitat mapping), the specific management objectives, and the levels of enforcement and compliance.

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Your comment. Cite your work?

### 3.7 Invertebrate-bycatch quotas

This measure establishes quotas that limit trawl bycatch of vulnerable structure-forming species, such as coral and sponge. At present, it is being implemented for groundfish management in British Columbia, Canada where fleet-wide and individual limits are intended to reduce and manage impacts on corals and sponges (Wallace et al. 2015). The bycatch quotas are tradable between vessels, and are combined with more traditional spatial closures in areas with high coral and sponge concentrations. For example, the move-on protocol requires vessels to notify the fleet if the catch of corals and sponges in an individual tow exceeds a threshold (20 kg). This management approach meets conservation goals for sensitive biota, without reducing landings of target species or displacing fishing effort. During the first two years of the program (2012-2013), total sponge and coral bycatch was the lowest recorded in 17 years and fell well below the prescribed maximum (848 kg, Wallace et al. 2015).

**Commented [JGH23]:** But in a previous section we say that move-on does lead to displacement.

**Commented [JGH24]:** For the whole fleet or per vessel?

The application of this approach has demonstrated that an invertebrate bycatch quota can indeed reduce trawling impacts on benthic habitats. The primary limitation is the substantial resources and costs associated with 100% observer coverage and enforcement. However, in data-poor or resource-limited situations at smaller geographical scales, a self-enforcement strategy among the fishers could substitute for the fishery management authority. Although the only known use of the measure is in the British Columbia groundfish fishery, favorable conditions seem to exist in other regions, such as Alaska, Australia, and parts of Europe.

### 3.8 Habitat-impact quotas

This management measure combines detailed mapping of sensitive habitats with vessel-location tracking to monitor the aggregate impacts of trawling by each vessel in relation to an overall impact quota, as measured by time spent fishing in pre-defined habitat types (Holland and Schnier 2006a, 2006b). Vessels, for example, could use their habitat quota by fishing for long periods on less-sensitive habitats or short periods on more-sensitive habitats, with their choice of location governed by the trade-off between catch rates of target species and the rate of use of habitat quota. The primary advantage of habitat-impact quotas over invertebrate-bycatch quotas is that they do not rely on onboard observers, but on remote-vessel-tracking systems such as VMS that are a less expensive means to monitor fleet activity. The primary disadvantage is that bycatch controls based on time spent fishing rather than actual bycatch may be inherently less precise. Habitat-impact quotas also require stakeholder agreement on high-resolution habitat-sensitivity maps that may not exist and may be expensive to create.

Habitat impact quotas have not been implemented to date, but they would be powerful management tools if the objective is to limit benthic impacts from trawling. Results from a dynamic, spatially explicit fishery-simulation model indicate that individual habitat quotas were more cost-effective for achieving habitat-management objectives than both fixed and rotating closures, although effectiveness depended on characteristics of the target-species fishery (Holland and Schnier 2006a). The primary advantage of quotas over permanent closures is that they allow trawlers to access high concentrations of target species in sensitive habitats that might otherwise be unavailable to them. A negative aspect of this system is that it leaves open the possibility for some disturbance of sensitive habitats. Maintaining overall benthic habitat status would require a habitat-quota system that imposes a tariff that is proportional to the reduction in benthic status.

### 3.9 Removal of effort

Total trawling effort is related to fleet capacity and the level of fishing activity. Fleet capacity encompasses the equipment and operational characteristics of vessels operating in a fishery and is commonly expressed in terms of total vessel tonnage (or length) and total engine power, or more simply as the number of vessels (Felthoven & Paul 2004). FAO Guidelines provide information on the effects of different management programs on fleet capacity and outline the key concepts and techniques involved in monitoring, measuring, and assessing fleet capacity (FAO 2008). Fishing activity can be represented as the number of standard fishing days or trips, sets, hours trawling, area swept, or other measures, which is usually expressed on a per vessel basis and then aggregated for the fishery (Eigaard et al. 2017; Amoroso et al. 2018).

Management authorities may directly reduce total fishing effort by enacting regulations that limit the fishing capacity of individual trawlers as well as the overall capacity of the fleet. Fleet reductions through buybacks, licensing, and capacity controls can also incidentally limit the intensity and distribution of trawling and the resulting impacts of the gear on benthic habitats and communities (Section 312(b) of the Magnuson-Stevens Fishery Conservation and Management Act; Rijnsdorp et al. 2008; Beare et al. 2013; Pitcher et al. 2015; Pitcher et al. 2016).

Limiting days spent fishing is another form of effort control that has implications for fishing footprints and benthic impacts. In the Celtic Sea, the implementation of a fixed cap on days at sea on scallop vessels saw a redistribution of the fleet away from distant offshore grounds toward grounds that were closer to the coastline or major fishing ports (T. Portman, pers. comm.). In this case and perhaps in general, a zonal days-fishing approach may have been more appropriate to avoid compression of activity into coastal areas where there is potentially greater overlap with habitats and species of conservation concern.

Lowering trawling effort tends to cause a reduction in footprint and a contraction to core areas that are repeatedly fished (Kaiser 2005), with a corresponding reduction in the extent of benthic impacts. The total catch of target species may decline at first, but if the target stock is overfished then fishery production should eventually improve in response to increased survivorship of the stock~~ and reduced habitat impacts~~. Reduced competition should improve the economic performance of the remaining fishers. However, some of the benefits of regulations intended to change the level of effort can be countered by changes in one or more of the other controlling factors that affect catching power and which may not be regulated, such as changes in vessel or engine size when effort is regulated by days at sea (e.g. Eigaard et al. 2014). Total benthic impacts could inadvertently increase despite removal of effort, for example, if fishers invest their buyback grants to increase fishing capacity and move to other fisheries in more vulnerable habitats. In general, limiting effort will indirectly reduce the distribution and intensity of trawling and the associated impacts on benthic biota, and may have more positive effects than implementation of MPAs which lead to fleet redistribution (Dinmore et al. 2003; Hiddink et al. 2006; Abbott and Haynie 2012). However, effort reductions can be problematic to implement, especially in developing countries where one of the goals of management may be to employ a large number of people. It is noteworthy that the economic and societal costs of buyback programs are immediate and have a larger societal impact (Ye et al. 2013), whereas the potential ecological benefits of reduced effort tend to accrue more slowly and permit a more gradual societal readjustment to the management changes.

## 4. Management Capacity

The success of ~~management measures and industry actions~~measures will depend greatly on the management capacity of the region. Melnychuk et al. (2017) have shown that while many of the richer countries have the capacity to identify and enforce fisheries-harvest regulations and to regulate location and gear used in bottom-trawl fisheries, many other countries lack these abilities. For example, the Asia-Pacific region is a well-studied example that illustrates the challenges of open-access trawl fisheries with full-utilization markets that are managed for the "triple bottom line", namely economic, environmental, and societal goals (e.g. Pho 2007; FAO 2012, 2014). Millions of people are directly and indirectly employed by ~80,000 trawlers operating in mostly coastal areas throughout the region. Nearshore waters with characteristically sensitive habitats are particularly important; for example, 90% of the marine catch in Vietnam is taken at depths <30 m (Pho 2007). Under these circumstances, broadly applicable measures such as spatial controls have been the most widely supported (FAO 2014). In other cases, much more resource-intensive practices have been successfully implemented with the participation of multiple stakeholders, such as the invertebrate-bycatch quota system in British Columbia.

## 5. Interactions With Existing Management Systems

Based on our review of the effects of different ~~management measures~~ measures~~and voluntary industry actions~~, we conclude that there ~~will~~ can be positive or negative interactions between these and many existing management systems. These would need to be considered systematically when considering the introduction of any new measure or practice and, for this reason, we summarise such interactions and their consequences in Table 2. For example, freezing the trawl footprint to reduce benthic impacts could inadvertently affect existing catch controls (e.g. a TAC) by reducing the probability of achieving quota uptake if stock redistribution occurs but, at the same time, it is unlikely to interact with a technical measure for closed areas (Table 2). Similarly, the development of pulse trawling in the North Sea highlights the important point that any one measure will have both positive and negative consequences and suites of measures may need to be introduced simultaneously. Furthermore, interactions unrelated to fishery management might also be considered, such as protective measures intended for iconic species and de facto trawling prohibitions associated with disputed borders, shipping lanes, and hydrocarbon operations.

## 6. Fishery Yield and the Relative Benthic Status

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An evaluation of the effects of ~~management measures and industry actions~~measures on the relative impact of bottom trawling should assess the relationship between the impact on the benthos and the weight and value of landed catch. These trade-offs were discussed for ~~many~~ each ~~management measures and voluntary industry actions~~measure in section 3. Here we explore how measures and actions which change these parameters affect the trade-off between catches and benthic impacts using a simple heuristic model to explore and visualize the potential consequences of different management actions. ~~Here we explore the principles that affect these trade-offs between benthic status and fish yield.~~ The main parameters that can be changed by measures and actions are: the overall level of fishing effort; the catchability of the target species and~~,~~ the fraction of benthos removed per trawl pass, through gear modifications; and the recovery rate of the benthos that is affected by trawling, through a redistribution of fishing effort to areas with higher or lower recovery rates.

~~Here we explore how measures and actions which change these parameters affect the trade-off between catches and benthic impacts using a simple heuristic model to explore and visualize the~~

~~potential consequences of different management actions.~~ The key assumptions of the model are that fishing will result in ~~an optimum~~the highest fish yield at an intermediate level of effort, with that level depending on the catchability and the fish population growth rate, and that benthic biota decreases in abundance with increasing effort, with the magnitude of the decrease depending on the depletion and the benthos population growth rate. We implemented this by assuming that the dynamics of both the benthic biota and the exploited fish stock can be described by logistic population growth using the equilibrium solution of the Schaefer (1954). ~~(Schaefer 1954). Our approach does not consider the positive or negative effects of trawling-induced changes in benthic habitat on the productivity of the target species. The review of Collie et al. (2017) implies these are relatively small and localized in relation to the direct impacts of trawling on target stock productivity.~~

**Commented [JGH26]:** Not essential I think.

~~Using the equilibrium solution of the Schaefer (1954) model, t~~The effect of bottom trawling on benthic biota (reported as relative benthic status, RBS, defined as the current benthic biomass $B_b$ as a fraction of unimpacted benthic biomass $K_b$) can be estimated from only three parameters: depletion $d$ which is the fraction of benthic biomass killed by a trawl pass, recovery rate of the benthos $r_b$, and trawling intensity $F$ (Pitcher et al. 2017):

$$RBS = B_b/K_b = 1 - d/r_b\ F \qquad (1)$$

The effect of fishing on target stock biomass ($B_f$) can be described as:

$$B_f = K_f\ (1 - q/r_f\ F) \qquad (2)$$

Where $q$ is the catchability of the gear (the fraction of the exploited stock caught in a trawl pass), and $K_f$ is the carrying capacity for fish and $r_f$ is the recovery rate of the fish. Accordingly, fishery yield can be calculated as:

$$Y = F\ q\ B_f \qquad (3)$$

Predictions from this simple impact-yield model not only serve to reinforce metric-based evaluations, they also provide a useful description of the relationship between target-stock dynamics, maximum sustainable yield (MSY), and the RBS (Fig. 2; Table 1). In particular, technological developments of trawling gears such as elevated footropes, which reduce the $d$ to $q$ ratio (i.e. they ~~catch a larger fraction of the fish while causing a~~ lower mortality of benthic fauna; Fig. 2, curve c) are shown to reduce benthic impact per unit of fisheries yield, while gears with a higher $d/q$ ratio (Fig 2., curves a, b) do not. If gear modifications and gear prohibitions do not change the $d/q$ ratio because $d$ and $q$ decline at the same rate, then RBS will likely decrease because $F$ will need to increase proportionally to achieve the same yield. Gear and operational modifications that do not change impact on the seabed ($d$) but do increase $q$, reduce impact per unit landed weight, at least while $F \leq F_{MSY}$. Therefore, implementing any gear modifications that make a fishing gear less effective at catching the target species ~~is~~ are unlikely to have beneficial effects on the RBS when catches are maintained. Input controls to reduce fishing effort would generally increase RBS and increase yield if $F > F_{MSY}$, with the greatest increase in RBS achieved with reductions in effort for high-$d$ gears and/or in low-$r_b$ (more sensitive) areas. Better targeting of aggregations of the target species is beneficial, as it will result in a higher catch per unit effort and therefore a higher yield at a lower benthic impact.

Curve (c) in Fig. 2 represents fisheries where the ratio of the recovery rates of the benthos and the fish ($r_b$ / $r_f$) is high (i.e. benthic-fauna biomass has relatively higher rates of increase than fish biomass, and MSY is achieved at a lower $F$), while the curve (a) represents fisheries where the recovery rate for benthos ($r_b$) is lower than fish ($r_f$). The relationship shows that it may be possible to achieve a high yield with only a small reduction in RBS for trawl fisheries that exploit fish in resilient benthic habitats (high $r_b$) using gears that cause a low benthic mortality ($d$) but catch a large fraction ($q$) of the exploited stock. This relationship also implies that any form of spatial management that displaces trawling to benthic ecosystems with a higher $r_b$ will be beneficial, provided that $r_f$ remains the same (i.e. fish redistribute to those areas or have the same amount of food and productivity). ~~Moreover, freezing the trawling footprint would cause a move to the higher curves (i.e. b, c) and greater RBS, if we assume that mean $r_b$ at fished locations increases with $F$, since only the most resistant organisms survive after trawling (Hiddink et al. 2017).~~ Output controls in the form of invertebrate-bycatch or habitat-impact quotas effectively increase the RBS by moving trawling effort away from sensitive areas (low $r_b$) to more resilient (high $r_b$) areas.

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"RBS" considers Rb at F=0, i.e. R of the initial untrawled community. RBS as defined does not provide for R increasing with F.

Identifying at which point on which of these curves a fishery is currently positioned may assist in the identification of initiatives that may be most effective at reducing benthic impacts while maintaining catches.

## 7. Conclusions

A performance-based evaluation showed that best practices and the likelihood of reducing impacts of trawling on seabed habitats and biota will be influenced by the characteristics of the fishery and the ecosystem, as well as the local, regional or national values, priorities, and resources. That is, regions where protection of seabed habitats and biota is a high priority may choose to accept only a low level of impact or no impact, particularly for sensitive species such as corals and sponges. Other regions may decide that conserving a representative proportion of habitats within a network of MPAs is sufficient, or that current trawling footprints are minimal and additional measures are not required. Because of the multiple and potentially interacting policy drivers that influence the management of fisheries and their environmental impact, we anticipate that the best practices for any particular region will enhance or adjust the emphasis of the existing management system, rather than overhaul it. For these reasons, and without regional context, we cannot be prescriptive about the selection of measures to manage these impacts and how to improve trade-offs between food production and environmental protection. However, we have drawn attention to the broad range of potential practices that exist and that could be considered by managers and industry, as well as the interactions between them and the existing management system.

Based on the issues we have considered, four steps could be followed to help managers, industry, and other stakeholders, gather and generate the evidence needed to evaluate potential best practices in their region, and identify which measures would be most effective at reducing benthic impacts while maintaining fish yield. ~~.~~First, to identify all fisheries, environmental and socio-economic management objectives that may be ~~compromised~~ affected by bottom trawling. Second, to evaluate the current bottom trawling footprint and concentration of activity within this footprint, preferably using high-resolution effort data but if necessary using data-limited methods. Third, to evaluate the distribution of sensitive habitats and any other habitats of concern in relation to the footprint of trawling. Fourth, to evaluate in a regional context the effects of the alternate ~~management measures~~ measures discussed in this paper, using the information from step 2 and 3 (Table 1), both individually and in combinations, on the probability of achieving objectives identified under step 1, while taking account of interactions between potential measures, and potential measures and the existing management system (Table 2). Suitable measures would help to achieve management objectives, have all required information available and would not lead to undesirable unintended consequences. This means that the most suitable measures strongly depend on both the objectives and the data availability, which will differ between jurisdictions, which in turn means that the most suitable measures will also be different between jurisdictions.

**Commented [JGH28]:** Some of them are positively affected, compromised is only negative, right?

Other important considerations for management that seeks to reduce bottom-trawling impacts are related to the links between fishery status and seabed status, as well as access to data and tools to evaluate impacts. For regions where bottom-trawl fisheries are implicated in generating high and unsustainable rates of fishing mortality on target stocks, actions taken to meet $F_{MSY}$ reference points are likely to lead to substantial reductions in seabed impact. Amoroso et al. (2018), for example, compared rates of fishing mortality on stocks caught with bottom trawls across a >200-fold gradient in bottom trawling-footprint. In regions with bottom-trawling footprints <10% of seabed area, fishing rates on bottom-dwelling fish stocks as expressed by the ratio of $F/F_{MSY}$ were almost always less than one and were therefore sustainable. But, when trawling footprints exceeded 20% of seabed area $F/F_{MSY}$ consistently exceeded one. Although this relationship is not strictly causal given many of these stocks are also caught in other fisheries and the varying attributes of the existing management systems (Amoroso et al 2018), it does imply that achieving sustainable rates of exploitation on target stocks leads to trawl fisheries that leave large areas (typically >80%) of seabed unimpacted by bottom trawling. Improvements in stock status would also reduce the effort required to take the quota and further reduce benthic impacts per unit catch weight or value (Fig. 2), perhaps obviating the need for additional protective measures outside of particularly sensitive habitats.

**Commented [JGH29]:** Not sure what you mean here.

~~Data and tools required to assess the impact of alternative best practices are increasingly available. The main technical considerations when evaluating best practices are the footprint of the trawl fisheries and the gear-specific sensitivities of the benthic habitats and associated fauna (Table 3). Trawl footprints have already been mapped in many regions (e.g. Eigaard et al. 2017; Amoroso et al. 2018). When the requisite high-resolution spatial effort data are not available,~~

~~[illegible]~~ change. In any management system, it is therefore advisable to include an adaptive process (and funding) to monitor performance and allow for future refinements. Overall, this framework for considering best practices provides a necessary focus for stakeholder engagement in the development and ongoing evaluation of management plans concerned with the impacts of towed bottom-fishing gears on seabed habitats and biota.

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**Commented [JGH30]:** We could lose this. Partly repeats some previous text.

Finally, best practices will evolve as knowledge and experience increase or circumstances change. In any management system, it is therefore advisable to include an adaptive process (and funding) to monitor performance and allow for future refinements. Overall, this framework for considering best practices provides a necessary focus for stakeholder engagement in the development and ongoing evaluation of management plans concerned with the impacts of towed bottom-fishing gears on seabed habitats and biota.

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**Table 1.** Expected performance of the different management measures and voluntary industry actions intended to minimize trawling effects based on four evaluation metrics and predicted impacts from the yield-impact model (see text sections for references and details). Impact is expressed as effects on fractional depletion of benthic biomass per trawl pass (d) or catchability of target species (q), recovery rate of the benthos ($r_b$), and trawling intensity *(*F) on relative benthic status at regional scales (RBS; eq. 1).

| | | **Performance** | | | | |
|---|---|---|---|---|---|---|
| **Measure / Action** | **Objective** | **Benthic biota** | **Sustainable fish populations & food production** | **Ecosystems and ecosystem services** | **Fleet performance** | **Impact** |
| Prohibitions by gear type (§3.1) | Eliminate high-impact gears in a defined region. | Comprehensive protection & decreased *d*. More follow-up studies needed. | Reduced harvest of some target species if high-impact gears were more efficient. Bycatch or product-quality complications possible for different gears or fishing grounds | Increased stability & function with increased RBS. | New economic opportunities for artisanal fisheries. In the short term, reduced catches of target species unless other gears compensate. In the long term, increased costs if less efficient gears adopted. Reduced costs if less efficient gears are replaced. New transition/allocation costs & socio-economic impacts. | RBS ↑<br>d↓ |

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| Measure / Action | Objective | Performance | | | | |
|---|---|---|---|---|---|---|
| | | **Benthic biota** | **Sustainable fish populations & food production** | **Ecosystems and ecosystem services** | **Fleet performance** | **Impact** |
| Gear design & operations (§3.2) | Reduce impacts & maintain or increase catchability of target species. | Less depletion per unit effort and/or catch. Reduced gear penetration could open access to new grounds thereby increasing overall footprint. Smaller footprint if operational changes improve efficiency and/or reduce total effort. | Higher catch per unit effort and/ or catch per unit of benthic impact – may be lower if gear durability limits bottom contact. | Increased stability & function with increased RBS. Limited knowledge of electrical-stimulation effects. | Reduced operating costs for more-selective/energy-efficient/"smart" gears. Increased *F* for same yield if *d & q* decrease equally. Must recover capital costs for conversion. Extended gear life. Experimental access to closed areas. Better product quality? | RBS ↑<br>d↓<br>q↑↓ |
| Freeze fishing footprint (§3.3) | Confine impacts to previously disturbed areas. | Minimizes benthic impact on previously unfished areas. | Reduced catch if distributions of target species change. Constrains full exploitation of an expanding fishery. May prevent fishery development & overexploitation (creates *de facto* MPA). Combine with input/output controls? | Preserves ecosystem integrity & function in untrawled areas, with potential spillover benefits for trawled areas. | Opportunity costs if unable to prospect for new stocks/areas. Limits adaptive capacity. May deter development of new fleets & technologies. | RBS ↑ |

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| Measure / Action | Objective | Performance | | | | |
|---|---|---|---|---|---|---|
| | | Benthic biota | Sustainable fish populations & food production | Ecosystems and ecosystem services | Fleet performance | Impact |
| Nearshore restrictions & zoning (§3.4) | Limit trawling in shallow sensitive habitats & minimize gear conflicts. | Protects shallow or nearshore (nursery) habitats. Displaced effort could increase footprint. | Initial decline offset by future benefits if sensitive nursery areas for target species are protected, unless markets exist for juvenile stages. | Beneficial if sensitive habitats or nursery areas are included. | May be allocative, protecting nearshore/recreational fisheries & eco-tourism. Possible expenditures to increase fleet capacity for new grounds. | RBS ↑ (inshore)<br>RBS =↓ (offshore) |
| Prohibitions by habitat type (§3.5) | Protect small-scale sensitive habitats. | Beneficial when sensitive habitats identified & permanently protected – particularly useful offshore. | Probably very small because these are small areas – difficult to estimate. | Provides protected representative habitats (ecological reference points). Preserves unique ecological functions. | Lost yield if target species are strongly associated with sensitive habitats. Economic benefits for small-scale fisheries & eco-tourism. Real-time closures impose movement costs. | RBS ↑ (designated area)<br>RBS =↓ (other areas) |
| Multipurpose habitat management (§3.6) | Broadly protect essential, representative, & vulnerable habitats. | Protects sensitive habitats when trawling is restricted. Spillover effects benefit depleted areas. Displaced effort could increase footprint. | Benefits of larval export & spillover of juveniles/adults into adjacent fisheries, but may be limited by poaching & trawling along the boundary. | Spatial extent/connectivity, population/habitat characteristics, & level of protection determine benefits. Serve as ecological references for trawled areas. | No-take rules modify fishing patterns. Networks may increase recruitment/prey availability, but large networks may reduce yields. | RBS ↑ (designated area)<br>RBS =↓ (other areas) |

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| Measure / Action | Objective | Performance | | | | |
|---|---|---|---|---|---|---|
| | | **Benthic biota** | **Sustainable fish populations & food production** | **Ecosystems and ecosystem services** | **Fleet performance** | **Impact** |
| Invertebrate bycatch quotas (§3.7) | Reduce bycatch of benthic invertebrates. | Provides incentives for fleet to avoid sensitive species at much smaller spatial scale than could be regulated top-down. | Effects could be very small - needs to be evaluated. | Should reduce impacts on sensitive habitats & associated functions - needs to be evaluated. | Extra costs for observer or observer systems. More flexible than other gear/area restrictions. | RBS↑<br>~~(for defined taxa)~~ |
| Habitat-impact quotas (§3.8) | Habitat conservation to protect benthic biota. | Limits impacts by reducing effort on sensitive biota, if habitat maps exist. | Provides limited access to stocks in sensitive habitats. Effects could be very small - needs to be evaluated. | Should reduce impacts on sensitive habitats & associated functions - needs to be evaluated. | Requirement for high-frequency VMS & habitat maps may impose costs. | RBS =↑<br>$r_b$↑ in the fished areas |
| Removal of effort (§3.9) | Reduce impacts by reducing fishing activity. | Generally reduces benthic impacts (especially high-impact gears in sensitive areas). Smaller footprint will relocate/ concentrate impacts. | Yield benefits for overfished stocks only. Limiting days at sea may concentrate effort nearshore. | Generally beneficial as degraded habitats recover. | Reduced competition for those that remain, but total catch may decline. Gains offset by increasing capacity & technology "creep". Problematic for employment goals. | RBS ↑<br>F ↓<br>$B_f$ ↑ |

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**Table 2.** Examples of potential risks and benefits resulting from the interactions between a management measure to reduce the benthic impact of trawling and characteristics of the management systems in which they are applied.

**Commented [bm32]:** Are references needed?

| **Measure / Action** | **Characteristics of existing management system** | | | |
|---|---|---|---|---|
| | **Effort control** | **Catch control: TAC, ITQ** | **Technical measures: closed areas** | **Technical measures: gear** |
| Prohibitions by gear type (§3.1) | Low risk of unintended consequences. | If prohibited gear is replaced by gears with lower catch efficiency for target species then effort required to take the TAC or quota would increase with consequent risk of increases in total environmental impact. | Closed areas will limit the areas where fisheries using alternate gears may operate; may increase risk of vessel interactions & gear conflicts. | Technical measures may increase the likelihood that any gear substituted for the prohibited gear will also have high environmental impacts per unit catch. |
| Gear design and operations (§3.2) | Low risk of unintended consequences. | If modified gear reduces catch efficiency for target species then effort required to take the TAC or quota would increase with consequent risk that effectiveness of measure is reduced or compromised. | Closed areas will limit the areas where fisheries using alternate gears may operate; may increase risk of vessel interactions & gear conflicts. | Technical measures may increase the likelihood that any modified gear or operation will also have low environmental impacts per unit catch. |

| Measure / Action | Characteristics of existing management system | | | |
|---|---|---|---|---|
| | Effort control | Catch control: TAC, ITQ | Technical measures: closed areas | Technical measures: gear |
| Freeze fishing footprint (§3.3) | Limits options for the fishery to respond to changes in stock distribution, risk of increasing effort in footprint to maintain catch, leading to lower profitability. | May reduce probability of achieving quota uptake, especially in case when stock distribution is changing. | Low risk of unintended consequences. | Reduce flexibility of industry to respond to consequences of freezing footprint. May prevent changes to gear that would maintain catchability of target species. |
| Nearshore restrictions & zoning (§3.4) | Increased vessel interactions and/or gear conflicts in offshore areas. | May reduce probability of achieving quota uptake for species using nearshore areas. | Increase vessel interactions and/or gear conflicts if closed areas are not in nearshore zone. | Reduce flexibility of industry to respond to consequences of nearshore restrictions. May prevent changes to gear that would help maintain catches. |
| Prohibitions by habitat type (§3.5) | Increased vessel interactions and/or gear conflicts in areas where trawling is not prohibited. | May reduce probability of achieving quota uptake for species associated with those habitats where trawling is prohibited. | Increase vessel interactions and/or gear conflicts. | Reduce flexibility of industry to respond to consequences of prohibitions by habitat type. May prevent changes to gear that would help to maintain catches. |

Commented [bm33]: Simon: Any changes since this measure now includes real-time closures for VMEs?

| Measure / Action | Characteristics of existing management system | | | |
|---|---|---|---|---|
| | Effort control | Catch control: TAC, ITQ | Technical measures: closed areas | Technical measures: gear |
| Multipurpose habitat management (§3.6) | Low risk of unintended consequences | May reduce probability of achieving quota uptake | Low risk of unintended consequences | Reduce flexibility of industry to respond & to develop & employ gears that reduce habitat impact. |
| Invertebrate bycatch quota (§3.7) | Low risk of unintended consequences. | May reduce probability of achieving quota uptake. | Low risk of unintended consequences | Reduce flexibility of industry to respond & to develop & employ gears that reduce invertebrate bycatch. |
| Habitat impact quotas (§3.8) | Low risk of unintended consequences. | May reduce probability of achieving quota uptake. | Low risk of unintended consequences | Reduce flexibility of industry to respond & to develop & employ gears that reduce habitat impact. |
| Removal of effort (§3.9) | New measure & existing effort control are compatible. | Removal of effort may reduce probability of achieving quota uptake. | Low risk of unintended consequences. | Low risk of unintended consequences. |

1166

**Commented [bm34]:** RP comment Nov 2018
BTW, the two Pitcher et al papers (2015 & 16) both compare effort reductions and closures.
In the GBR, the effort reductions alone always did better than closures alone.
In the SE, the 2 effort reductions together usually did better than all closures together, at least for a while, but the combination of both was the better option.
Somewhere we need to make the point that often a combination of measures is simultaneously required to get benefits and avoid side-effects.

**Table 3.** Data that are useful to evaluate the potential (P), implement (I), evaluate the effectiveness (E), and improve fishery monitoring, compliance, and surveillance (C) of management measures and voluntary actions to reduce trawling impacts on seabed habitats and biota. The summary is based on references cited in the text (e.g. §3.1), or are otherwise based on consensus judgement by the authors. Light shading indicates the data type would be very useful (for P and E), while dark shading indicates the data type is required (for I and C).

| Measure / Action | Data Requirements | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ecological Impacts | | | | | | | | Fishery Impacts & Fleet Performance | | | | | | | | | | | |
| | Habitat map | | | | Gear-habitat sensitivities | | | | Catch & effort | | | | Socio-economic | | | | Spatial effort by gear (VMS, observers) | | | |
| | P | I | E | C | P | I | E | C | P | I | E | C | P | I | E | C | P | I | E | C |
| Prohibitions by gear type (§3.1) | √ | | √ | | √ | | √ | | √ | √ | √ | | | √ | √ | | | | √ | |
| Gear design & operations (§3.2) | | | | | √ | √ | | | √ | | √ | | | | √ | | | | √ | |
| Freeze fishing footprint (§3.3) | | | √ | | | | | | | | √ | | √ | ?? | √ | | | √ | | √ |
| Nearshore restrictions & zoning (§3.4) | √ | | | | √ | | | | √ | | √ | | √ | | √ | | √ | | | ?? |
| Prohibitions by habitat type (§3.5) | √ | √ | | | √ | √ | | | √ | | √ | | √ | | √ | | √ | | √ | √ |
| Multipurpose habitat management (§3.6) | √ | √ | √ | | √ | | √ | | | | √ | | √ | √ | √ | | √ | √ | √ | √ |
| Invertebrate bycatch quota (§3.7) | | | | | √ | √ | | | | | √ | | | | √ | | | | | √ |
| Habitat impact quotas (§3.8) | √ | √ | √ | √ | √ | √ | | | | | √ | | | | √ | | √ | | √ | √ |
| Removal of effort (§3.9) | √ | | √ | | √ | | √ | | √ | √ | √ | | √ | √ | √ | | √ | | √ | √ |

**Commented [bm35]:** Added to improve the level of non-prescriptive support to decision makers. Based on small-group meetings in Cartegena and Marakech.

NOTE: the info is pretty subjective. Lots of options, such as merging P & I, reducing detail to reduce debate (only using shading and its guidelines, etc.). So, freely propose changes with tracking on & add comments with rationale. If this stays in, and the edits are inconsistent, we'll have a quick conference call to reach consensus.

**Commented [JGH36]:** I think this table may cause more problems than it solves, so I would be inclined to drop it, or maybe move to SM.

**Commented [JGH37]:** So what are the ticks?

**Commented [bm38]:** Aggregate, not spatial

**Commented [bm39]:** Employment, incomes

**Commented [bm40]:** By vessel

**Commented [bm41]:** Adjust quotas for alternative gears

**Commented [bm42]:** Need to understand for (expanded) alternate gears

**Commented [bm43]:** Low-tech (self) enforcement may suffice

**Commented [bm44]:** To know history fishing disturbance prior to designation

**Commented [bm45]:** Maybe no sensitive habitats…

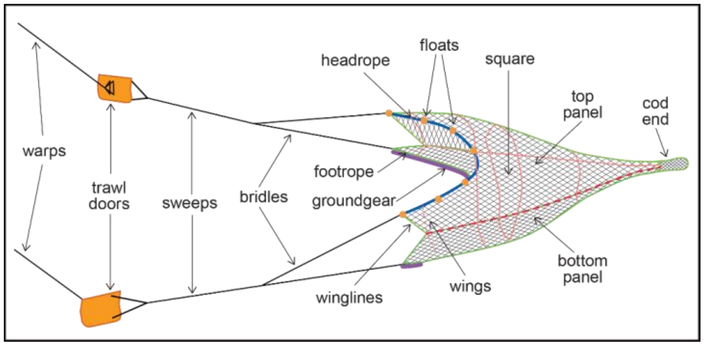


**Figure 1.** Schematic of a typical bottom trawl indicating components of the gear that can be modified to reduce benthic impacts. A typical demersal otter trawl consists of a funnel-shaped net attached to two trawl doors that open the net while it is towed through the water. The net is framed by a headrope with floats and a weighted footrope that maintain the vertical opening. The footrope is commonly made of wire or chain and may include accessories to minimize net damage resulting from contact with the seabed, ranging from small rubber disks to large spherical metal bobbins or truck tires depending on the roughness of the seabed. (Image credit to SEAFISH, adapted by R. White, NOAA.)

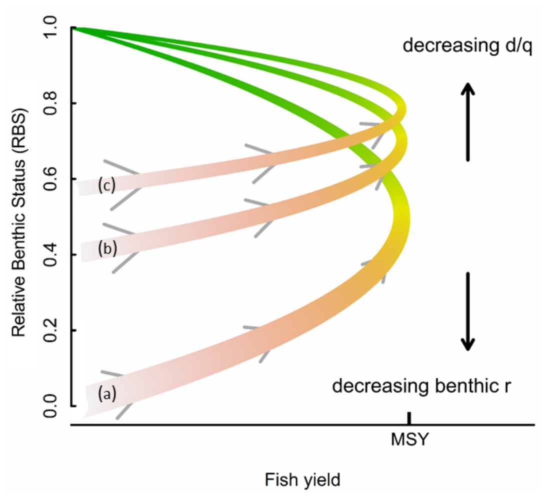


**Figure 2.** The relationship between the relative benthic status (RBS) and yield of bottom-trawl fisheries for three different scenarios. Relationship **(a)** is for fisheries with a high d/q ratio – i.e., where a trawl pass catches a low proportion of the fish present (*q*) and causes a high mortality of benthos (*d*), or where the fishery occurs on benthic communities with a low rate of recovery *r*. Relationships **(b)** and **(c)** are for fisheries with a low d/q ratio - i.e., where a trawl pass catches a high proportion of the fish present while causing low mortality of benthos, or when fishing on benthic fauna with a fast rate of recovery *r*. On parts of the curve that are not coloured green, a reduction of fishing mortality (as indicated by arrows) increases both yield and RBS. The weight of the lines is proportional to the fishing mortality *F*, indicating that fishing gears that efficiently catch the target species need a lower *F* to achieve the optimum yield at a lower benthic impact. The figure illustrates that if the fish stock is fished beyond $F_{MSY}$, a reduction in *F* will result in an increase of both yield and the benthic status (arrows in the grey to orange part of the curves). Reducing *F* from above $F_{MSY}$ to $F_{MSY}$ always reduces impacts on benthic biota and increases fishery yield, especially for gears with a high *d* and for trawling in sensitive areas with low *r*. Because this is a heuristic model, parameter values are not specified and no values are given on the x-axis as the conclusions do not depend on these values. No separate figures are shown to separate the effects of, for example, increasing *q* from decreasing d or increasing in r as they result in equivalent changes.

**Commented [bm46]:** (1) Text revised by JH 10/17/19 (Model section 4_jh.docx)

**Commented [bm47]:** **Jan:**
RP comment Nov 2018
The “catch-22” is these (VMEs) are the ones where there is interest in maintaining high status (e.g. >80% for MSC) yet the plot goes green at around RBS=0.6 … so in this case catching MSY and maintaining VMEs at >80% cannot be achieved.
This may be the reality for deep VMEs where the costs of fishing are high and the management costs are high to ensure sustainability of VMEs – and the social costs are high – so the decision may be to not fish at all.

**Commented [JGH48R47]:** True, and I think that this message could be derived from the figure even if we do not spell it out.

**Commented [bm49]:** **Jan:**
RP comment Nov 2018
Here, conversely, there is less demand to maintain the benthos at high status even though it is more achievable.

**Commented [JGH50R49]:** True.

**Commented [bm51]:** **JAN:** is MSY placed correctly??

RP comment Nov 2018
Not sure if I’m interpreting this correctly, so apologies is I’m mistaken…but The curves in the figure all lie BELOW the MSY…should the MSY label on the x-axis be placed elsewhere along the axis?

**Commented [JGH52R51]:** MSY is placed correctly. The maximum fish yield is the MSY, so of course all the curves lie to the left of MSY.