Received: 30 May 2019 | Revised: 7 November 2019 | Accepted: 13 November 2019

DOI: 10.1111/faf.12431

ORIGINAL ARTICLE

FISH and FISHERIES WILEY

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

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Funding information
David and Lucile Packard Foundation; Walton Family Foundation; Food and Agriculture Organisation of the United Nations; The Alaska Seafood Cooperative; American Seafoods Group U.S.; Blumar Seafoods Denmark; Clearwater Seafoods; Espersen Group; Glacier Fish Company LLC U.S.; Gorton's Inc.; Independent Fisheries Limited N.Z.; Nippon Suisan (USA), Inc.; Pacific Andes International Holdings, Ltd.; Pesca Chile S.A.; San Arawa, S.A.; Sanford Ltd. N.Z.; Sealord Group Ltd. N.Z.; South African Trawling Association; Trident Seafoods

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, helping to meet sustainability objectives for fisheries, conservation and environmental management. These include changes in gear design and operation of trawls, spatial controls, impact quotas and effort controls. We review nine different measures and actions and use published studies and a simple conceptual model to evaluate and compare their performance. The risks and benefits of these management measures 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. There is no universal best practice, and multiple management measures and industry actions are required to meet sustainability objectives and improve trade-offs between food production and environmental protection.

KEYWORDS
benthos, dredging, ecosystem-based fishery management, impact-yield model, trade-offs, trawling

1 | INTRODUCTION

1. INTRODUCTION	320
2. MANAGEMENT OBJECTIVES AND TRADE-OFFS	321
3. MANAGEMENT MEASURES AND INDUSTRY ACTIONS	321
3.1 Gear design and operations	321
3.2 Prohibitions by gear type	322
3.3 Freeze fishing footprint	325
3.4 Nearshore restrictions and zoning	326
3.5 Prohibitions by habitat type	326
3.6 Multipurpose habitat management	327
3.7 Invertebrate bycatch quotas	327
3.8 Habitat-impact quotas	328
3.9 Removal of effort	328
4. MANAGEMENT CAPACITY	329
5. INTERACTIONS WITH EXISTING MANAGEMENT SYSTEMS	329
6. FISHERY YIELD AND THE RELATIVE BENTHIC STATUS	329
7. CONCLUSIONS	331
ACKNOWLEDGEMENTS	333
DATA AVAILABILITY STATEMENT	333

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, Mills, Aldridge, Houghton, & Rogers, 2007; Foden, Rogers, & Jones, 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). Trawling may modify sediment texture (grain size), the presence and nature of bedforms and chemical exchange processes (Oberle, Storlazzi, & Hanebuth, 2016; Simpson & Watling, 2006). 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, Hall, Kaiser, & Poiner, 2000; Hiddink et al., 2017; Kaiser et al., 2006; McConnaughey, Syrjala, & Dew, 2005; Sciberras et al., 2018). Exposure is widespread because trawls 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; Suuronen et al., 2012; Valdemarsen, Jørgensen, & Engås, 2007).

The impacts of bottom trawling at a particular location are determined by the design of the gear and its operation, the frequency 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 & Butman 1994; Hiddink et al., 2019; Kaiser, Hormbrey, Booth, Hinz, & Hiddink, 2018) and the background level of natural disturbance (e.g., McConnaughey & 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., Jennings, Lee, & Hiddink, 2012; Kaiser, 2005), 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, Rice, & Charles, 2014). A range of management measures and voluntary industry actions 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.

Here, we review and evaluate the effectiveness of management measures and industry actions that are intended to minimize the impacts of trawling on seabed habitats and biota. These include changes in gear design and operations, 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 previous analyses of the impacts and management of trawling activities (Collie et al., 2017; Hiddink et al., 2017, 2019; Pitcher et al., 2017; Sciberras et al., 2018), 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 and the industry 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 exploitation with minimal habitat impacts or losses of ecosystem services and to ensure the unintended bycatch is minimized. Habitat protection measures may therefore limit exploitation benefits because of trade-offs. 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

In the following section, we present nine management measures and voluntary industry actions (hereafter 'measures') that can be used to reduce and manage trawling effects on seabed habitats and biota (Table 1). These measures can be grouped into four classes: (1) *technical measures* that refer to changes in gear design and operations, (2) *spatial controls* that include gear-specific prohibitions, freezing the trawling footprint, 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), (3) *impact quotas* that are output controls that include invertebrate bycatch or habitat-impact quotas and (4) *effort controls* that affect the overall amount and distribution of trawling. Several of these measures can be used simultaneously, where their relative effects depend on characteristics of the fishery, environment and management system in which they are applied.

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 for evaluation include the positive and negative effects of trawling on (a) benthic biota, (b) sustainable fish populations and food production, (c) ecosystems and ecosystem services and (d) economic performance of the fishery. In the following sections, we evaluate the efficacy of selected measures using one or a combination of these four performance metrics and predictions from a simple impact-yield model.

3.1 | 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 (Figure 1; Jennings & Revill, 2007; Valdemarsen et al., 2007; Valdemarsen & Suuronen, 2003). 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), while maximizing catch of target species under the trawl. Reductions in bottom

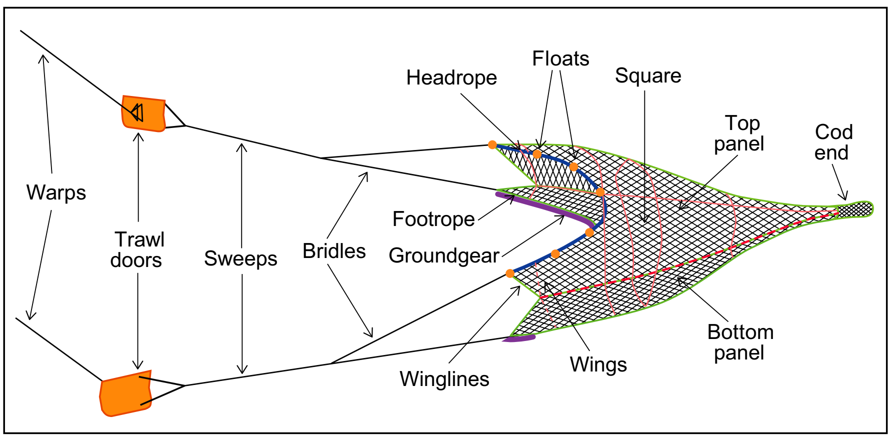

FIGURE 1 Schematic of a typical bottom trawl indicating components of the gear that can be modified to reduce benthic impacts. A typical demersal otter trawl consists of a funnel-shaped net attached to two trawl doors that open the net while it is towed through the water. The net is framed by a headrope 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.)

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).

A number of gear modifications will reduce the direct impacts of bottom trawling on benthos by reducing physical contact and penetration depth of gear within the seabed. For example, large-diameter rubber bobbins separated by rows of small-diameter discs create openings under the footrope that reduce unobserved mortality of commercially valuable crab species (Hammond, Conquest, & Rose, 2013; Rose, Gauvin, & Hammond, 2010). This design requirement reduced habitat disturbance by 24% since it was implemented in the Bering Sea (2011) and central Gulf of Alaska (2014) flatfish fisheries (50 CFR § 679.24; Smeltz, Harris, Olson, & Sethi, 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 (Brewer, Eayrs, Mounsey, & Wang, 1996; Broadhurst, Sterling, & Millar, 2015; Ramm, Mounsey, Xiao, & Poole, 1993; Valdemarsen et al., 2007). A wing that skims just above the bottom on a sumwing beam trawl reduces both penetration depth and fuel consumption by 10% (van Marlen et al., 2009). Pulse trawls in the North Sea have been shown to increase target species (*Solea solea*, Soleidae) selectivity and to catch 40% less benthos and undersized fishes compared to conventional beam trawls rigged with multiple tickler chains (van Marlen, Wiegerinck, Os-Koomen, & Barneveld, 2014). In addition, pulse trawls are towed at a lower speed, around five knots as compared to six to seven knots with beam trawls, and the electrodes penetrate less deeply into the seabed (Depestele et al., 2016, 2018). Concerns still remain about limited knowledge of the effects of electricity on marine organisms and the benthic ecosystem (Soetaert, Decostere, Polet, Verschueren, & Chiers, 2015).

Gear modifications that limit the weight and durability of gear may also 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 (50 CFR § 679.2). Industry-sponsored studies have shown that alternative designs and materials can reduce the penetration depth and overall weight of scallop dredges, thereby reducing gear wear, fuel consumption, bycatch and seabed impacts, while increasing catch efficiency (Abram, 2009; Hinz, Murray, Malcolm, & Kaiser, 2012; Humphrey, 2009).

Operational changes by fishers combined with innovative technology can further reduce the impacts of trawling, 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 and correspondingly reduce the trawling footprint (e.g., Barents Sea cod). Regulation in the Gulf of Alaska limits the proportion of time pelagic trawls may be on bottom to 10% (50 CFR § 679.24), which is a 75% reduction on previous estimates of unregulated bottom-contact time (NMFS, 2005).

Gear modifications that reduce bottom contact will usually reduce impacts on benthic species and habitats per unit of effort, 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 (Hammond et al., 2013; Mensink et al., 2000). The use of the more efficient electrical pulse trawl and expansion to new trawling grounds (ICES, 2018) may cause conflicts with other fisheries that experience reduced catch rates on shared fishing grounds (Sys, Poos, Van Meensel, Polet, & Buysse, 2016). Although potentially advantageous, modifying existing gears (or substituting other gears) is often problematic because their effectiveness often relies on close contact with the seabed due to the behaviour of many target species (Creutzberg, Duineveld, & Noort, 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, Curtis, Johnson, & Noble, 2017). Furthermore, the effects of changing gear design on benthic communities can be estimated through the strong relationship between penetration depths of fishing gears and depletion of benthic biota (Hiddink et al., 2017; Szostek et al., 2017).

3.2 | 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 by competing gears. The primary objective of gear-specific prohibitions is to shift fishing to other gears that have lower benthic impacts, such as stationary nets, pots and longlines (Pham et al., 2014; Suuronen et al., 2012). For example, the prohibition of trawling in Venezuela inshore in 2001 and territorial waters in 2009 led to increased catches by small-scale fishers who supplied 70% of annual fisheries production (compared to only 6%, or 70,000 t, by trawlers in 2007). In Qatar, the number of artisanal fishers (+52%), the artisanal catch (+159%) and the size of artisanal-class vessels increased after closure of its bottom-trawl fishery in 1993 (Al-Abdulrazzak, 2013; El Sayed, 1996; FAO, 2003; Walton et al., 2018). Bottom trawling was banned in favour of longlines around Madeira, the Azores and Canary Islands

TABLE 1 Expected performance of the different management measures and voluntary industry actions intended to minimize trawling effects

		Performance				
Measure/action	**Objective**	**Benthic biota**	**Sustainable fish populations and food production**	**Ecosystems and ecosystem services**	**Fleet performance**	**Impact**
Technical measure						
Gear design and operations (Section 3.1)	Reduce impacts and 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 and function with increased RBS. Limited knowledge of newly developed designs.	Reduced operating costs for more-selective/energy-efficient/'smart' gears. Increased *F* for same yield if *d and q* decrease equally. Must recover capital costs for conversion. Extended gear life. Experimental access to closed areas.	RBS ↑ *d*↓ *q*↑↓
Spatial controls						
Prohibitions by gear type (Section 3.2)	Eliminate high-impact gears in a defined region.	Comprehensive protection and 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 and 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 and socio-economic impacts.	RBS ↑ *d*↓
Freeze trawling footprint (Section 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 and overexploitation (creates de facto MPA).	Preserves ecosystem integrity and 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 and technologies.	RBS ↑
Nearshore restrictions and zoning (Section 3.4)	Reduce trawling in shallow sensitive habitats and 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 and eco-tourism. Possible expenditures to increase fleet capacity for new grounds.	RBS ↑ (inshore) RBS =↓ (offshore)

(Continues)

TABLE 1 (Continued)

		Performance				
Measure/action	**Objective**	**Benthic biota**	**Sustainable fish populations and food production**	**Ecosystems and ecosystem services**	**Fleet performance**	**Impact**
Prohibitions by habitat type (Section 3.5)	Protect small-scale sensitive habitats.	Beneficial when sensitive habitats identified and 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 and eco-tourism. Real-time closures impose movement costs.	RBS ↑ (designated area) RBS =↓ (other areas)
Multipurpose habitat management (Section 3.6)	Broadly protect essential, representative and vulnerable habitats.	Protects sensitive habitats when trawling is restricted. Spillover effects benefit depleted areas. Displaced effort could increase footprint.	Benefits of larval export and spillover of juveniles/adults into adjacent fisheries, but may be limited by poaching and trawling along the boundary.	Spatial extent/connectivity, population/habitat characteristics and 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) RBS =↓ (other areas)
Impact quotas						
Invertebrate bycatch quotas (Section 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 and associated functions—needs to be evaluated.	Extra costs for observer or observer systems. More flexible than other gear/area restrictions.	RBS↑
Habitat-impact quotas (Section 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 and associated functions—needs to be evaluated.	Requirement for high-frequency VMS and habitat maps may impose costs.	RBS =↑ r_b↑ in the fished areas
Effort control						
Removal of effort (Section 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 and technology 'creep'. Problematic for employment goals.	RBS ↑ *F* ↓ B_f ↑

Note: Evaluation of each measure/action is 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; Equation 1) and on target-stock biomass (B_f; Equation 2).

in 2005 to protect coral reefs, where it has been estimated that one deep-sea bottom trawl will have an impact on cold-water corals similar to 296–1,719 longlines (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), 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 specifically for beam trawls in Malaysia (1967; Ooi, 1990) and Namibia (2002; Ministry of Fisheries and Marine Resources, Government Notice no. 241).

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. The only known follow-up study suggested possible recovery of the stomatopod assemblage 3.5 years after the ban in Hong Kong, but highlighted the need for adequate experimental controls to detect biological changes after a ban (Tao et al., 2018). On the other hand, 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), 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 soon became 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 1980 Indonesian ban, however, is remarkable because trawling was the nation's most important fishing method at the time, in terms of both landings and export revenue (Bailey, 1997). Despite the trawl ban, the industrial trawler fleet in Indonesia started to increase in the 1990s (Duto, Damianus, & Mahiswara, 2013), often in the form of joint ventures with neighbour countries (e.g., Af-idati & Lee, 2009). A new Ministerial Regulation banned all types of fishing with trawls and seine nets in Indonesia effective 1 January 2017 (Ministerial Decree No. 2/PERMEN-KP/2015). The implementation of the ban has been delayed in many coastal areas but a substantial part of the industrial trawling has been phased out (Endroyono, 2017).

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, Dwiponggo, Ilyas, & Martosubroto, 1987; Endroyono, 2017). For example, close to 25,000 trawl fishers 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 years), the ban eliminated the supply of trawl-caught so-called trash fish to 13 fishmeal factories, production dropped from 4,000 t in 1980 to 6 t in 1983, and Indonesia began to import fishmeal as a result. There is anecdotal and some fishery information that indicates improvements in catch of shrimp per unit of effort by small-scale fisheries closer to port 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 its shrimp resources (Endroyono, 2017). Similarly, the ban in Venezuela directly affected 263 Venezuelan trawlers, as well as Italian and Spanish vessels operating in the area. Approximately 6,500 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). Ecological effects of the bans have not been reported.

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 measure protects sensitive as well as resilient habitats, it may also have severe consequences for direct and downstream livelihoods. Even seasonal prohibitions can cause significant socio-economic disruptions, if alternative employment or fishing strategies are not available (Salim, Vijayan, & Sandhya, 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.

3.3 | Freeze trawling footprint

The impacts of trawling can be limited by confining activities 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, Mardle, Pascoe, & Clark, 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 trawling 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). The trawling 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 is carried out (NAFO, 2016). In 2016, the Norwegian cod fleet voluntarily froze the trawling footprint in the Barents Sea and committed to mapping sensitive habitats as part of a fishery recertification effort (https://fiskerforum.com/trawl-footprint-frozen/).

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 (Abbott & Haynie, 2012; Dinmore, Duplisea, Rackham, Maxwell, & Jennings, 2003; Hiddink, Hutton, Jennings, & Kaiser, 2006). 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, Peterman, & Tyler, 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 fished sustainably. 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 trawling footprint has been frozen. Other potential risks involve reducing the adaptive capacity of fleets to respond to changes in fuel prices, landings sites or inclement weather, and increasing competition among vessels for space and resources (e.g., Abernethy, Trebilcock, Kebede, Allison, & Dulvy, 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 vs. industrial, trawl vs. trap) but more often are based on administrative units (Funge-Smith, Briggs, & Miao, 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 provides 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 (Bitunjac, Jajac, & Katavić, 2016; Mackelworth, Holcer, Jovanović, & Fortuna, 2011; Mikuš, Zrakić, Kovačićek, & Rogelj, 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 limits 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 to 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 a more formalized approach; it could be used to preferentially benefit local economies dependent on nearshore and recreational activities including small-scale and recreational fishing and eco-tourism. While the unsuitability of many inshore vessels for offshore fishing precludes nearshore trawlers from fishing in offshore zones, 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 colours assigned to different harbours 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).

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 (Clark et al., 2016; Freese, 2001; Kaiser et al., 2018; Neckles, Short, Barker, & Kopp, 2005). 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 horse mussel (*Modiolus modiolus*, Mytilidae) 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, Davies, & Narayanaswamy, 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 & 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 initiatives and compliance are effective.

Real-time closures are another type of prohibition, whereby encounter-and-move-on rules substitute for strict avoidance of encounters. Real-time closures typically require a particular vessel to move a minimum distance away from the position of its 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. Temporary, move-on rules may 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

Trawling is commonly prohibited in designated areas, as part of a multipurpose habitat-conservation programme with much broader objectives than preventing local trawling impacts (Gell & 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, Fish, Laughren, & Pauly, 2008), although 65% of the total MPA coverage of 27.2 million km^2 was attributable to the 20 largest MPAs in 2019 (https://www.protectedplanet.net/marine).

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 et al., 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, 2017; 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 10 major seamounts and 10 active hydrothermal vents and together comprise 30% (1.1 million km^2) of New Zealand's EEZ. Most of these areas are beyond 1,000 m depth and so have little or no previous trawling history (Rieser, Watling, & Guinotte, 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 (FAO, 2011; Hilborn et al., 2004; 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, Brown, Lai, Rago, & Hendrickson, 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, Wigley, Fogarty, Rago, & Mountain, 2005). The overall effectiveness of multipurpose habitat 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. The designation of areas as MPA will not necessarily mean that trawling does not occur, unless it is prevented as part of the MPA management plan and compliance is good (Dureuil, Boerder, Burnett, Froese, & Worm, 2018).

3.7 | Invertebrate-bycatch quotas

These measures establish quotas that limit trawl bycatch of vulnerable structure-forming species, such as coral and sponge. At present, they are 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). During the first two years of the programme (2012–2013), total sponge and coral bycatches were the lowest recorded in 17 years and fell well below the prescribed fleet-wide maximum target (884 kg; Wallace et al., 2015).

This management approach meets conservation goals for sensitive biota, without reducing landings of target species or displacing much fishing effort. The primary limitation is the substantial resource and cost 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 current known use of the measure is in the British Columbia groundfish fishery, favourable conditions seem to exist in other regions, such as Alaska, Australia, and parts of Europe, where such an approach could be implemented.

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 fishing activity (e.g., time or swept-area) in pre-defined habitat types (Holland & 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 fishing activity rather than actual bycatch may be inherently less precise. Habitat-impact quotas also require stakeholder agreement on the veracity of high-resolution habitat-sensitivity maps. These may not exist in many regions and are also expensive to create.

Habitat impact quotas have not been implemented in real fisheries 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 & Schnier, 2006a). The primary advantage of habitat-impact quotas over permanent closures is that they allow trawlers to evaluate where they fish in relation to catch returns per unit area of habitat disturbed. 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 programmes 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 metrics, which are usually expressed on a per-vessel basis and then aggregated for the fishery (Amoroso et al., 2018; Eigaard et al., 2017).

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. Further fleet reductions through buybacks, licensing and capacity controls can 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, Ellis, Althaus, Williams, & McLeod, 2015; Pitcher et al., 2016).

Limiting days spent fishing is another form of effort control that has implications for trawling footprints and benthic impacts. In the Celtic Sea, the implementation of a fixed cap on days at sea for 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, personal communication). 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, Marchal, Gislason, & Rijnsdorp, 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 (Abbott & Haynie, 2012; Dinmore et al., 2003; Hiddink et al., 2006). 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 programmes are immediate (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 to reduce trawling impacts on the benthos will depend greatly on the management capacity of the region. Melnychuk, Peterson, Elliott, and Hilborn (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 capacities. For example, the Asia-Pacific region provides 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., FAO, 2012, 2014; Pho, 2007). 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 measures, we conclude that there can be positive or negative interactions between these and many existing management systems. Potential interactions would therefore need to be considered systematically when considering the introduction of any new measure and, for this reason, we summarize such interactions and their consequences in Table 2. For example, freezing the trawling 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 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 need to 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

An evaluation of the effects of management 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 each measure in Section 3. The key parameters that can be changed by the measures 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 that 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 (a) fishing will result in the highest fish yield at an intermediate level of effort, whereby that level depends on the catchability and the fish-population growth rate, and (b) biomass of benthic biota decreases with increasing effort, whereby the magnitude of the decrease depends on the depletion of biota following each trawl pass and the benthos-population growth rate. The model assumes 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) model. 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.

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):

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

	Characteristics of existing management system			
Measure/action	**Effort control**	**Catch control: TAC, ITQ**	**Spatial control**	**Technical measures: gear**
Gear design and operations (Section 3.1)	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 and gear conflicts.	Technical measures may increase the likelihood that any modified gear or operation will also have low environmental impacts per unit catch.
Prohibitions by gear type (Section 3.2)	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 and 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.
Freeze trawling footprint (Section 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 and zoning (Section 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 (Section 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.
Multipurpose habitat management (Section 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 and to develop and employ gears that reduce habitat impact.
Invertebrate bycatch quota (Section 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 and to develop and employ gears that reduce invertebrate bycatch.
Habitat impact quotas (Section 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 and to develop and employ gears that reduce habitat impact.
Removal of effort (Section 3.9)	New measure and 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.

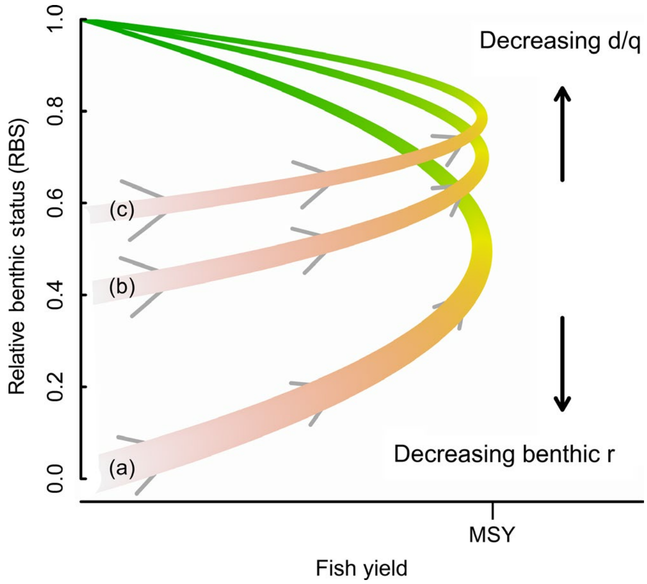

FIGURE 2 The relationship between the relative benthic status (RBS) and yield of bottom-trawl fisheries for three different scenarios. Relationship (a) is for fisheries with a high *d/q* ratio—that is where a trawl pass catches a low proportion of the fish present (*q*) and causes a high mortality of 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—that is 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

$$\mathrm{RBS} = B_b/K_b = 1 - d/r_bF \quad (1)$$

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

$$B_f = K_f(1 - q/r_fF) \quad (2)$$

where q is the catchability of the gear (the fraction of the exploited stock caught in a trawl pass), 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

$$Y = FqB_f \quad (3)$$

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 (Figure 2; Table 1). In particular, technological developments of trawling gears such as elevated footropes, which reduce the *d* to *q* ratio (Figure 2, curve c) are shown to reduce benthic impact per unit of fisheries yield, while gears with a higher *d/q* ratio (Figure 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. Modified gear and operations that do not change impact on the seabed (*d*) but do increase *q*, reduce impact per unit landed weight, at least while $F \le F_{MSY}$. Therefore, implementing any gear modifications that make a fishing gear less effective at catching the target species is unlikely to have beneficial effects on the RBS when catches are maintained. Effort control 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 Figure 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). Impact quotas in the form of invertebrate-bycatch or habitat-impact effectively increase the RBS by moving trawling effort away from sensitive areas (low r_b) to more resilient (high r_b) areas.

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

7 | CONCLUSIONS

Our 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

TABLE 3 Data needed for a preliminary evaluation and implementation (PI), and the subsequent evaluation of effectiveness and fishery monitoring, compliance and surveillance (EC) of management measures and voluntary actions to reduce trawling impacts on seabed habitats and biota (Habitat maps and gear-habitat sensitivities are primarily applicable to PI.)

Measure / Action	Data Requirements							
	Ecological Impacts		Fishery Impacts & Fleet Performance					
	Habitat map	Gear-habitat sensitivities	Catch & effort (aggregate)		Social & economic		Spatial effort by gear	
	PI	PI	PI	EC	PI	EC	PI	EC
Gear design & operations (§3.1)	Light	Light		Dark	Light	Dark	Light	Dark
Prohibitions by gear type (§3.2)	Light	Light		Dark	Light	Dark	Light	Dark
Freeze fishing footprint (§3.3)				Dark		Dark	Dark	Dark
Nearshore restrictions & zoning (§3.4)	Light	Light		Dark	Light	Dark	Light	Dark
Prohibitions by habitat type (§3.5)	Dark	Dark		Dark	Light	Dark	Light	Dark
Multipurpose habitat management (§3.6)	Light			Dark	Light	Dark	Light	Dark
Invertebrate bycatch quota (§3.7)				Dark		Dark		Dark
Habitat impact quotas (§3.8)	Dark	Dark		Dark		Dark	Light	Dark
Removal of effort (§3.9)			Dark	Dark	Light	Dark		Dark

Note: The summary is based on material cited in the text (e.g., Section 3.1) or is otherwise based on consensus judgement by the authors. Catch and effort refers to aggregate landings/logbook data. Spatial effort by gear refers to the trawling footprint based on VMS or observer information. Light shading indicates the data type would be very useful, while dark shading indicates the data type is required. A particular data type should be considered an important prerequisite for a measure if it is required for PI, EC or both.

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 to identify which measures would be most effective at reducing benthic impacts while maintaining fishery yields: first, identify all fisheries, environmental and socio-economic management objectives that may be affected by bottom trawling; second, 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, evaluate the distribution of sensitive habitats and any other habitats of concern in relation to the footprint of trawling; and fourth, evaluate in a regional context the effects of alternative management measures (Table 1), both individually and in combinations, on the probability of achieving objectives, while taking into account interactions between potential measures, and potential measures and the existing management system (Table 2). The most suitable measures strongly depend on both the objectives and the data availability, which will differ among jurisdictions, which in turn means that the most suitable measures will also be different among jurisdictions. In Table 3, we identify the data requirements for implementing management measures and for subsequent evaluation of their effectiveness in terms of ecological and socio-economic impacts and compliance.

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). Trawling footprints have already been mapped in many regions (e.g., Amoroso et al., 2018; Eigaard et al., 2017), and when the requisite high-resolution spatial effort data are not available, trawling footprints can be estimated from the relationship between the regional swept–area ratio (area trawled in one year/area of region) and footprint (Amoroso et al., 2018). Regional swept–area ratio can be estimated from the product of mean vessel speed, mean trawl width and hours of trawling summed across fleet segments. Information on the broad-scale distributions of seabed habitats (Jenkins, 1997) and results from experiments describing the gear- and habitat-specific depletion and recovery rates of benthic habitats and biota (Hiddink et al., 2017; Sciberras et al., 2018) have also been compiled. These data can be combined with footprint in a quantitative risk-assessment framework to estimate the RBS and test options for management (Mazor et al., 2017; Pitcher et al., 2017; Rijnsdorp et al., 2016). Individual-based simulation models are available to evaluate management options in both biological and economic terms, although the data requirements are considerable (Bastardie, Nielsen, & Miethe, 2014).

The linkage between fishery status and seabed status is another important consideration for management that seeks to reduce bottom-trawling 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 (Figure 2), perhaps obviating the need for additional protective measures outside of particularly sensitive habitats.

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.

ACKNOWLEDGEMENTS

The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the author(s) and do not necessarily reflect those of NOAA or the Department of Commerce. This paper is a product of the 'Trawling Best Practices Project'. The authors acknowledge their organizations for salary support. The study was funded by the David and Lucile Packard Foundation; the Walton Family Foundation; the Food and Agriculture Organisation of the United Nations; The Alaska Seafood Cooperative; American Seafoods Group U.S.; Blumar Seafoods Denmark; Clearwater Seafoods; Espersen Group; Glacier Fish Company LLC U.S.; Gorton's Inc.; Independent Fisheries Limited N.Z.; Nippon Suisan (USA), Inc.; Pacific Andes International Holdings, Ltd.; Pesca Chile S.A.; San Arawa, S.A.; Sanford Ltd. N.Z.; Sealord Group Ltd. N.Z.; South African Trawling Association; and Trident Seafoods. The authors declare there is no conflict of interest. Helpful input from A. Caveen (SEAFISH); R. Felthoven, R. Foy, S. Kotwicki, J. Lee, J. Napp, L. Rugolo, R. White (AFSC); and two anonymous reviewers improved the manuscript.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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How to cite this article: McConnaughey RA, Hiddink JG, Jennings S, et al. Choosing best practices for managing impacts of trawl fishing on seabed habitats and biota. *Fish Fish*. 2020;21:319–337. https://doi.org/10.1111/faf.12431