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Prioritisation of knowledge needs to achieve best practices for bottom-trawling in relation to seabed habitats

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Abstract

Management and technical approaches that achieve a sustainable level of fish production while at the same time minimising or limiting the wider ecological effects caused through fishing gear contact with the seabed might be considered to be ‘best practice’. To identify future knowledge-needs that would help to support a transition towards the adoption of best practices for trawling a prioritisation exercise was undertaken with a group of 39 practitioners from the seafood industry and management, and 13 research scientists who have an active research interest in bottom-trawl and dredge fisheries. A list of 108 knowledge-needs related to trawl and dredge fisheries was developed in conjunction with an ‘expert task force’. The long list was further refined through a three stage process of voting and scoring, including discussions of each knowledge-need. The top 25 knowledge-needs are presented, as scored separately by practitioners and scientists. There was considerable consistency in the priorities identified by these two groups. The top priority knowledge-need to improve current understanding on the distribution and extent of different habitat types also reinforced the concomitant need for the provision and access to data on the spatial and temporal distribution of all forms of towed bottom-fishing activities. Many of the other top 25 knowledge-needs concerned the evaluation of different management approaches or implementation of different fishing practices, particularly those that explore trade-offs between effects of bottom-trawling on biodiversity and ecosystem services and the benefits of fish production as food.

Keywords: Habitat impact, knowledge-needs, trawl fisheries, best practices

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Introduction

Approximately sixteen million tonnes of wild captured fish and shellfish are caught annually using bottom trawls and dredges, comprising about twenty percent of global landings (Watson *et al.,* 2006). Bottom trawls and dredges have become the subject of considerable controversy due to their interaction with seabed habitats and their associated fauna. Some claim that any trawl fishery is unsustainable due to its environmental and ecosystem impacts (Watling & Norse, 1998; Jacquet *et al.,* 2010); leading to calls for bans of some types of trawling (Morton, 2011; Roberts, 2012; Watling, 2013). Trawls and dredges typically use trawl doors, heavy ground ropes, chains or tooth bars to displace, herd and guide fish and shellfish from the seabed into nets. These gear components physically disturb the seabed and its associated flora and fauna (Eigaard *et al.,* in press). The effects of different fishing gears on the seabed vary considerably among gear types and according to the environmental context in which they are fished (reviewed in Stephan *et al.,* 2000; Collie *et al.,* 2000; NRC, 2002; Løkkeborg, 2005; Kaiser *et al.,* 2006; Grabowski *et al.,* 2014). The effects of disturbance from fishing gear can be relatively minor and short-lived in some habitats (e.g. McConnaughy & Syrjala, 2014, Sciberras *et al.,* 2013, Stokesbury and Harris, 2006), and in others, severe and long-lasting, especially in habitats formed by living organisms (e.g. Turner *et al.,* 1999; Beukema, 1995; Hall-Spencer & Moore, 2000; Koslow *et al.,* 2001; Cook *et al.,* 2013; Clark *et al.,* 2015).

The ecological effects of bottom-fishing with trawls and dredges on non-target benthic invertebrates have been summarized in review papers (Jennings & Kaiser, 1998; Kaiser *et al.,* 2002; Thrush & Dayton, 2002) as well as meta-analyses that quantify the relationship between the fishing gear and habitat type and the mortality of benthic invertebrates (Auster, 1998; Collie *et al.,* 2000, Kaiser *et al.,* 2006). These meta-analyses lead to the conclusion that the effects of bottom-trawling on benthic invertebrates may include reductions in biomass, diversity and body size, changes in the functional trait composition of the community (e.g. McConnaughey *et al.,* 2005; Tillin *et al.,* 2005). Furthermore the effects differ greatly between different fishing gears and habitats (Collie *et al.,* 2000; Kaiser *et al.,* 2006). While the latter studies have informed the degree of impact of bottom trawling under different environmental and biological conditions, there has been a concomitant focus on gear design and deployment to reduce the area of contact or pressure exerted to the seabed (He, 2007; He & Winger, 2010). Current research has demonstrated that trawl designs can be made lighter or fished in a manner that has less contact area without significantly affecting the catch rate of target species, while presumably reducing the mortality of escaping animals (Rose *et al.*, 2010) or reducing fuel consumption (Suuronen *et al.*, 2012).

The changes in benthic ecosystems that result from the physical contact of bottom-trawl fisheries with the seabed are the focus of an increasing number of legislative initiatives. For example, in the U.S., reauthorization of the Magnuson-Stevens Fishery Conservation and Management Act (Sustainable Fisheries Act, SFA) in October 1996 (Benaka, 1999) mandated fisheries managers to consider the implications of fishing on those habitats upon which the fish depend at key life history stages (Essential Fish Habitat; e.g. Link, 2002). In Europe, the Marine Strategy Framework Directive requires Member States to put in place measures to achieve Good Environmental Status (GES) for marine waters (EU, 2008). The effects of seabed disturbance by trawling is regarded as an impact that may compromise GES (Rice *et al.*, 2010). The New Zealand government with the support of the fishing industry implemented Fisheries (Benthic Protection Areas) Regulations 2007, closing 1.2 million square kilometres of seabed to bottom trawling and dredging (Rieser *et al.*, 2013). Recent amendments to the Chilean Law of Fisheries and Aquaculture have been made for protecting vulnerable and sensitive habitats (implementing protection for 117 seamounts) within it Exclusive Economic Zone from bottom trawling (Hernández-Salas, 2015).

The impacts of bottom trawling on the seabed and the associated mortality of non-target species often concern consumers, especially in wealthy countries, and have thus come to play a central role in consumer-driven information campaigns about product choice. The impact of fishing gear on the seabed is a scoring factor in many sustainable seafood recommendation systems that are aimed at members of the general public and seafood businesses (e.g. Environmental Defense Fund Seafood Selector: www.seafood.edf.org; Monterey Bay Aquarium Seafood Watch: www.seafoodwatch.org;

World Wildlife Fun Sustainable Seafood Consumer Guides: www.wwf.panda.org). Furthermore the Marine Stewardship Council recently revised its standard such that it now places a much stronger emphasis on the evaluation of the effects of trawl gear on seabed habitats and their associated biota.

Considering the need to maintain the yield from wild capture fisheries to feed an increasing world population, there is a pressing need to evaluate whether trawl and dredge fisheries may impact the productivity of demersal fish species that depend on specific habitats for food and shelter (Auster & Langton, 1999). For the reasons above, the issue of trawl and dredge impacts on seabed habitats and fauna remains an important policy and management question at a global level. This policy need has continued to stimulate considerable investment in experimental and comparative studies to quantify the effects of different fishing gears in different environmental contexts. As such it is timely to ask the science and practitioner community to identify the key questions in this area that need to be addressed to inform appropriate policy and management.

The concept and process of knowledge exchange is increasingly receiving attention from funding agencies as a means to maximise the impact of public expenditure on research. The identification of knowledge-needs relevant to policymakers and practitioners is itself a research exercise, for which there exists a systematic methodology (Sutherland *et al.*, 2006, 2011). This systematic methodology is tried and tested for a variety of fields of ecology (Table 1) and the strength of this process lies in the implementation of a collaborative, cross-sectoral approach based on 'experiential, theoretical and empirical knowledge' (Nutley *et al.*, 2007; Dicks *et al.*, 2012).

The process and its outputs have had a high impact, specifically in shaping national science policies. For example, in the U.K. Government's Marine Science Strategy research questions across each section were acknowledged as being informed by the 'U.K. 100 ecology questions exercise' (Sutherland *et al.*, 2006). Moreover, the questions identified by Jones *et al.* (2014) stimulated a £10M investment in aquaculture research by the national research councils while outputs of the prioritisation exercise were also used to frame the structure of the research call.

Bottom trawling takes place in most of the world’s oceans, so the present paper seeks to identify and prioritise global knowledge gaps that, if addressed, would lead to significant advances in the development of best practices for bottom-trawl fisheries (including dredging) globally, such that fisheries production could be maintained (or increased) while minimising adverse impacts on the seabed and its constituent fauna.

Methods

Hereafter, and unless otherwise stated, we use the phrases ‘bottom-trawl fisheries’ and ‘bottom trawling’ to include all towed fishing gears that have physical contact with the seabed; including otter and beam trawls, seines and dredges (this definition could also extend to other fishing activities that directly impact the substratum such as hand raking). To identify and prioritise knowledge-needs necessary to inform the development of best practices for bottom-trawl fisheries, a two-stage process was implemented based on the method of Sutherland *et al.*, (2011) and Dicks *et al.*, (2012). In stage one; knowledge-needs were collaboratively identified by a wide range of stakeholders (Annex 1). In stage two, the resultant list of needs that had been generated was prioritised during two voting sessions followed by a final scoring session. The generation of knowledge-needs and initial voting session were conducted remotely (using on-line voting). The final voting and scoring sessions were conducted at a one-day workshop held in the New England Aquarium, Boston, MA, U.S.A. on the 18th March 2015.

Who was involved?

In total, 52 stakeholders participated in one or more stages of the process and are included as authors of the present study (thus their addresses demonstrate the breadth of the participation). Participants involved in the process were based in 11 different countries (Australia, Argentina, Canada, Chile, China, Denmark, New Zealand, Norway, Spain, U.K., U.S.) and were categorised as either ‘research scientists’ (n=13) or ‘practitioners’ (n=39). The practitioners were drawn from the fishing industry (16), processing industry (8), environmental Non-Governmental Organisations (11) and Government agencies (3) and one inter-governmental organisation. The term ‘research scientist’ refers to participants that are actively engaged in research focused on understanding the how trawling interacts with the seabed or engaged in research to mitigate these effects through the use of technical modifications to the fishing gear. In addition to the 52 stakeholders, 12 expert scientists with a range of specialisms (ranging across population and ecological modelling, trawl impact experiments and fishing gear technology) were selected to help the discussion of knowledge-needs throughout the process, these individuals were termed ‘the expert task force’. Of this group, only two individuals participated in the final scoring of the priority questions to ensure broader representation from the wider scientist community.

Identification of knowledge-needs

The process is summarised in a flow diagram (Figure 1). The 64 Participants were asked to consult widely (which drew together the views of a further 56 stakeholders) and then to identify areas where scientific knowledge is most needed (and is currently lacking) to underpin the development of best-practice. Best-practice was defined as bottom-trawling that would achieve sustainable fisheries production while minimising adverse impacts on the environment (Figure 1). Each participant was requested to submit up to ten specific knowledge-needs that could be answerable through scientific research within a three to five year period. As a guide, participants were provided with example knowledge-needs developed through a comparable exercise that had focused improving the environmental sustainability of aquaculture for the UK food system (Jones *et al.*, 2014). Knowledge-needs with a similar theme were grouped by MJK and scrutinised by the expert task force. Each knowledge-need featured on the list just once. Categories of knowledge-needs (Table 2) were identified post-hoc to facilitate the face-to-face process at the final stage of the prioritisation exercise.

Prioritisation of knowledge-needs

In the first voting stage, participants voted remotely on the long list of knowledge-needs. The original wording of the individual knowledge-needs was retained to avoid misinterpretation of the author’s intention and to ensure transparency in the process. Participants were asked to select the 20% of the items listed within each category that represented the most pressing knowledge-needs required to underpin best management practice of bottom-trawl fishing. Participants were invited to make anonymous comments and/or suggest alternative wording for a specific knowledge-need. The knowledge-needs in each category were ranked according to the number of votes that each received. The number of votes that were allocated to each of the questions were visible to participants during the subsequent workshop.

At the workshop, knowledge-needs were discussed during 90-minute sessions dedicated to each of the four categories (Table 2). Four sessions ran in parallel, therefore each participant was involved in three discussion sessions (two separate categories and the final plenary session). Each session had approximately equal numbers of participants and captured a wide range of interests and expertise which is best-practice as recommended by social-psychologists (Hussler *et al.*, 2011; Yaniv, 2011). As the discussion sessions were designed to be practitioner-led, groups contained a maximum of eight research scientists to prevent them dominating the discussion. Group numbers were small enough to encourage discussion, yet large enough to enable a consensus position to be reached. Research scientists were able to provide insight into completed and on-going research surrounding each knowledge-need. Practitioners were asked to identify knowledge-needs that, if met, would lead to their organisations changing policy or practice, with the objective of enhancing the sustainability of their catches or supplies. Each session had a non-voting chairperson to facilitate the discussion process without influencing the decisions.

Knowledge-needs with more votes were allocated more discussion time. Nevertheless, sufficient opportunity was afforded to discuss knowledge-needs with few or no votes as previous experience demonstrates that some of these questions may be promoted after discussion (for method and rationale see Dicks *et al.*, 2013). At this stage any re-wording or amalgamation of knowledge-needs was established through group consensus. Through discussion, knowledge-needs were eliminated to create a short list within each category. A maximum of 25% of the original list was retained. A list of 26 knowledge-needs, drawn from across all four category sessions, was generated but not ranked (e.g. Dicks *et al.*, 2013).

A plenary session was dedicated to the final voting stage and involved all workshop participants. Each of the 26 knowledge-needs was briefly outlined (for the benefit of those who had not been in the relevant sessions). Further rewording of the questions was permitted to improve clarity but only with consensus of the group. Individual participants privately scored each knowledge-need on a scale between 1 and 10, with 10 equal to highest importance. Participants were requested to score across the full range of values. Workshop chairpersons and observers neither voted nor scored the questions at any stage.

Data analysis

Based on the 108 original knowledge-needs a final list of the top 25 priority knowledge-needs was identified according to median practitioner scores (Table 3). When median practitioner scores were equal across knowledge-needs, ranking was determined by combining both practitioners and research scientist scores, and in the case of continued ties, thereafter ranked according to the lowest inter-quartile range (least variability amongst scores). While a decision was made to rank the top 25 knowledge-needs according to practitioners' scores in order to emphasize information gaps relevant to stakeholders directly involved in the management and implementation of commercial fisheries, scoring between scientist and practitioner groups was highly consistent (see below).

A Friedman test (Friedman 1940) was used to identify whether any of the top 25 knowledge-needs were scored significantly differently from others. In order to understand to what extent practitioners and scientists agreed or disagreed in their prioritisation of the top 25 knowledge- needs, we used a suite of tests. First, we examined the strength of relationship between median scores for knowledge-needs for practitioners and median scores for scientists using Spearman rank correlation and simple linear regression. Second, we investigated the pattern of differences in the ranking given to each of the top 25 knowledge-needs between the practitioner and scientist groups using one-way analysis of similarity (ANOSIM) and non-metric multidimensional scaling implemented in PRIMER version 6.1 (Plymouth Routines in Multivariate Ecological Research, Plymouth Marine Laboratory, Plymouth, U.K.; Clarke, 1993; Clarke & Gorley, 2006). Non-metric multidimensional scaling utilized a resemblance matrix calculated with the Bray-Curtis coefficient on untransformed data (Bray & Curtis, 1957; Field *et al.*, 1982).

Results

Of the 108 potential knowledge-needs that were split into four categories, 26 were promoted through to the final scoring session (Annex 2; Annex 3; Table 2), of which the 25 top ranked priority knowledge-needs were identified through the scores generated by the participants (i.e. one knowledge need was dropped from the list as it was ranked 26th) (Table 3). Median scores for practitioners and research scientists are presented separately (Table 3). Knowledge-needs from each of the four categories are represented in the top 10 priority knowledge-needs identified by practitioners (Table 3). Interestingly, the knowledge-need *'What is the extent and distribution of different seabed habitat types?'* which was the top ranked knowledge-need by both practitioners and scientists achieved only one vote in the original list of 108 knowledge-needs. Significant differences occurred between the scores attributed to the top 25 knowledge-needs (Friedman test, χ^2=135.2, d.f. = 24, P<0.001) which indicated that there was a robust basis on which to prioritize them.

The median scores obtained from practitioners and research scientists were strongly positively correlated for each of the top 25 knowledge-needs from across the themes and hence indicated agreement among practitioners and scientists (Figure 2; Spearman rank correlation=0.68, P=0.0003). Simple linear regression indicated that a 95% confidence interval for the slope between median practitioner scores and median scientists' scores includes 1.0 (Figure 2; slope coefficient = 1.20, SE = 0.28, P=0.0004, 95% confidence interval = 0.68, 1.80). Differences between median scores for practitioners and scientists were subtle. The lowest median score for any of the top knowledge-needs for practitioners (range=6.0,10.0) was larger than the lowest median score for scientists (range=4.0,10.0). The two groups had high agreement (low median score discrepancy) for the top-ranked and bottom-ranked knowledge-needs, with somewhat more variability in median scores for the middle-ranked knowledge-needs (Figure 3). This variability was typified by two questions in particular; Q16 was scored more highly by scientists and was much more specific, whereas Q64 was score more highly by practitioners but dealt with much broader and interacting issues. However despite these individual discrepancies, the analysis of similarity of the scoring given to individual knowledge-needs revealed no significant difference in the scoring patterns amongst knowledge-needs between practitioners and research scientists (ANOSIM, R= 0.057, P= 0.26). Multivariate analysis revealed that the scientist and practitioner scores did not differ in terms of the scores given within each category of the top 25 knowledge-needs (Figure 4; Ecosystem effects and productivity, ANOSIM, R=0.01, P=0.47; Direct effects, ANOSIM, R= -0.074, P=0.20; Operational, ANOSIM, R=0.08, P=0.20; Management and indicators, ANOSIM, R= 0.08, P=0.20).

Discussion

The scoring between practitioners and research scientists was remarkably consistent within and between discussion sessions and it was not possible to separate the scores of the two groups statistically. There was sufficient differentiation between the individual knowledge-needs to allow them to be differentiated statistically and hence prioritised. The differentiation between the knowledge-needs is important if the outcome is to be used as a basis for prioritizing research funding or investment in the acquisition of knowledge that would make a significant difference to the environmental performance of fishing or businesses that depend upon fishing.

Both practitioners and research scientists agreed consistently that the top priority knowledge-need was '*Q94 - What is the extent and distribution of different seabed habitat types?*' which had a median score of 10 and the lowest inter-quartile range (1.5). This consensus is reassuring given the wide range of stakeholders engaged throughout the process, but underlines the importance of understanding better the overlap between bottom-trawl fishing and different habitat types. The extent and distribution of some marine habitats such as shallow coral reefs and seagrass beds is relatively easily determined using remote sensing technology such as satellite imaging, however for the majority of seabed that occurs in areas with high water turbidity or below the depth of 50 m our knowledge is limited to direct sampling of the seabed or ad hoc surveys using acoustic technologies (see Kenny *et* *al.,* 2003). Thus any attempt to understand the consequences of bottom-trawling on seabed habitats is likely to be prone to variable amounts of error depending on the quality of the underlying habitat information that is available for the relevant location.

The focus on 'knowledge gathering' to address specific questions is perhaps indicative of a relatively mature area of science for which understanding the key issues are quite well understood. This contrasts with the recent 'aquaculture' prioritisation exercise (Jones *et al.,* 2014) for which a mechanism of knowledge exchange was deemed to be the highest priority knowledge-need. In the case of bottom-trawl fishing there exist already management mechanisms and legal instruments that integrate a consideration of the interaction between bottom-trawling gears and seabed habitats (e.g. the Magnuson–Stevens Fishery Conservation and Management Act (MFCMA) and in Europe the Marine Strategy Framework Directive). Furthermore there have been a number of attempts to develop risk evaluation matrices into which existing empirical information can be fed and the outputs used to advise on management actions (e.g. NRC, 2008; Eno *et al.,* 2013).

All four of the categories of research needs were represented in the top 10 of the top 25 knowledge-needs. However, the category 'Management and indicators' was most prominent with six knowledge-needs in the top 10. Of these, the second ranked question (*Q53 - What level of trawl fishing impact on other ecosystem services is acceptable such that sustainable seafood production can be maintained?*) is interesting in that it seeks to understand the biological threshold of change to ecosystem services that can occur as a result of bottom -trawling without impeding sustainable food production from the sea, but at the same time taking account of the wider societal view of what level of change society is prepared to tolerate. While there exist well established targets for what can be considered sustainable levels of exploitation of harvested species (e.g. a fishing mortality associated with maximum sustainable yield, F_{MSY}) there exist few similar management or conservation targets specifically for wider ecosystem services (Carwardine *et al.,* 2009). Some biodiversity conservation policy initiatives have addressed the latter to some extent, with targets to protect or maintain a proportion of features (e.g. 30% by area) within networks of marine reserves (Natural England and Joint Nature Conservation Committee, 2010). These are set to meet objectives such as improving or maintaining biodiversity (De Santo & Jones, 2007; Day *et al.*, 2008). A novel example of reference points for benthic fauna has been developed in Canada in relation to coral and sponge bycatch through an agreement between the fishing industry and a coalition of environmental non-governmental organisations (Fisheries and Oceans Canada, 2013). The knowledge-need on acceptable impacts also implies that the biological responses of the stock and the associated changes in ecosystem services that result from bottom-trawling need to be weighed against the social and economic outcomes given different scenarios of bottom-trawling. Information on these trade-offs would be used to inform the debate about what is acceptable.

Knowledge- needs Q44 (rank 3) and Q50 (rank 6) were closely associated with Q53 above. Firstly, as for the top priority question, Q50 addresses the need to understand how much bottom-trawling activity occurs and where this is located. While we have access to vessel monitoring system (VMS) data in many developed countries (e.g. Piet & Hintzen, 2012) the resolution of these data are often restricted through confidentiality such that it becomes less useful to answer scientific questions such as Q50 (e.g. Hinz *et al.*, 2012). Furthermore these data are usually only available for a selection of vessels (e.g. in Europe all vessels >12 m in length) such that there is no information for the more numerous remainder of the fleet. In many developing countries either VMS does not exist or there is limited capacity to process this data. Q44 evolved as an amalgamation of three of the original questions that all sought to evaluate the performance of different management measures using spatial, effort-based or technical measures (fishing gear design, configuration or operation). It is impossible to answer this question without a good understanding of the spatial and temporal distribution of fishing activity (Q50). While spatial management measures may be the only means to protect sessile or site specific conservation features, the displacement of fishing effort into adjacent waters where target species may be less abundant, can lead to negative outcomes depending on the biodiversity conservation or fisheries management objective (Hiddink *et al.*, 2006).

Knowledge-needs Q15 (rank 4), Q6 (rank 5), Q63 (rank 8) and Q83 (rank 13) were all closely related in that they dealt with understanding the recoverability of habitats in relation to trawling, how we evaluate the associated changes in habitat status and how these changes relate to the changes that occur in response to natural disturbances. It should be noted that these knowledge-needs are equally relevant in the context of improving performance in relation to biodiversity conservation. Specifically Q15 seeks to understand whether we can use the physical and biological attributes of seabed habitats and the environment in which they occur (i.e. the water column processes overlying them) to infer resilience (and recovery) from bottom-trawl impacts. A large number of empirical studies have demonstrated the wide range of responses of different habitats to different types of fishing gear (reviewed in Kaiser *et al.*, 2006), but only recently have large scale comparative studies started to address the issue of recovery post-fishing at spatial scales that are appropriate (e.g. Sciberras *et al.*, 2013; McConnaughey *et al.*, 2014). Understanding which combination of habitat variables predicts recovery would facilitate the development of broad scale predictive maps of habitat sensitivity that could be used for management purposes (see Hiddink *et al.*, 2007). Linked to this, Q63 seeks to understand to what extent bottom-trawl disturbance differs from, or is similar to, natural perturbations of marine habitats which set the natural background context within which fishing occurs. For example, it is often cited that shallow nearshore areas that are subject to winter storms are more resilient to bottom fishing disturbance (e.g. Kaiser *et al.*, 2002), but the effects of that fishing disturbance may have more profound effects on the habitat if it occurs in the summer c.f. the winter when many benthic biota are senescent (van Denderen *et al.*, 2015). McConnaughey and Syrjala (2014) suggested that the benthic habitat in their Bering Sea study area is affected more by natural storm events than trawl disturbance. If we are to assess change in seabed habitats and their biota in relation to fishing this implies that we understand the status of those habitats prior to the commencement of fishing. Q6 emphasises that at present we have no established reference points against which to evaluate the effects of trawling that could be used to trigger management action, although Holland and Schnier (2006) have suggested the use of ‘habitat quotas’ as a means of limiting the effects of trawling on the seabed. Extending this idea further (Q83), beyond the initial impact of a single trawl disturbance of the seabed, it is important to understand the additional effects of repeated trawling within the original trawl footprint in a way that is quantifiable (e.g. Hiddink *et al.*, 2006). Indeed, participants cited the continued productivity of trawled areas as a key question among users of bottom-trawl gears when considering habitat impacts.

In the last decade, there has been considerable research investment in attempting to design fishing gear that have reduced contact with the seabed and by implication reduced impacts on physical and biological attributes of the seabed (e.g. Suuronen *et al.,* 2012). For example, in the North Sea flatfish fisheries, the tickler chain beam trawl gear is being replaced by electrical bottom trawls with a reduced bottom impact and bycatch of benthic invertebrates (van Marlen *et al.,* 2014; Depestele *et al.,* 2015). Six of the knowledge-needs addressed issues that were to some extent related to understanding better the interaction between fishing gear and the seabed or improving catch efficiency in a way that reduces seabed interaction (Q13 rank #7; Q102 rank #10; Q16 rank #11; Q18 rank #17; Q34 rank #18; Q12 rank #20). To date, most evaluations of the effects of fishing gear on benthic communities have made no differentiation between the impact of the different components of the fishing gear (e.g. Collie *et al.,* 2000; Kaiser *et al.,* 2006). However, as there is now greater scrutiny of the effects associated with bottom-trawl fishing and greater capability to assess them, it will become increasingly necessary to understand more precisely which components of fishing gear are responsible for direct contact with the seabed (Q16) (Eigaard *et al.,* in press). The need to identify and to devise mitigation measures through modifications to gear designs and/or operational methods is also identified as a priority (Q102). Indeed some designs and methods are available for adoption in different bottom trawl fisheries with local tests and adaptation (He and Winger 2010; Moran and Stephenson 2010).

Understanding how to measure these interactions and which measurements provide a predictive basis to infer ecological consequences on the seabed is important from a management perspective. For example, in the case of European scallop dredge fisheries, there is a tendency to assume that the tooth bars on the dredge have the largest impact on benthic fauna, whereas the scouring of the steel-ringed belly bag is the element of the gear that has the largest effect on the seabed (Hinz *et al.,* 2012). Q12 recognises the need of managers to have a consistent means of categorising gear in terms of the interaction that each has with the marine environment such that the effects of one gear can be objectively assessed against other options. For that reason, understanding the interaction of different gear components with the seabed is highly relevant (Eigaard *et al.,* in press).

The lower ranked of the top 25 knowledge-needs (Q32 rank #21, Q43 rank #23, Q42 rank #25) were related to understanding how the spatial configuration of bottom-trawling interacts with seabed habitats at differing landscape scales. At the broadest biogeographic scale, fishing tends to be highly aggregated (e.g. Rijnsdorp *et al.,* 1996; Mangano *et al.,* 2014) and while the small scale (~3 km) effects of trawl fishing will alter benthic community and habitat structure over different timescales, these effects may be relatively small if accounted for at a larger scale. Furthermore, the configuration of unfished areas of the seabed among and around the sites of trawl fishing may play a critical role in facilitating the recovery of fished areas of the seabed (Lambert *et al.,* 2014) and may facilitate the survivorship of different life-history stages of commercially important species of fish (e.g. Walters & Juanes, 1993). In some cases bottom-trawling could enhance or replace habitat complexity through the creation of scour pits and ridges (e.g. in mud habitats) that would normally be generated by bioturbating megafauna, however this remains speculation without formal investigation.

Finally, bottom-trawling may impact the productivity (Q30 rank #12, Q97 rank #9) of demersal fish species that depend on seabed habitats for food and shelter (Auster& Langton, 1999). For example, trawling may negatively affect prey availability, potentially leading to reduced food intake, body condition and yield of fishes in chronically trawled areas (Hiddink *et al.,* 2011; Johnson *et al.,* 2014 ; but see van Denderen *et al.,* 2013). Removal of sessile epifauna, like sponges and corals, could also increase exposure of juvenile fish to predators. These indirect effects of trawling through changes in habitat and food availability occur next to the direct removal of target fish biomass that would occur with any fishing gear. For these indirect effects to be important, their negative effects on fish productivity would need to be larger than the effect of the release from competition caused by the reduction in fish stocks. The latter requires evaluation at the appropriate spatial scales if these effects are to be included in appropriate management plans that seek to maximise efficient food production through fisheries while limiting effects of bottom-trawling on the seabed in a proportionate manner. Undertaking a full environmental and efficiency evaluation of fish production using bottom-trawls would be particularly useful in evaluating the potential advantages or disadvantages of alternative approaches to harvesting wild capture species (Q21 rank #24).

Next steps

The knowledge-needs identified through the current exercise are already quite specific and many are additive in that answering one knowledge-need would facilitate progress towards another (e.g. Q94 and Q50 underpin the many of the other knowledge-needs). Future research in this field should continue to draw upon the combined knowledge of producers, processors, retailers and eNGOs, government representatives and research scientists. Continuation of collaborative work across sectors, including iterative discussions, will facilitate ongoing appraisal of the extent to which the priority knowledge-needs identified are being met by emerging knowledge and where knowledge gaps remain.

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Conflicts of interest

With the exception of the scientist authors listed, all remaining authors represented the interests of organisations in this process. We do not interpret this as a conflict of interest because the process was designed to take account of a wide range of interests, including those of commercial, government and other organisations (Annex 1).

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Table 1. Natural science topics for which the prioritisation of research knowledge-needs has been undertaken.

Ecology	Sutherland *et al.*, 2006
Agriculture	Pretty *et al.*, 2010
Conservation of wild insect pollinators	Dicks *et al.*, 2012
UK food security	Ingrams *et al.*, 2013
Poverty alleviation	Sutherland *et al.*, 2013
Aquaculture	Jones *et al.*, 2014

Table 2: Content of the four knowledge-need categories necessary to inform the development of best practices for bottom-trawl fisheries.

Category	Key	Description of proposed knowledge-needs
Direct effects	D	Direct physical effects on either the geological or biological features of the seabed habitat.
Ecosystem and production	E	Wider ecosystem effects of disturbance of the seabed that occurs as a result of bottom-trawling, consequences for fisheries production.
Operational	O	Alteration to the design of existing fishing gear, or use of alternative fishing gears, or changes to the mechanism of fishing that alleviate contact with the seabed.
Management and indicators	M	Evaluation of the efficacy of different approaches or applications of knowledge to mitigate the effects of fishing on the seabed, examination of trade-offs between production of fish as food and the consequences of bottom-trawling, indicators of seabed habitat and faunal status in relation to bottom-trawling and natural disturbance.

Table 3: Top 25 priority knowledge-needs necessary to inform the development of best practices for bottom-trawl fisheries. The knowledge-needs are ranked by median practitioner score (P_MD; 1= low priority, 10= high priority). When practitioner scores were equal, knowledge-needs were ranked according to overall medians (both practitioner and scientist median scores (T_MD)) then according to lowest inter-quartile range (IR). Scientist median scores are given separately (S_MD). Category codes are explained in Table 2. The original question number is shown in the left-hand column.

Rank	Number	**Knowledge-needs**	Category	P_MD	S_MD	T_MD
1	94	What is the extent and distribution of different seabed habitat types?	M	10	10	10
2	53	What level of trawl fishing impact on other ecosystem services is acceptable such that sustainable seafood production can be maintained?	M	9	8	9
3	44	What are the relative benefits of spatial management to constrain the trawl fleet footprint versus trawl effort and technical (gear modification) controls, and how can we evaluate the outcomes of using different combinations of these management measures?	M	8	8	8
4	15	What are the habitat-related variables (e.g., biota, substratum type, current flow, etc) that determine resilience (recovery time) to disturbance from different types of trawling and in different benthic habitats?	E	8	8	8
5	6	What are the reference points and indicators of habitat status that are needed to assess the sustainability of trawling within any particular habitat, and can we define the thresholds beyond which habitat change is irreversible?	M	8	8	8
6	50	What is the spatial and temporal extent and variation in the intensity of bottom-trawling activity for all vessels?	M	8	9	8
7	13	What kind of information do we need to quantify about seabed habitats, and about the mode of operation, prevailing environmental conditions and attributes of fishing gear to understand their interaction?	D	8	9	8
8	63	How does the disturbance by towed gear and subsequent recovery rate of habitats and biological communities differ from the frequency, timing, and magnitude of natural perturbations experienced by seabed habitats?	E	8	8	8
9	97	What is the functional relationship between the biological and physical attributes of the seabed and the survival and reproduction of managed stocks?	E	8	9	8
10	102	What gear configurations (e.g. semi-pelagic) exist to mitigate habitat impacts and how can these benefits be quantified (e.g. through numerical models, physical models in a flume tank, or use of technology or direct observation)?	O	7.5	9	8
11	16	What role does the entire fishing gear and its individual components, such as the doors, sweeps/bridles and footrope, play in the disturbance of different habitat types?	D	7.5	10	8
12	30	Does the management of the effects of trawling on the seafloor result in a change in the productivity of managed stocks?	E	7.5	6	7
13	83	Within areas that have a history of being trawled, what ongoing ecosystem changes occur by continuing to trawl within the trawl footprint?	E	7.5	7	7
14	100	How do we evaluate risks and the opportunities associated with trawling in areas that presently are not trawled?	M	7.5	5	7

15	62	How do different types of benthic structure-forming biota differ in their susceptibility to impacts from towed gear and their ability to recover after such impacts?	D	7	8	7
16	57	How can we enhance the knowledge obtained from past comparisons between trawled, previously trawled and untrawled areas to extract more specific information on the magnitude of trawl-induced change?	D	7	5	7
17	18	How can knowledge of fish distribution and behaviour, such as aggregation and flight response, be better used to increase efficiency and/or reduce bottom time for bottom-trawl gear?	O	7	6	7
18	34	How can we identify an optimal seabed clearance range to achieve both efficient fish capture and avoid seabed impacts?	O	7	5	6
19	64	To what extent are the impacts of towed fishing gear mediated by variation in habitat susceptibility, in species recovery rates and in spatial overlaps between distribution of fishing effort intensity and the distribution of habitats?	D	7	4	6
20	12	What types of attributes and gear characteristics can be used to provide a consistent and systematic way of ranking or measuring the relative impact of different fishing gears across the same range of different habitats?	D	6.5	6	6
21	32	To what extent does the spatial and temporal pattern of trawling, and variable impacts within trawl tracks, create a pattern of effective refuges within fished areas and how does this vary by fishery and fishing intensity?	D	6.5	6	6
22	56	In the absence of specific survey data, to what extent can the distributions of species and habitats vulnerable to trawling be predicted with sufficient reliability to enable successful assessments and management responses?	M	6.5	6	6
23	43	What are the wider seascape scale ecological consequences of the interaction between the spatial arrangement of habitat and trawling?	E	6	6	6
24	21	What are the economic costs and total environmental impacts per unit value of fish caught, and how does this compare to other gears and practices?	O	6	7	6
25	42	What influence do scour marks and topographic changes from trawl gear components have on benthic community structure?	E	6	5	6

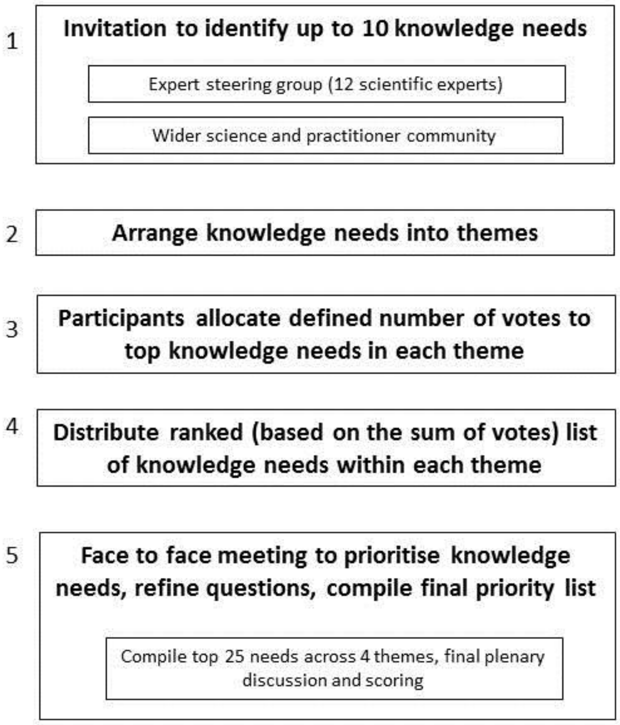

Figure 1: Schematic flow diagram to illustrate the different stages in the prioritisation process as described in the methodology.

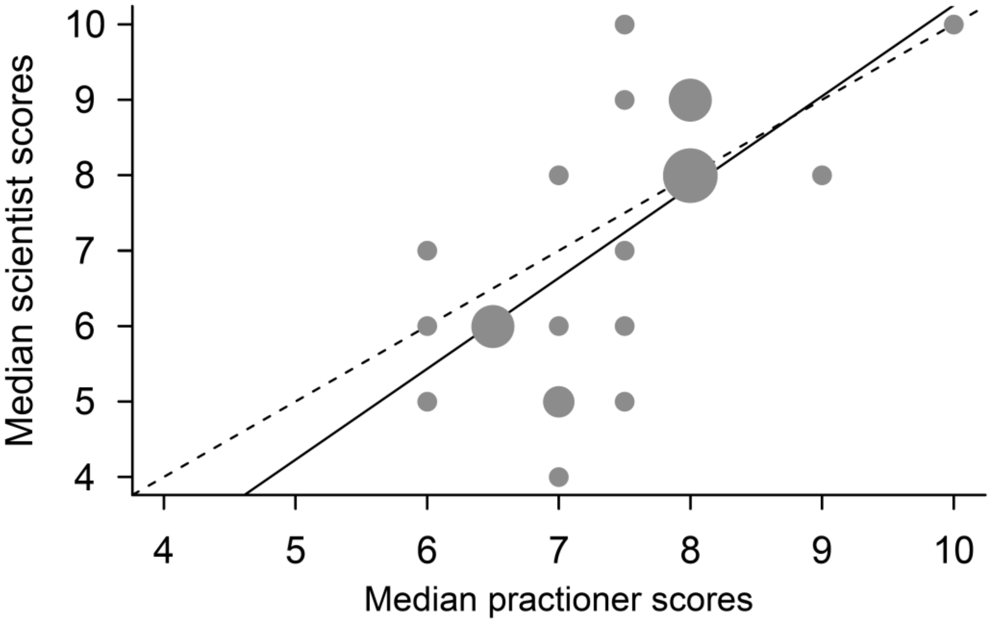

Figure 2. Median scores (1= low priority, 10= high priority) for each of the 25 knowledge needs given by practitioners (n=39) and scientists (n=13). Points are sized according to the number of knowledge needs within each combination of scores (largest circle =4 knowledge needs, smallest circle =1). The dashed line is a 1:1 line; the solid line is a simple linear regression best fit line (slope coefficient = 1.20, SE = 0.28, P=0.0004, 95% confidence interval = 0.68, 1.80). Spearman rank correlation between practitioner median scores and scientist median scores = 0.68 (P=0.0003).

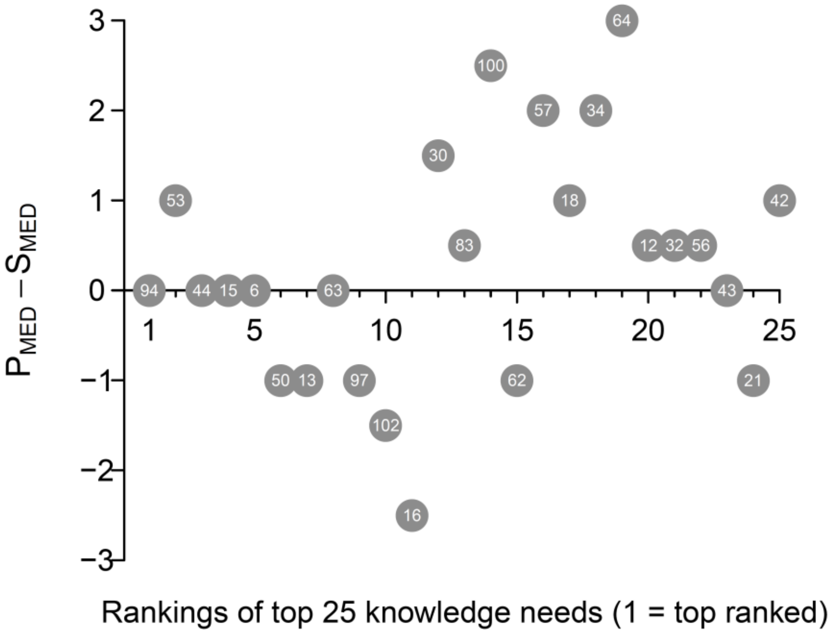

Figure 3. Differences in the median scores (practitioner – scientist) for each of the top 25 knowledge needs given by practitioners (n=39) and scientists (n=13). Questions are plotted in rank order and point labels correspond to question numbers in Table 3. Spearman rank correlation between difference in median scores and knowledge need rank number = 0.32 (P=0.114).

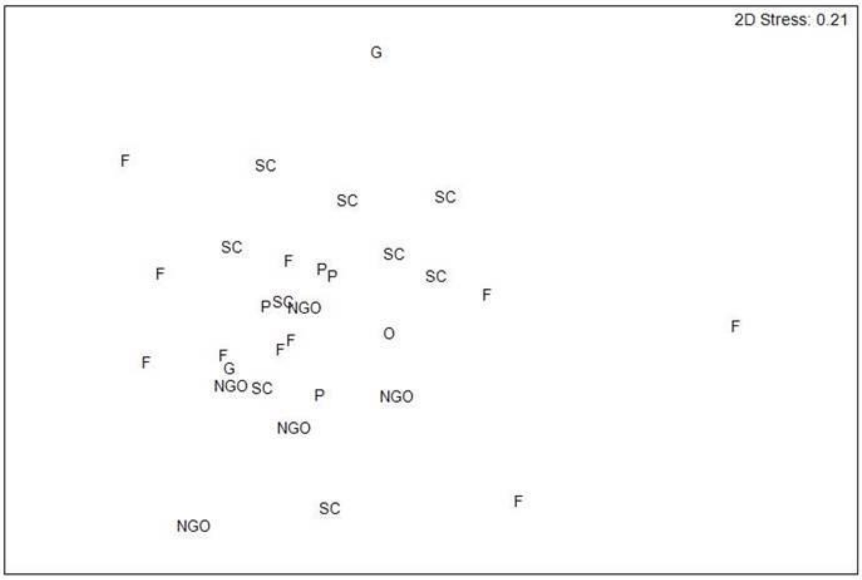

Figure 4: Non-metric multidimensional scale ordination of scores given to the top 25 knowledge-needs by the practitioners. F=Fishing industry, G=Government, NGO=Non-Governmental Organisation, P=Processor and SC=research scientist.

Annex 1: A list of participants in the knowledge-needs identification exercise showing their sector, their affiliation, nationality and their participation in the process. Note * represents an inter-governmental agency.

Surname		Sector	Group	Organisation	Country
Amaroso	R.	Scientist	Expert	University of Washington	US
Andersen	M.	Fishing Industry	Stage 2	Danish Fishermen Producer Organisation	Dk
Balliet	K.	NGO	Stage 2	Sustainable Fisheries Partnership	US
Barratt	E.	fishing industry	Stage 1	Sanford Limited	NZ
Bergstad	O.A.	Scientist	Stage 1	Institute of Marine Research	No
Bishop	S.	fishing industry	Stage 1	Independent Fisheries Ltd	NZ
Bostrom	J.L.	NGO	Stage 1 & 2	Marine Stewardship Council	US
Boyd	C.	Fishing industry	Stage 2	Clearwater Seafoods	Ca
Bruce	E.A.	Fishing Industry	Stage 2	Friosur S.A.	Cl
Burden	M.	Fishing industry	Stage 2	Marine Conservation Alliance	US
Carey	C.	fishing industry	Stage 1	Independent Fisheries Ltd	NZ
Clermont	J.	NGO	Stage 1	New England Aquarium	US
Collie	J.S.	Scientist	Expert & Stage 2	University of Rhode Island	US
Delahunty	A.	Fishing industry	Stage 2	National Federation of Fishermen's Organisations	UK
Dixon	J.	Processor	Stage 1	Pacific Andes Group	Ch
Eayrs	S.	Scientist	Stage 2	Gulf of Maine Research Institute	US
Edwards	N.	Processor	Stage 1	Icelandic Group Ltd.	UK
Fujita	R.	NGO	Stage 1	Environmental Defense Fund	US
Gauvin	J.	Fishing Industry	Stage 1 & 2	Alaska Seafood Cooperative	US
Gleason	M.	NGO	Stage 1	The Nature Conservancy	US
Harris	B.	Scientist	Stage 2	Alaska Pacific University - FAST Lab	US
He	P.	Scientist	Stage 2	University of Massachusetts Dartmouth	US
Hiddink	J.G.	Scientist	Expert	Bangor University	UK
Hilborn	R.	Scientist	Expert	University of Washington	US
Hughes	K.M.	Scientist	Expert	Bangor University	UK
Inostroza	M.	Processor	Stage 2	EMDEPES	Cl
Jennings	S.	Scientist	Expert	Centre for Environment, Fisheries and Aquaculture Science	UK
Kaiser	M.J.	Scientist	Expert	Bangor University	UK
Kenny	A.	Scientist	Stage 1	Centre for Environment, Fisheries and Aquaculture Science	UK
Kritzer	J.	NGO	Stage 2	Environmental Defense Fund	US
Kuntzsch	V.	Fishing Industry	Stage 1 & 2	Sanford Limited	NZ
Lasta	M.	Scientist	Stage 1	Independent Scientist	Ar
Lopez	I.	Fishing Industry	Stage 2	CEPESCA	Cl
Loveridge	C.	Government	Stage 1	South Pacific Regional Fisheries Management Organisation	NZ
Lynch	D.	Processor	Stage 2	Gorton's Inc.	US
Masters	J.	NGO	Stage 1	Marine Conservation Society	UK
Mazor	T.	Scientist	Expert	CSIRO	Au
McConnaughey	R.	Scientist	Expert	NOAA	US
Moenne	M.	Fishing Industry	Stage 2	Pacificblu	Cl
Neat	F.	Scientist	Stage 1	Marine Scotland Science	UK

Nimick	A.M.	Scientist	Stage 2	Alaska Pacific University	US
Olsen	A.	Processor	Stage 1	A. Espersen	Dk
Parker	D.	Processor	Stage 1	Young's Seafood	UK
Parma	A.	Scientist	Expert	Centro Nacional Patagonico	Ar
Penney	C.	Processor	Stage 1	Clearwater Seafoods	Ca
Pierce	D.	Government	Stage 2	Mass. Division of Marine Fisheries	US
Pitcher	R.	Scientist	Expert & Stage 1	CSIRO	Au
Pol	M.	Scientist	Stage 2	Division of Marine Fisheries, MASS State	US
Richardson	E.	Fishing Industry	Stage 2	Pollock Conservation Cooperative	US
Rijnsdorp	A.D.	Scientist	Expert	Wageningen University	NL
Rilatt	S.	Processing	Stage 2	A. Espersen	Dk
Rodmell	D.P.	Fishing industry	Stage 2	National Federation of Fishermen's Organisations	UK
Rose	C.	Scientist	Stage 2	FishNext Research	US
Sethi	S.A.	Scientist	Stage 2	Alaska Pacific University - FAST Lab	US
Short	K.	NGO	Stage 1	WWF	NZ
Sutherland	W.J.	Scientist	Expert	Cambridge University, U.K.	UK
Suuronen	P.	Government*	Expert & Stage 2	FAO, Fisheries and Aquaculture Department	I
Taylor	E.	NGO	Stage 2	New England Aquarium	US
Wallace	S.	NGO	Stage 1	The David Suzuki Foundation	US
Webb	L.	Processor	Stage 2	Gorton's Inc.	US
Wickham	L.	Fishing Industry	Stage 1	Fishing business	US
Wilding	S.R.	NGO	Stage 2	Monterey Bay Aquarium	US
Wilson	A.	Government	Stage 1	Department for Environment, Food and Rural Affairs, U.K.	UK
Winger	P.	Scientist	Stage 2	Memorial University	Ca

Annex 2: The full list of 108 knowledge needs submitted in stage 1 of the process, showing the question number that relates to Table 3 and their assigned category (for definitions see Table 2).

Number	Knowledge need	Category
1	How do trawl designs and operational practices influence impact characteristics and patterns?	D
2	Under what conditions can benthopelagic trawling replace bottom-contact trawling for demersal target species?	O
3	How can trawling on/above summits of seamounts and on steep slopes be conducted without significant adverse impacts on sessile benthos?	O
4	How can instrumentation for real-time monitoring of trawling improve targeting and enhance impact prevention?	O
5	Lasting impact of trawling on 'vulnerable marine ecosystems' (*sensu* FAO Guidelines) occurred and may still happen. What are the more efficient mitigation measures? (e.g. area closures, technical measures, overall effort reductions, etc.)	M
6	What outcome reference points and indicators of habitat status are possible given today's knowledge level? What are the most significant issues to consider in relation to qualifying or quantifying impact extremes?	M
7	What sort of mitigation measures are in line with best practices? What examples are available for each measure?	M
8	What sort of area (e.g., regional, bioregional) should be considered when defining habitat status reference levels in quantitative terms?	M
9	What sort of global benchmarks, if any, exist for determining an acceptable habitat impact and for determining irreversible harm?	M
10	How can benthic impacts be managed and mitigated?	M
11	How best can the status and outcome of benthic impacts be measured? What best practices exist?	M
12	What types of attributes (or gear characteristics) can be used to provide a consistent and systemic way of ranking or measuring relative impact on habitat across different gear types? How can such attributes be assessed in a uniform and consistent manner?	D
13	What kind of information is necessary to best understand the interaction between fishing gear and habitats (i.e., what kind of information about habitats and about gear types do we need to know)?	D
14	At what "intensity" (e.g., amount of fishing effort) are fisheries employing pelagic gear that occasionally contacts the seafloor (e.g., pelagic trawls) as impactful as full-bottom contact fisheries? Should these fisheries be regulated in the same way as bottom trawl fisheries?	D
15	What are the habitat-related variables (e.g., biota, substrate type, physical characteristics, current flow, etc) that are correlated with resilience to disturbance from trawling in benthic habitats?	E

16	What part of the gear (e.g., doors, sweep/bridle area, footrope) plays the largest role in disturbing particular habitat types? Does the part of the gear causing the most disturbance change with different habitat characteristics (e.g., cobble, mud/sand, high relief, etc)?	D
17	What aspects of towing a mobile bottom-tending gear (e.g., tow length and time, tow path, speed, etc.) causes the most disturbance to particular habitat types? Does the relative impact differ by habitat type?	D
18	How can fish behavior (e.g., aggregating, flight response) be better used to increase efficiency and/or reduce bottom time for bottom-tending gear?	M
19	What types of post-trawl CPUE effects would need to be exhibited in an area to dissuade further trawling for a period of time (i.e., a disincentive for fishing) in both the short-term and long-term. In what ways could a fishery benefit from a short-term avoidance of a typically productive area?	M
20	How are units of fish productivity quantitatively related to units of trawl impact?	E
21	How much does trawling cost per unit value of fish caught, and how does this compare to the cost/value of other kinds of gear/practices?	O
22	How does trawling affect biodiversity and ecosystem service production?	E
23	How much greenhouse gas emissions are associated with trawling and can carbon credits based on estimated reduced trawl hours (and associated emissions) resulting from policy change (e.g., a buyout or shift to ITQs) be used to finance the policy change and/or transition to other types of fishing?	O
24	What are the benefits of trawling and how can they be realized while minimizing the economic and environmental costs of trawling?	O
25	What are the “best practices” for trawling in order to minimize impacts on other fisheries, habitat, biodiversity, and ecosystem services?	E
26	What is the magnitude of bycatch and discard impacts associated with trawling and how can they be reduced?	O
27	What does the trawling system map look like and where are the highest leverage interventions that would improve social, environmental, and economic outcomes?	M
28	We have harvested upwards of 1.5 million tonnes of groundfish annually in the Bering Sea with bottom contact trawls for 40 plus years and the effects of trawling literature would suggest that stocks would be reduced, species diversity would have changed but trawl survey does not show this. Could effects on habitat be so lagged that we have not seen them yet or are we below some threshold where trawling is not intense enough over the area to cause noticeable effects? What gives?	D

29	A large percentage of the Bering Sea sand/mud shelf of <200 meters depth is closed bottom trawling (some to Pollock trawling as well); this no doubt has increased effects on the area left open by concentrating effort and intensity but is there net benefit to stocks and habitat?	E
30	Are there any studies that show how management of trawl effects on the seafloor have demonstrably increased productivity of managed groundfish and crab species in temperate ecosystems?	E
31	If there are studies as described in Q30 above, how have the researchers separated the differences in fish harvest rates and climate/environmental changes over time from effects on habitat?	E
32	To what extent does the haphazard spatial and temporal pattern of trawling, and variable impacts within trawl tracks, create a pattern of effective refuges within fished areas and how does this vary by fishery and fishing intensity? Can these be studied in lieu of closing more areas to trawling?	D
33	Does the presence or frequency of seafloor invertebrates in samples from trawl catches (survey or in observer data) provide a useful measure of their distribution on the seafloor? How might observer basket sampling methods and coverage issues affect this utility?	M
34	How close does trawl gear have to be to the seafloor to effectively capture benthic fish and how high off the seafloor does it have to be to avoid most benthic impacts? Is there a clearance range that achieves both?	O
35	Are there non-contact stimuli that could herd fish and move them into a net that could replace conventional trawl components?	O
36	From a fish habitat perspective, are small patches of structure here and there on an otherwise featureless/flat seafloor potentially more important than free-standing deep sea corals and sponges anchored to high relief rocky outcrops and rock ledges?	E
37	Sweep modifications required for Bering Sea flatfish trawls have been shown to reduce seafloor contact by approx. 90% and decrease effects on typical epibenthic invertebrates, but the elevated trawl sweeps increase penetration of the seafloor where the bobbins make contact (spaced every 30 meters). Is this on balance a benefit to preserving the productivity of the habitat?	O
38	How does trawling affect the micro-topographic complexity and diversity of the seafloor and invertebrate communities that inhabit it and how do recovery patterns differ between different habitat types (eg. Various types of hard and soft bottom substrates)?	D
39	How does trawling affect macro-faunal (both sessile and mobile) invertebrate communities and how resilient are these invertebrate communities to varying levels or intensities of trawl effort?	D
40	How does the impact of trawling and recovery times post-trawling differ by depth (say along the continental shelf vs. slope) and sediment grain size?	D

41	What impact does trawling have on the density and diversity of species typically discarded (eg. Skates, rays, non-marketable finfish, etc)?	E
42	One of the more common observed impacts of trawling is the grooves in the seafloor caused by trawl door scour. What effect do those trawl door scour marks play in shaping benthic community structure?	E
43	What role, if any, do these sessile and mobile invertebrate communities play in terms of providing habitat/shelter for the recruitment juvenile and larval fishes?	E
44	What are the relative benefits of spatial management to constrain the trawl fleet footprint versus trawl effort controls or both? (ie. Should a lower intensity of trawl effort be spread out over a larger area of trawl grounds or should trawl effort be concentrated into a smaller footprint, but perhaps a higher intensity of trawling per unit area?	M
45	What are the rates of recovery/ re-growth for different benthic species and habitats to various fishing gears and components (dredge, trawl doors, ground gear etc.)?	D
46	What proportion of each habitat type is subject to fishing gear damage?	D
47	Are there a sufficient number and size of unfished patches of habitat type to enable re-colonisation of an impacted habitat?	E
48	What proportion and arrangement of each habitat type needs to be protected by closures to ensure viable populations of benthic organisms and enable recovery of impacted areas?	E
49	What is the benthic species mortality rate per trawl by substrate type?	D
50	What is the spatial extent and level of effort of bottom fishing by smaller (inshore) vessels not equipped with VMS?	M
51	How could trawling help to improve biodiversity?	E
52	What is the sustainable level of biodiversity in specific habitats?	E
53	What level of biodiversity do we wish to attempt to maintain?	M
54	Large sessile megafauna (eg. sponges, gorgonians, soft/hard corals, bryozoans — individually, or as aggregations) that form biogenic structured habitat are thought to be highly vulnerable to trawl impacts, but what are the actual impact rates, recovery rates, distributions, and overlap with trawling of these fauna.	D
55	What is the relative importance in the ecosystem of large sessile (“charismatic”) megafauna and what important processes may be affected if these habitats are substantially damaged by trawling	E
56	In the absence of specific survey data, to what extent can the distributions of species and habitats vulnerable to trawling be predicted with sufficient reliability to enable successful assessments and management responses	M

57	How can we enhance the knowledge obtained from past comparisons between trawled and untrawled areas (lacking data on 'before' status and on the 'intensity' of effort), by making use of good environmental predictors and modern reconstructions of trawl effort distribution, to extract more specific parameters for impact rates and magnitudes of (trawl-induced) change	D
58	What have been the observed benefits of spatial management versus effort management in terms of reducing environmental impact / improving sustainability.	M
59	Alternatively, under what circumstances does spatial management lead to improvements and under what circumstances does effort management lead to improvements	M
60	What are the impact & recovery implications of aggregated effort, at multiple scales, and how stable are patterns of aggregation across space and time, at different scales	M
61	How do different types of bottom fishing gear differ in their interactions with the seabed	O
62	How do different types of seabed habitats differ in their susceptibility to impacts from towed gear and their ability to recover after such impacts?	D
63	How does disturbance by towed gear differ from natural perturbations experienced by seabed habitats?	E
64	To what extent are the impacts of towed fishing gear mediated by variation in habitat susceptibility, in species recovery rates and in spatial overlaps between distribution of fishing effort intensity and the distribution of habitats?	D
65	To what extent is the identification of best practice management measures contingent upon differences in management objectives and the values that are sought to be maintained?	M
66	Are benthic trawl impacts generally greater upon substrates that have physically complex and diverse communities, compared to simple/bare substrates? Is this regardless of whether the fishing effort is 'patchy' in time or space?	D
67	How can BRD design and deployment reduce benthic impacts, by ensuring a high proportion of the benthic fauna and flora is expelled from nets close to where it enters the net. That is, is highest mortality associated with being brought to the surface and being discarded, and is this mortality avoided by BRDs. Does this have more relevance to mobile fauna (i.e., fish and invertebrates) than the sessiles. Can net design features reduce 'towed bottom fishing gear' impacts on seabed	O
68	What is the relative biomass removed by trawling/contributed by discarding compared with the natural amount of total biomass/detritus arriving at the seabed. How might bottom fishing gears affect the basic geochemical cycling of nutrients.	E

69	To what extent would plumes from benthic fishing gears alter light penetration and photosynthetic processes, which may affect the biochemical cycling, at levels significantly greater than those associated with natural events/processes.	E
70	How to develop and implement management strategies that could be considered informed in relation to target species as well as other at risk aspects (e.g. ecological) of the fishery	M
71	What are the risks of trawling to various components of the ecosystem. What research can give some confidence around understanding of the risks and nature of impacts on seabed communities from trawl fishing	E
72	What are the risks of trawling to various components of the ecosystem. How can these risks be assessed and managed in largely unstudied areas of seabed, often in deepwater areas	M
73	What are the perceptions of the impacts trawling is having, and to what extent can any additional information change some of the entrenched views currently being expressed	M
74	What impact is trawling having on species harvested by other sectors	M
75	Do impacted communities have predictable trajectories to original ‘successional’ states following trawl disturbance, or remain in altered states of structure and functional process? How might this vary between benthic ecosystems? Do systems based on biogenic habitats represent the least resilient? Can resilience be built into management planning — is this key to long term sustainable use of benthic habitats for trawling, especially when climate impacts are overlaid.	D
76	Restricting trawling within a footprint is implemented in a variety of different structured fishery seascapes; is this a tractable and effective method for management. Where trawling occurs, and where trawl impacts are expected to be long-lived, what options are there for estimating the rate at which never-trawled habitats are 'opened up' and the regional scale of impact gradually increases? How can this be measured and quantified given the scale of the habitat and activities compared with the resolution and uncertainty of the effort data.	M
77	What is the evidence for the importance of physical structures as refuges, and for other mechanisms resulting in flow-on effects to ecosystems. For example, do benthic megafauna provide substrata for fish eggs (seapens-rockfish), structures for associate fauna (echinoderms-corals), and physical substrata providing shelters for early life history stages of commercial species. Is there evidence for other mechanisms – e.g. enhanced prey densities, water flow refuges, sediment re-suspension, disturbance providing advantage to colonisation by weedy species. Is this knowledge necessary to understand the impacts and articulate the case for when/where management is needed.	E

78	Can the extraction of feature-aggregating species (e.g. Orange Roughy on seamounts) be ecologically sustainable when side-by-side with vulnerable benthic communities? What is the potential for partly impacted features to contribute to broader spatial scale recovery, i.e. provide propagules for local to regional scale dispersal? Is this information essential to manage and understand the impacts on VMEs and high seas areas	E
79	To what extent is understanding and management assisted by understanding what/where/how much habitats are untrawlable at a variety of scales. Should such areas be considered (along with closures) in making environmental assessments of trawling. To what extent do better maps of habitat, improved navigational technology, and changing fishing practices (eg. increased risk taking when market prices are high) contribute to determining trawlable and untrawlable bottom.	M
80	To what extent can landed invertebrate bycatch represent the damage to seabed fauna. Would this underestimate the damage to fauna because many are not retained well in nets. Can such methods quantify the direct impacts in different community types and help understand the importance of fishing intensity and the cumulative effects across gears.	M
81	Can faunal categories potentially emphasise taxonomic relationships, size categories, ecological function, and vulnerability to trawling. Are standardised descriptors of ‘habitat fauna’ needed	M
82	Do standards need to be developed for improving incorporation of trawl impacts into risk assessment frameworks, with focus on separating impact from risk, increasing quantification, and being explicit about the spatial and temporal scales being considered.	M
83	Once an area has had a history of being trawled (inside the trawl footprint as known fishing grounds), what ongoing ecosystem damage is occurring by continuing to trawl in this area? Does this include changes in composition. What is the best way to measure trawling over a certain area (number of tows, hours, etc)	E
84	What level of damage occurs from using different net and ground gear designs for each habitat type (as classified under the habitat and communities ERA framework)? Will this need to look at different combinations of gear (including Danish seine, demersal trawl and midwater trawl).	O
85	What is the recovery time of the different habitat types (as categorised under the habitat and communities ERA framework) for different levels of effort, for each fishing method?	D
86	How does the intensity of trawling by different trawl methods affect the ecosystem?	D
87	Once trawling has taken place what is the recovery process? Is it succession based; does it ever get back to “virgin” state; what are the timelines for recovery?	D

88	What are the effects of trawling on species richness and diversity of the different habitat types (as categorised under the habitat and communities ERA framework)	D
89	How large and how many closure areas are needed to provide adequate protection for a type of community and/or habitat?	M
90	Specifically, what are the impacts of fish trawling on the benthos, fish communities and commercial fish stocks.	E
91	Is physical damage to habitats caused by trawling irreversible. What is required to test for reversibility or recovery.	D
92	Do series of closed areas and areas with different levels of fishing effort represent a ‘natural’ experiment.	M
93	What are the post-trawling recovery levels of habitats and benthic ecosystems in areas closed to trawling, and what are the responses of dependent fish populations and communities that rely upon them. Are there interactions effects (or benefits) of areas closed to trawling in/adjacent to fished area (does it affect recruitment levels etc).	D
94	What and where are the various seabed types	M
95	What effect does bottom trawling have on the various seabed types.	D
96	What specific effect does twin rigging have on the various seabed types.	D
97	How important are the various seabed types to fish life through the various stages of fish life.	E
98	What effect does seabed disturbance by trawling have on the sustainability of fishstocks.	E
99	What natural events will change seabed environments	E
100	What is the current trawl footprint and is this likely to change-this should incorporate closed areas,areas too deep to trawl,areas too rough to trawl,etc	M
101	What types of bottom trawl caught species live near but off the bottom and could be caught off the bottom completely with midwater trawls but currently there is no incentive to do so? Example, several rockfish species, west coast Canada.	O
102	What gear configurations exist to mitigate impacts and how much net reduction in impact is gained? Example, off bottom doors	O
103	What are the potential or measured impacts of resuspending sediments in areas of low oxygen concentration (example, west coast North America oxygen minimum zones)?	E
104	Are there any greenhouse gas/ocean acidification concerns around sediment resuspension?	E
105	What changes are made to a specific type of bottom i.e. coral, mud gravel etc. by repeated bottom trawling?	D
106	Are these changes [to habitat by repeated trawling] reversible? If so how?	D
107	If trawl gear is towed a fraction of a meter off the bottom is there any damage to the habitat?	O

108	If the number of trawl tows are limited over a specific area can the damage be limited?	M