Recent advances in understanding the environmental footprint of trawling on the seabed

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Abstract

Bottom trawling accounts for nearly a quarter of wild-capture seafood production, but it is associated with physical disturbance of the seabed leading to changes in benthic abundance, habitat structure and biogeochemical processes. Understanding the processes of benthic depletion and recovery in relation to different types of fishing gears, and in different seabed types, is an important pre-requisite to inform appropriate management measures to limit or reduce the effects of trawling on the seabed. The combined approaches of meta-analysis and modelling that link fishing gear penetration of the seabed to benthic depletion, and recovery to taxon longevity, have enabled the development of a modelling framework to estimate relative benthic status in areas subject to trawling. Such estimations are highly sensitive to the spatial resolution at which fishing footprint (trawl track) data is aggregated, and this leads to over-inflated estimates of fishing impacts on benthos when coarse level aggregation is applied. These approaches present a framework into which other 'sustainability' criteria can be added, e.g., the consideration of carbon footprints of fishing activities.

Introduction

The environmental impacts of trawling on the seabed have generated a polarized debate in the media and scientific literature. Some have rejected the notion that bottom trawling could ever be considered as 'sustainable' (Watling and Norse 1998). This debate highlights the need to better understand the resilience of habitats and communities to different levels of trawl activity with the goal of informing management and operational practices that might mitigate the effects of trawling on the seabed environment (e.g. Lambert et al. 2014; Pitcher et al. 2017; Eigaard et al. 2017; Hiddink et al. 2018). Irrespective of the philosophical considerations of what amount of trawling activity is, or is not, sustainable, there now exist numerous international and national policies that require the scientific community to assess the impacts of bottom fishing in relation to the maintenance of marine biodiversity, essential fish habitats and other marine ecosystem processes (Freidman et al. 2018). Furthermore, approximately 24% (c. 19 MT) of global landings of wild caught fish and shellfish are harvested using trawl gears that have direct physical contact with the seabed (FAO 2016). Thus, trawling activities are a globally important harvesting practice that provides food for billions of people around the world.

For the purposes of this paper, the term 'trawl' is used to include any towed bottom fishing device that is physically in contact with the seabed (including scallop dredges, hydraulic dredges, beam and otter trawls and seine nets). From an ecological perspective, the physical interaction associated with bottom trawling is one category of physical disturbance to which habitats are exposed. In this respect, the effects of trawling should be considered in the wider context of other forms of natural and anthropogenic disturbance (e.g. hurricane disturbance, anoxia, iceberg scouring, erosion from tidal currents, seabed mining, pipeline excavation) that lead to changes in community composition or structure (Hall 1994). The magnitude of changes to, and potential for recovery of, seabed habitats and communities will be related to the intensity, frequency and spatial scale of trawling impacts as for any other source of ecological disturbance. Understanding these interactions is key to developing management strategies to limit the negative effects of trawl disturbance on benthic ecosystems to achieve desired management or conservation outcomes.

A brief historical context

Research into understanding the ecological effects of trawling on seabed habitats and their associated communities began as far back as the 1950s and 1970s, with preliminary studies designed to understand the penetration mechanics of beam trawls into the seabed (e.g. Graham 1955; Bridger 1972). Interest was then sporadic until the end of the 1980s when two consecutive European funded projects (IMPACT I and II), together with other national studies, undertook intense research programs into this issue. These programs marked a step-change in research interest in this topic around the globe, with the notable production of a series of review papers (e.g. Jones 1992; Watling & Norse 1998; Kaiser 1998). By the late 1990s there were sufficient (39) empirical studies of trawl effects on the seabed to undertake the first meta-analysis of the response of benthic biota to trawl disturbance (Collie et al. 2000). These early studies were insightful, but the rigor of these studies was often impeded by a lack of replication (i.e. pseudo-replication) and many did not even include Before After Control Impact (BACI) design principles (e.g. Eleftheriou & Robertson 1992). The lack of experimental rigor in these early studies was no doubt linked to insufficient funding to support more robust designs. In a more recent meta-analysis (Sciberras et al. 2018), many of these studies were excluded due to their lack of rigor.

In addition to financial constraints, early experimental studies were confronted with a lack of access to sufficiently accurate global positioning systems (GPS) that were necessary to enable the accurate positioning of research platforms used for the collection of samples from within experimentally trawled areas. For this reason, intertidal fishing impact studies most often were associated with the clearest outcomes (e.g. Cotter et al. 1997). The development of differential GPS and a greater access to accurate positioning was the precursor to the eventual introduction of monitoring systems (VMS) on board fishing vessels. The introduction of VMS (in Europe from the early 1990s) meant that nationally compiled data on the distribution of fleet activity and the spatial distribution of fishing activity, could be mapped by fishing gear type and in terms of fishing intensity (frequency of fishing per unit area per year) with km^2 accuracy (e.g., Lee et al. 2010) compared with the previously available spatial scales of c. 4000 km^2 (e.g. Kaiser et al. 1996). These insights revolutionized the accuracy with which the quantification of fishing impacts could be undertaken. Previously, scientists had relied on crude estimates of fishing intensity (high vs. medium vs. low) derived from more coarse scale data recorded in log-books, from overflight observations, or from records of physical injuries to animals such as bivalves or starfish (Witbaard et al. 1994; Ramsay et al. 2000). VMS data, when provided with a minimum frequency of once every 2 h, can be used to infer vessel heading, speed and hence fishing and non-fishing activities.

The analysis of VMS data soon spawned its own mini-field of research into the methodology of filtering and analyzing these activities such that non-fishing events could be excluded to provide a true insight into the gradient of fishing intensity across areas covering 10,000s km^2 (Rijnsdorp et al. 1998; Dinmore et al. 2003; Hintzen et al. 2012; Lambert et al. 2012). Knowledge of vessel identity and access to log-book records meant that the type of fishing gear used by each vessel could be inferred, and assumptions about gear width could be combined with distance towed over the ground, to compute the area swept across the seabed. Access to maps of fishing intensity enabled the scientific community to use comparative approaches to compare the composition and structure of animal communities found in areas subjected to differing intensities of fishing in comparable habitat types (e.g., Hiddink et al. 2006; Jennings et al. 2001; Aldridge et al. 2012; Mangano et al. 2013). These studies have provided a much more realistic insight into large-scale community recovery dynamics. In contrast, while small-scale experimental studies provided an accurate estimate of instantaneous mortality or depletion of community metrics such as abundance and biomass, they were acknowledged to provide estimates of post--impact recovery rates that were only applicable to small-scale impacts.

The long history of research into the impacts of trawling on the seabed means that the knowledge of this topic is now mature enough to generate sophisticated models that enable different management scenarios to be investigated in relation to community metrics such as abundance, biomass, and production. The purpose of the present paper is not to provide a comprehensive review of all the relevant literature. Rather, it will provide an overview of the very latest developments in this field and highlight remaining research gaps. Insight is also provided into the potential for the application of emerging models to inform different best-practice approaches to mitigate the physical impacts of fishing on the seabed.

Response of benthic communities to trawl impacts

Empirical studies of the effects of trawling on seabed communities fall into two broad categories: small scale experimental studies and large-scale comparative studies. Despite the scale limitations of experimental studies, they have provided a much more precisely controlled system in which to directly quantify those changes that occur in the abundance or biomass of benthic biota in response to bottom trawling. The results of each of these studies is context specific to the fishing gear under investigation, the habitat/s in which the study was undertaken, and any other context specific variables. This specificity limits the applicability of the emergent results of each study to a narrow set of circumstances. A more informative means of looking for general patterns and predictive relationships derived from published data is to use meta-analytical approaches, whereby each study becomes a 'replicate' in an overall synthesis. Two previous meta-analyses (Collie et al. 2000; Kaiser et al. 2006) integrated both experimental and comparative studies in the same analysis, with no differentiation between the two approaches. This was necessitated by the limited number of individual studies on which to perform the meta-analysis (i.e., a restricted number of 'replicates'). However, since then, there has been a more than three-fold increase in the number of both experimental and comparative studies of trawl impacts, and this culminated in two publications that have treated experimental (Sciberras et al. 2018) and comparative approaches (Hiddink et al. 2017) separately. Of equal importance, these meta-analyses were built upon a systematic review protocol (Hughes et al. 2014) which ensured that bias was not introduced through the literature search and review process, and had clearly defined inclusion and exclusion criteria for each relevant study encountered in the literature (Pullin and Knight 2009). The lack of the use of such protocols led to high variability in the quality of the main meta-analytical studies that focused on the response of marine communities to interventions, such as marine protected areas or reserves (Woodcock et al. 2017).

Quantification of the immediate effects of bottom trawling

One of the key confounding issues encountered when measuring the short-term response of benthic communities to trawl disturbance is the counter-intuitive short-term positive response (increase) shown by some fauna. Many of these positive effects are related to short-term changes in the abundance of scavenging fauna. In addition, some sessile species may become 'more abundant' due to sampling artefacts associated with the disruption that occurs to trawl-disturbed sediment, and this may lead to greater sampling efficiency by devices that penetrate the seabed. Previous empirical studies of the short-term response of scavenging fauna to trawl disturbance have demonstrated increases in abundance within trawl disturbed areas ranging from 3 – 10 times for a range of different species including fish (Kaiser & Spencer 1994; Kaiser and Ramsay 1997; Link and Almeida 2002; Demestre et al. 2000) and crustaceans (Ramsay et al. 1997; Kaiser et al. 1998). These responses are highly context specific, with factors such as prevailing tidal current strength and the local background abundance of scavenging species, affecting the strength of the responses. These increases in abundance are consistently short-lived and last no more than 72 h depending on the mobility of the scavenging fauna (e.g., Ramsay et al. 1998; Demestre et al. 2000). Despite the strength of these responses to the carrion generated through trawl disturbance, the population level impacts of these energy subsidies are negligible as consistently shown in a number of studies that have computed the potential contribution of this carrion to the annual energy budget of the scavenger population (Groenwold & Fonds 2000; Kaiser and Hiddink 2007; Collie et al. 2017).

A key innovation in the Sciberras et al. (2018) paper was that due consideration was given to the short-term abundance changes that occur within 48 h of trawl impacts due to the influx of scavengers into the trawl disturbed area. Sciberras et al. (2018) removed the responses of scavenging fauna to ensure that the change in overall community abundance would not be masked by the positive responses in scavengers that aggregated within the trawl disturbed areas. By omitting the responses observed in the first 48 h of the experimental studies, sufficient time was allowed for scavengers to disperse, after which period any carrion generated by trawling would have been removed or consumed by the scavenger community. Sciberras et al. (2018) reported that, on average, a single pass of a trawl gear reduced abundance and species richness by 26% and 19%, respectively. The strength of these effects was modified by sediment composition (% mud content), and this parameter had a significant influence on the depletion of fauna within trawled areas, such that biogenic habitats experienced the greatest depletion of fauna as a result of trawling. These responses were also highly dependent on how fishing gear interacted with sediment habitats, such that fishing gears that penetrate more deeply into the seabed have a predictably stronger effect on the reduction in species abundance and richness. The longest projected recovery times for species richness post trawl disturbance were associated with deeper penetration depths, and were particularly high for increasing penetration depth in biogenic habitats.

Quantification of the aggregated effects of fishing disturbance across trawl gradients

The advent of the use of vessel monitoring systems (VMS) and other satellite tracking devices such as AIS has revolutionized our ability to map the spatial distribution of fishing activity in both space and time. Irrespective of the scale at which these activities are mapped, the conclusion is highly consistent, i.e., that fishing activities are aggregated in space and occur repeatedly in similar locations from one year to the next (e.g., Rijnsdorp et al. 1996; Hinz et al. 2013; Kroodsma et al. 2018; Amoroso et al. 2018a).

When it is possible to link the fishing activities to the landed catch recorded in electronic log books, it becomes apparent that 90% of landed fish are derived from 'core' areas of the fishing footprint, such that the remaining 10% of catches are derived from so called 'marginal' areas (i.e., those that are fished infrequently). Although these marginal areas may support significant economic activity, the ratio of biomass of benthos removed to biomass of fish landed is probably higher than for the 'core' fishing areas, and hence, more 'costly' from an environmental or conservation perspective (Jennings et al. 2012).

In terms of understanding to what extent fishing impacts benthic communities, the insight provided by access to maps of patterns of fishing disturbance has been invaluable. These maps enable the intensity of fishing disturbance to be determined in both space and time. As a result, surveys of benthic communities can be designed that control for habitat variation and fishing intensity, and thereby, enable the cumulative large-scale effects of fishing disturbance on benthic communities to be ascertained. The attraction of such studies over small-scale experimental studies is that they are scaled to the actual spatial scale at which fishing occurs, and thus, capture the temporal scale at which ecological recovery processes occur from both active and passive immigration during post-disturbance recolonization.

There are two key parameters that can be ascertained from fishing gradient studies: the depletion (d) of benthos associated with a known intensity of fishing disturbance, and the recovery rate (r) to a given conservation or population status e.g., 80% of carrying capacity, (K). Hiddink et al. (2017) undertook a meta-analysis of comparative trawl impact studies and found that (d) was directly predicted by the depth to which a fishing gear penetrates the seabed, such that (d) is greater with increasing penetration depth. This important finding was built on the empirical evidence and modelling approaches of fishing gear penetration into seabed sediments (Eigaard et al. 2015), and provides a much more powerful predictive relationship than previous approaches that have treated fishing gear identity as a categorical variable. The attraction of using penetration depth as the predictor of (d), assuming that an average penetration depth can be measured empirically or estimated through modelling, is that it is possible to estimate (d) for any gear type (including novel gear designs such as electric 'pulse' trawls [Depestele et al. 2018]), and hence, compute their impact on benthic communities.

A further extension of this research has shown that taxon longevity predicts recovery rate (Rijnsdorp et al. 2018; Hiddink et al. 2018). The latter finding concurs with expectations based on our understanding of the likely response of long-lived species (Jennings et al. 2002). These expectations were underlined in a 10 year study of the response of rock reef fauna to fishing disturbance. This study showed that shorter-lived species with long duration larval phases had more rapid recovery rates (e.g., scallops 2-3 yrs, soft corals <5 years) compared to longer-lived species with low larval dispersal capabilities (e.g., gorgonians ~ 17 years, bryozoans ~ 20 years, sponges ~ 50 years) (Kaiser et al. 2018). The implications of such findings are that when trawling overlaps with areas inhabited by long-lived species, these communities will be held in an alternative stable state for many decades due to their low resilience to disturbance. Given that ecological data is typically lacking for benthic taxa in many parts of the world, models that can predict post-trawl impact recovery rates, based on an understanding of more generic parameters, will be more broadly applicable to a wider range of situations, and hence, more useful for management.

Consequences for fish production

Considering that trawling leads to the depletion of benthic biomass, this will result in a seabed that is a mosaic of biomass-depleted, recovering and unfished areas, at different spatial scales. While there is no empirical evidence of increases in populations of scavenging species that can utilize carrion associated with trawl disturbances, there remains the possibility that the prey resources for fish and other benthivorous species may be degraded with potential consequences for fish survivorship or condition. This issue has been largely overlooked, and is no doubt linked to the perception that some fish are highly mobile species capable of moving or migrating over large distances. However, this view overlooks the typical movement pattern of fishes when they are concentrated in feeding areas. Based on empirical observations, we know that the same species of fish may exhibit very different condition indices across a wide range of habitat types, and that this indicates potential differences in 'the quality' of feeding grounds at spatial scales of 50 km or more (Hinz et al. 2003; Shucksmith et al. 2005; Hiddink et al. 2008). In addition, fish are attracted towards trawl disturbed areas where they aggregate. However, the energy subsidies from trawl related carrion are short-lived as outlined already. The outcome is that fish (and other scavengers) may find themselves within a degraded prey field, where prey are less abundance and perhaps of lower quality (i.e., energy density) compared to untrawled areas. Evidence for these effects is found in ~~a~~

papers describing studies from contrasting areas including the Mediterranean, the Irish Sea and the Baltic Sea (Hiddink et al. 2008; Lloret et al. 2012; Johnson et al. 2015; Hiddink et al. 2017; Mangano et al. 2018). In each of these examples, either the diet or the condition indices of benthivorous fishes such as plaice, dab and red mullet were most strongly affected (lowered) in areas subject to higher levels of trawl intensity, although these responses were not always consistent among studies. Fishes that had multiple modes of feeding (e.g~~.~~., gadoids) were able to compensate for reduced benthic prey availability by feeding in midwater on fishes and crustaceans (Hiddink et al. 2008). Modelling studies of the possibility that trawling could reduce fish production indicate that when prey that are least resilient to trawling are the most profitable (in terms of energetic reward), a negative impact on condition is anticipated, whereas positive effects are predicted when systems are bottom-up controlled or when fish predation is relatively unimportant (ecologically) relative to other factors that limit the benthos (Van Denderen et al. 2013). This remains an understudied area of research, and would greatly benefit from small scale acoustic tagging studies aimed at understanding the spatial pattern of movement and habitat use by fish when confronted with a mosaic of different quality habitats.

Impacts on biogeochemistry and geophysical properties

Most studies of the impacts of trawling have focused on biological responses, whereas far fewer have studied the implications of physical disturbance by bottom trawls on the geophysical properties of the sediment habitat and on the biogeochemical processes associated with changes in sediment structure and community composition. From the few studies undertaken, the general conclusion is that the effects on nutrient exchange and other biogeochemical processes are far more pronounced in finer sediments than in coarse sediment environments, which is no doubt related to the greater microbial activity associated with finer sediments (Sparks-McConkey & Watling 2001). Shelf systems are prone to a wide range of natural disturbances from wave action (where shear stresses reach to the seabed) and daily tidal currents. Diesing et al. (2013) computed the relative impact of natural and trawl related disturbance for the shelf seas around the coast of the UK, and were able to map those areas of the seabed where fishing was likely to lead to greater seabed erosion that natural disturbance. This study revealed that half of the shelf in the greater North Sea experiences increased levels of natural disturbance in terms of the amount of sediment that is resuspended compared with sediment resuspension associated with bottom trawling. Trawl effects on sediment resuspension were greatest in areas of the shelf where wave and tidal energy were low. The effects of trawling on sediment properties are more pronounced as depth increases. Planques et al. (2012) demonstrated that trawl related resuspension of fine muddy sediments under stratified waters led to the production of a fine nepheloid layer at the sediment-water interface that was subject to resuspension on several successive tides. This indicates that the fine sediments within trawl tracks become unconsolidated, and are themselves more prone to erosion by natural physical processes, in the immediate period following initial disturbance. In a recent study of an intensively trawled area off the NW Iberian Peninsula, Oberle et al. (2016) found that trawling caused a significant increase in the off-shelf transport of sediment, and that this resulted in a depleted sediment budget in the system. The implications of this study have wider potential ramifications for animal communities on the continental shelf slope that would receive the sediment subsidy (and presumably organic matter) arising from the elevated levels of sediment resuspension. Finally, Puig et al. (2012) reported how intense trawling in the Mediterranean along the edges of canyons running off the shelf and down the continental slope increased the frequency of underwater landslides, and hence, the frequency of sediments smothering fauna on the canyon floor. In summary, geophysical effects are likely to be greatest in areas where natural disturbances are relatively infrequent and where physical energy from currents and waves is low.

Mapping fishing impacts

As outlined above, the advent of satellite and other means of tracking fishing vessel activity has revolutionized our understanding of patterns of fishing, and has spawned its own subset of research. It is rare for scientists to have access to high accuracy tracking data on a temporal scale of < 15 minutes polling frequency. It is more typical for data to be available at polling intervals of 2 hours or more. Systems such as VMS were designed for the purpose of enforcement and were not envisaged as research tools. As a result, VMS has various limitations, which include reduced accessibility for the scientific community. This results in the aggregation of fishing data for third party use to protect fisher confidentiality. However, this lack of data accessibility inevitably leads to an over-estimate of the spatial footprint of fishing, and hence, inflation of the projected impact of trawling on the seabed (Hinz et al. 2011). In the context of conservation management, if a fishing disturbance trigger point was defined in relation to ecosystem-based management, the use of aggregated data would most probably lead to the closure of a fishery sooner than if high resolution data was available for the relevant computations of seabed disturbance (Hinz et al. 2011).

Computation of the area of contact between a fishing gear and the seabed is a key issue if the depletion of benthos associated with a single pass of fishing gear across an area of seabed is to be computed. This requires knowledge of two metrics, the width of the fishing gear (and its average penetration depth) and the distance towed. Calculation of the distance towed is relatively simple if fishing occurs in straight lines. However, for some fishing activities this is a flawed assumption. For example, scallop dredging often requires fishers to fish complex figure of eight patterns as they exploit spatially restricted areas of seabed (see Shepperson et al. 2017). Irrespective of the limitations of the data, the resultant outputs of the computation of swept area of individual trawl tracks will result in a mosaic of disturbed (at different frequencies) and undisturbed areas of the seabed. The spatial scale at which such data is reported is a key consideration when portraying the resultant outputs. It follows that the higher the resolution of the data the more representative it will be of the real footprint of fishing disturbance. The importance of such considerations was made clear in recent papers in which fishing patterns were either selectively shown at a coarse scale or reported at a range of scales. Kroodsma et al. (2018) reported global patterns of fishing disturbance derived from AIS data, but showed this in the main body of the paper as aggregated at a coarse scale (0.5 degree resolution). This led to the conclusion that >50% of the globe is fished. In contrast, two other papers highlight the potentially misleading perception of the extent of fishing that such coarse-scale aggregations provide (Amoroso et al. 2018a, b). The latter papers demonstrated that when fine-scale (0.01 degree resolution) positioning data are used, for some areas of the world very little of the seabed down to 1000 m is fished,; in contrast to the perception provided when the data were aggregated at coarse scales. In the critique of the Kroodsma et al. (2018) paper by Amoroso et al. (2018a) the latter demonstrated that the scale of aggregation used by Kroodsma et al. (2018) inflated the apparent footprint of trawling by a factor of 7.4 and 9.8 for illustrative regional areas of the North and South Pacific, respectively. The introduction of inaccuracies into the estimation of fishing footprint has inevitable consequences for the estimation of the reduction in benthic abundance (biomass) as a result of fishing. This is illustrated in Figure 1, where it is assumed that the impact of fishing is uniformly distributed across the seabed. The estimate of benthic depletion drops to 1.7% for the North Pacific, and to 0.6% for the South Pacific, as compared to the values of 13.8 and 9.9%, respectively, as provided in Amoroso et al. (2018a).

Inevitably, finer grained position data of fishing activity provides a much more useful and accurate portrayal of the extent of fishing footprints. Hence, it is ironic that it is the fishing industry that is least enthusiastic to share such data. This reluctance is no doubt due to concerns that the outputs of an evaluation of fishing footprint would lead to the generation of a map that could reveal specific fishing locations. However, while a map is useful to managers, it is certainly not a requirement to report the status of defined areas in relation to seabed disturbance (see Figure 2). A much more useful output is a frequency histogram showing the number of cells in a given area that are subject to different frequencies of fishing. Such an output would permit an annual evaluation of changes in the shape of the frequency distribution as a means to evaluate changes in fishing performance with respect to seabed disturbance (Figure 2).

Risk based analysis and other potential environmental performance indicators

From the perspective of managing (limiting) the consequences of bottom trawling on benthic communities, the estimation of depletion and recovery, and the ability to map the frequency and intensity of trawling footprints, are essential components if an assessment of the status of benthic communities is to be performed. Further refinement of this computational approach can be achieved if we have access to maps of habitat type and information of the distribution of different components of the benthic community. This also assumes that depletion and recovery of the benthos differs with habitat and life-history traits. The outcome of integrating these separate parameters into a risk-based framework is an output that provides insights into the status of benthic fauna relative to a starting condition prior to trawl disturbance. Pitcher et al. (2017) and Mazor et al. (2017) demonstrated how this approach can be applied to large sea-basin scaled areas. Although the approach sounds quite data intensive, it can be simplified to compute the average response of the whole community biomass to trawling. This estimate would be without reference to any variation introduced by habitat specific variables and thus, would require suitable precaution in the absence of finer grained data on habitat type and taxon specific information.

Linkages to other environmental performance indicators

Relative benthic status (RBS) could be just one of a number of environmental performance metrics that are likely to be altered by changes in the footprint of trawl-based fisheries. For example, given access to more detailed information on fishing tracks, and with the potential to link haul by haul catches to particular tows, it is feasible to quantify the energy consumption per unit weight of fish landed. The latter would form the basis for estimates of the Energy Return on Investment (EROI). This parameter enables the harvesting of fish using trawls to be compared to other forms of fishing and other forms of protein production (e.g., terrestrial food productions systems). When fisheries are well managed with appropriate incentives for fishers to improve their environmental performance, the outcome can be impressive.

A good example of this approach is a scallop fishery in the Isle of Man (Irish Sea) where the government introduced a Territorial User Rights Fishery that was integrated into a conservation zone (Bloor et al. in press). The fishery (for scallops) had strict management criteria, and was well informed by industry participatory scallop surveys in advance of the open season for the fishery. The environmental and financial performance of this fishery compared to the surrounding open access areas was impressive, with a 6-fold reduction in fuel consumption per weight of scallops landed. The fishery quota was achieved from 3% of the available fishing area, i.e., 97% of the available area remained unfished. Vessels were fitted with a GPS enabled position recorder that logged vessel position every minute. The vessels also had log books in which tow by tow landings were recorded. In addition, seabed habitats were well mapped from previous video and underwater camera surveys. While it may seem prohibitive for many of the world's fisheries to have access to such data, in this case-study, the relevant information was either provided by the fishing industry (e.g., GPS and logbook data) or collected within a 2 year time-frame with industry collaboration (habitat data). The collation of this type of data is not restricted to industrial fleets, as GPS technology is widely available through mobile phone applications.

Summary

Bottom trawling remains an important and policy relevant issue of scrutiny, particularly in relation to concerns about the conservation status of seabed habitats and long-lived species. The research focus stimulated by such concerns has resulted in a maturing area of science sufficient to inform predictive models that can be used to explore the outcome of different management scenarios. Insights offered through the use of technology mean that it is possible to evaluate the environmental cost of fish and shellfish production associated with trawling, and hence, evaluate both different approaches to spatial management and the possible benefits of technical advances (e.g., through fishing gear modifications; Suuronen et al. 2015). Stakeholders remain concerned about the trade-off between the economic benefits of trawl fishing, and its impact on the marine environment as demonstrated in a recent prioritization of knowledge needs exercise (Kaiser et al. 2016). The need to evaluate different approaches to managing the impact of bottom trawling requires a framework such as the development of best-practice guidelines for bottom trawling. Such a framework, would be informed by the approaches outlined in the present study, together with economic and social considerations of consequences of management actions. Current evidence suggests that well-managed fisheries reduce seabed impact (in terms of the extent, and hence, the depletion of benthos) compared with those fisheries for which management is lacking.

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Figure 1: The outcome of using coarse scale (0.5 degree) and fine scale (0.01 degree) gridding resolution for the estimation of the swept area ratio of seabed disturbance by trawling which underpins the calculation of the depletion of benthic faunal abundance. Here, it is assumed that a 26% reduction in abundance of benthos occurs with a single pass of a trawl across the seabed and assumes a uniform distribution of trawl activity (Sciberras et al. 2018). The examples given are for areas of the North and South Pacific as illustrated by Amoroso et al. (2018).

Figure 2: Hypothetical change in the proportion of geographically defined 'cells' within a give area of the seabed that experience a reducing trawling footprint from year 1 (black bars) to year 2 (grey bars). The increase in cells that experience no trawling in year 2, and the reduction in the percentage of cells with other values of relative benthic status (RBS), leads a steepening curve. The slope of this curve could be used as an indicator of improving benthic status over time. An RBS value of 1 = no impact from fishing, whereas 0 = complete removal of benthos by fishing.