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Effects of Sound from Seismic Surveys on Fish Reproduction, the Management Case from Norway

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Abstract: Anthropogenic noise has been recognized as a source of concern since the beginning of the 1940s and is receiving increasingly more attention. While international focus has been on the effects of noise on marine mammals, Norway has managed seismic surveys based on the potential impact on fish stocks and fisheries since the late 1980s. Norway is, therefore, one of very few countries that took fish into account at this early stage. Until 1996, spawning grounds and spawning migration, as well as areas with drifting eggs and larvae were recommended as closed for seismic surveys. Later results showed that the effects of seismic surveys on early fish development stages were negligible at the population level, resulting in the opening of areas with drifting eggs and larvae for seismic surveys. Spawning grounds, as well as concentrated migration towards these, are still closed to seismic surveys, but the refinement of areas and periods have improved over the years. Since 2018, marine mammals have been included in the advice to management. The Norwegian case provides a clear example of evidence-based management. Here, we examine how scientific advancements informed the development of Norwegian management and how management questions were incorporated into new research projects in Norway.

Keywords: management; fish; anthropogenic sound; seismic surveys; electromagnetic surveys

1. Introduction

Anthropogenic noise pollution is considered an important pollutant of terrestrial and aquatic ecosystems [1–3]. There are few records of systematic underwater anthropogenic noise measurements prior to 1990, but they show that ambient noise levels have increased by as much as 12 dB in 30 years in some parts of the ocean [4–6]. Impulsive anthropogenic sound is currently the subject of monitoring within the frame of the regional agreements such as OSPAR. Maximum sound exposure levels have been proposed for marine mammals and fish based on physical damage [7]. However, the masking of acoustic information from the environment may affect animals at a much lower sound level, and, thus, further away from the source. Most of the energy of anthropogenic caused sound lies in the lower frequency ranges [8]. This may affect a wide range of animals. For example, all fish can hear low-frequency sounds (<500 Hz) and can, consequently, be disturbed by man-made sound activities [7,9].

Noise disturbance can affect the physical integrity (at very high levels), the physiology, and the behavior of aquatic animals. This may affect individual fitness and could, ultimately, lead to population and ecosystem-level consequences [10–12]. The effects of noise on aquatic life have been reviewed extensively (e.g., [7,8,11–19]). These reviews highlight the absence of observational evidence of population-level impacts. Experimental data often show short-term damage or behavioral changes in individual animals only, while numerical models are needed to provide information on whether such changes can lead to population-level effects.

In Norway, the first research on the effects of sound generated by seismic sources has been developed in response to concerns from fishermen that fish may be scared away from fishing grounds. Fishing, a key industry in Norway, has been influenced by oil and gas exploration activities as the two industries operate in much of the same areas. Thus, there have been demands for balanced coexistence between fisheries and the oil industry since the start of the oil era in the 1970s, to ensure the acceptable development of both industries [20]. Therefore, protecting core habitats and fishing grounds of commercially important fish stocks with reproductive success from exposure to seismic surveys is an important element within this balance and is of major importance for the management of seismic surveys in Norway.

Reproduction is vital to population sustainability but can be very sensitive to stress and changes in environmental conditions [21]. Even if yearly variations in spawning stocks are not necessarily correlated to recruitment, long-term reduction in egg production is expected to lead to a mean decrease in the population [22]. In addition, spawning is the most clearly quantifiable investment in a specific mating and, as such, directly related to fitness. Moreover, for many fish species, the spawning period may be highly sensitive to impacts from noise, if individuals gather in dense, localized spawning aggregations [23]. Disturbances in the spawning period may thus affect a larger fraction of the population than disturbances during other periods. Additionally, fish may be vulnerable to external stressors during spawning [24], because fish are often in their poorest body condition in this period [25,26].

In this study, we review how management advice has been given through a period of about 30 years and how improved scientific knowledge has transferred into scientific advice. There was an additional focus on how external drivers have induced scientific questions and how weakly documented knowledge-based advice has exposed the need for more research to obtain better and more scientifically based advice. This process is shown in Figure 1.

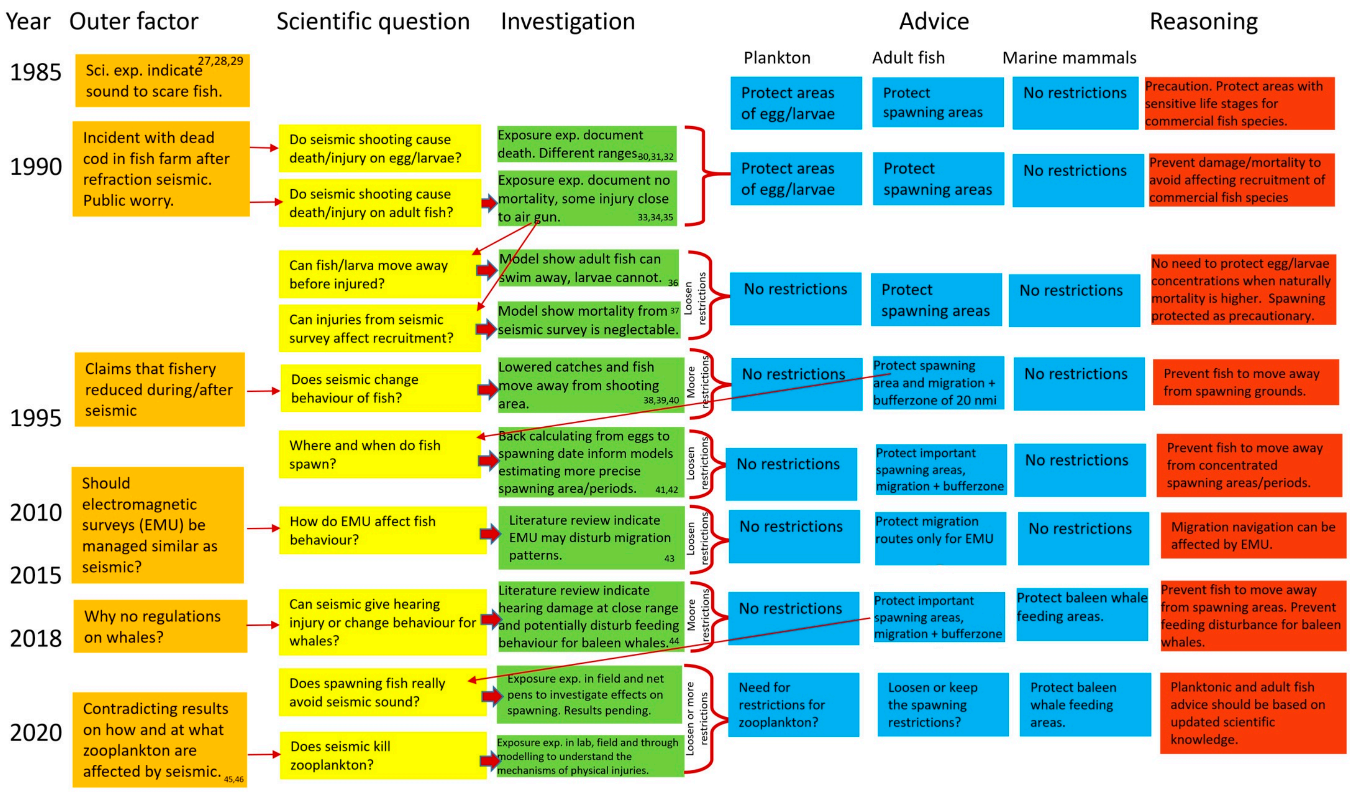

Figure 1. Overview of how management advice has changed since the beginning of the advisory practice in the late 1980s. The "Outer factor" column covers drivers from outside the scientific community that may induce new scientific questions and lead to research activity. The "Scientific question" column lists the research questions being raised to improve management advice, which may arise from outer factors or from existing research that raises new questions. The "Scientific investigation" column briefly describes the main findings from research projects. The "Advice" column summarizes the management advice from IMR to the Norwegian Petroleum Directorate and is divided into different advice given for three specific groups of animals; plankton (small organisms with very little or no self-movement, including egg, fry, larvae, and zooplankton), adult fish, and marine mammals. The "Reasoning" column describes the rationale for the particular advice given. Timeline is indicative and not to scale. The numbers in the bottom corner refer to publications given in the reference list; [27–46].

2. The Norwegian Story—A Journey through the History of Management Advice

Since the beginning of oil exploration in the 1960s, seismic surveys applying different sound sources have been carried out within the Norwegian Exclusive Economic Zone (NEZ) to locate and estimate oil and gas resources. To reach an optimal basis for development it has been a goal for the Norwegian Government to have a good coexistence between the traditionally existing fishing industry and the newly established oil industry. The Norwegian Petroleum Directorate (NPD) issues licenses for seismic surveys in Norwegian waters, but several stakeholders within governmental organizations have been asked for advice since 1983. The Institute of Marine Research (IMR) is asked for advice on the potential impact on biology and ecosystems, while the Directorate of Fisheries is asked for advice on the likely impact and potential conflicts with ongoing fishery activities. In the beginning, the advice from IMR was mainly based on a precautionary approach; preventing potential impact on presumed sensitive habitats. Therefore, spawning areas and areas with spawning migration, as well as areas with drifting eggs and larvae in the periods of the respective migration, spawning, and drifting, were recommended to be closed for seismic surveys to avoid impact on these volatile ecosystem compounds.

Recommendations from IMR on the regulation of seismic activity have always been given in the form of geographical and temporal restrictions to avoid seismic exposure of sensitive habitats, i.e., specifically to protect fish engaged in susceptible activities such as spawning and concentrated spawning migrations. The NPD and the seismic operator are not obliged to follow the advice given, and, until the late 1990s, the NPD oversaw these recommendations to some extent, but due to frequent contact and communication over the years, the advice given today is almost always followed.

In July 1989, one particular incident brought attention to how sound from seismic surveys could potentially affect fish; in a fish farm in Northern Norway, high mortality of cod was observed after explosives for refractional seismic investigations were detonated nearby [47]. This raised the question of how seismic exposures could potentially cause damage in wild fish. In order to clarify these issues, several research projects were initiated in the early 1990s. The main concern was that seismic blasting could cause injury and even death in fish.

2.1. The Early 1990s: Physical Injuries and Death

Knutsen and Dalen [30] previously analyzed mortality and damage to fish eggs, larvae, and small juveniles of cod (*Gadus morhua)* after exposure to seismic airguns, describing that some of the larger larvae developed problems with their balance, but returned to normal swimming after few minutes and, overall, there were no significant differences in injuries and death between the control and exposed groups. A larger project was initiated that investigated the effects of airguns on fish eggs, larvae, and juveniles of cod, saithe (*Pollachius virens*), turbot (*Scophthalmus maximus*), plaice (*Pleuronectes platessa*), and herring (*Clupea harengus*) [32]. Despite some differences between species, results showed significantly increased mortality rates in exposed groups, but only rather close to the air guns; up to 1.35 m for eggs, 0.9–3 m yolk sac larval stage, 2–5 m for larval stage, up to 1.5 m for post-larval stages, and up to 1.3 m for the fry stages. Different sublethal effects, e.g., injuries to neuromats and swimbladder, and changes in behavior due to buoyancy were observed for some species and life stages. The studies concluded that the highest mortality rate was observed about 1.4 m from the airgun, with potential minor damages up to 5 m away from the airgun [32]. These Norwegian studies were in line with similar international studies at the time, documenting lethal and sublethal effects at distances equal or closer than 3 m from the airguns on fish egg and larvae [47–49].

These results thus showed that fish at early life stages could experience both indirect and direct mortality, but only at rather close range within a few meters of the air guns. To propose realistic scenarios for impacts from a seismic survey, results from these experiments, together with fish biology and physiology knowledge, the vertical distributions of larvae, and the sound intensity output from the seismic source were included in a modeling study. The results from this study demonstrated that adult fish would be able to swim away from the spatial zone of potential injuries, while the smallest larvae and fry would not, as they would suffer from total exhaustion, and, therefore, would not be able to escape from the zone of injury [36,50].

In summary, these studies show that some injuries, including lethal ones, may occur, but at ranges less than 5 m from the air gun. However, in a management context, the most interesting issue is whether these effects can translate into the negative development of the stock or stock recruitment. Sætre and Ona [37], therefore, used these results to assess the potential total mortality rate on fish larvae from a regular 3D seismic survey. Assuming a lethal radius of 2 m from the air guns, the mortality rate for cod larvae was 0.45%—in a worst-case scenario, and 0.3‰ in a more realistic scenario, compared to a natural daily mortality rate of 5–15%. Therefore, they concluded that the mortality due to 3D seismic surveying is negligible compared to the natural mortality in the larval stage.

The conclusion was, therefore, that mortality can occur at the earliest life stages of fish, but only at very close range, and that the risk that such mortality negatively affects recruitment to the fishable stock is close to non-existent. Therefore, the recommendations were updated to allow seismic surveys in areas and periods with drifting eggs and larvae [47]. This meant that larger areas of the NEZ became available for seismic surveys for a larger part of the year. The restrictions for spawning areas and areas with spawning migration, however, were kept as before.

2.2. The Later 1990s: Reduced Catches and Behavioral Response

Based on the above documentation, it seemed clear that physical injuries occurred only in the nearest few meters of the air gun and mostly affected early-stage larvae. However, fishermen claimed reduced catches at much further distances from operating seismic vessels than could be explained by the injured fish close to the air guns. This could only be explained if the fish heard and responded to the sound of the seismic shooting.

Fish hearing was intensively studied in the 1960s, showing that fish hear well, with the highest sensitivity below 1 kHz (e.g., [51–53]). Fish were also shown to be able to discriminate the direction of sounds (e.g., [54–57]). Fish can, therefore, hear seismic noise and determine the direction of its source [28,58,59]. In 1969, Chapman and Hawkins reported that shoals of whiting (*Merlangius merlangus*) dive deeper and form more compact schools in response to seismic air gun shots. Later in the 1980s, Dalen and Raknes (1985) found fish distribution, mainly saithe (*Gadus virens* L.), cod, and haddock (*Melanorammus aeglefinus* L.) recorded by echosounder and echo integrator to be reduced by 36%, and for blue whiting (*Micromesistius poutassou*) by 54% after the previously compared seismic blasting. Similar results were demonstrated for rockfish [58].

Reduced catches in areas of seismic investigations were, therefore, assumed to be associated with the fish either avoiding the shooting area, or descending closer to the bottom and thus becoming less catchable. Several research projects were initiated in the early 1990s, with the purpose of documenting whether catches were actually reduced, as well as trying to understand the underlying mechanisms. Holand et al. [38] conducted a controlled experiment with cod swimming freely in a bay, and cod enclosed in a net pen. They observed startle responses at the onset of the air gun, as well as that the largest fish stopped feeding during exposures. While free-swimming fish did not react with an increased heartbeat frequency, the enclosed fish increased their heartbeat after repeated exposure. Løkkeborg and Soldal [39] analyzed catch records from logbooks of longliners and trawlers operating in areas of ongoing seismic surveys, documenting that the lowest catch rates were closest to the seismic survey area and then that the catch rates increased with increasing distance from the seismic survey. These findings were, together with [31], used to design a full-scale fishery experiment in the Barents Sea, using trawl, longline, and acoustic quantity determination within and outside set distances from a seismic shooting area of 3×10 nautical miles. Both trawl and longline catches of cod and haddock were considerably reduced up to at least 18 nautical miles from the seismic blasting area [40]. The reduction was largest in the center of the area, with gradually decreased impact towards the outer edges of the area. Acoustic quantity determination showed that the decline in catch rates was caused by a reduction in spatial fish density in the area. These studies all point in the same direction; seismic exposure appears to disturb the fish, and responses may be in the form of avoidance of the exposed area and/or cessation of foraging. Repeated exposure of enclosed fish, which are thus unavailable to avoid exposure, can cause increased heartbeat frequency, indicative of an increase in stress level.

These results have had great importance for management advice. Before this, spawning areas of commercial fish were recommended to be closed to seismic surveys mainly on a precautionary basis. Now, scientific results support this advice. Many of the offshore fish populations are distributed over a large area most of the year, but gather within specific, smaller defined areas during spawning. These areas are not random, but may have specific characteristics, such as bottom type for the bottom spawners (e.g., herring and capelin (*Mallotus villosus*)), and are localized so that the spawned eggs will drift with current to favorable areas with the available food supply of specific zooplankton. The same holds for the temporal component; the spawning period usually occurs so that the fish eggs will hatch during the zooplankton spring bloom, ensuring food abundance. The scientific studies as described above show that seismic may cause fish to swim away from an area of seismic exposure, and that such avoidance may be in the order of more than 18 nmi [40]. If similar avoidance occurs when fish are at the spawning grounds, they may move too far away from these optimal geographical and oceanographical conditions, or if they delay or even stop their spawning, the spawning may be less successful with regards to time and physical conditions. From 1996, therefore, scientifically based advice was given that seismic surveys should avoid spawning areas during the spawning period. Additionally, based on the result that several fish species moved away for a distance of at least 18 nmi from the blasting area, an additional 20 nmi buffer zone around spawning grounds was recommended to be closed for 3D seismic surveys [40,60,61].

2.3. Into a New Millennium with New Studies Drawing a More Complex Picture

Into the new millennium, behavioral responses continued to be the main topic of interest and scientific focus. Until now, scientific results had shown a clear trend that fish avoided areas of seismic exposure. However, as we shall exemplify here, more research does not always draw a clearer picture.

Sometimes seismic surveys are conducted in areas and periods of potentially large ecosystem consequences. This was the case for a survey in the Norwegian Sea in April 1999 overlapping with an area of a high density of migrating pelagic fish, mainly post-spawned herring migrating out from the spawning areas at the coast. Therefore, the advice from IMR was to postpone the survey. When this was not possible, IMR agreed to monitor the fish density in the shooting area to make sure the density did not exceed a predetermined limit, otherwise, the seismic survey had to be stopped. This monitoring created the opportunity to study the abundance and vertical movement of pelagic fish before, during and after a seismic survey. Results showed that schools of blue whiting (*Micromesistius poutassou*) move deeper during exposure but found no horizontal or vertical response of herring [62]. Furthermore, in 2009, NPD planned a 3D seismic exploration in Vesterålen, an area normally closed to commercial seismic activity due to its status as a highly important ecosystem. In order to evaluate the potential negative impact on fish and fisheries, several studies were initiated. Løkkeborg et al. [63] summarize the findings from acoustic mapping with echo sounders and gillnet and longline catches before, during, and after the seismic survey, documenting that most fish species did not leave the area, but rather changed their onsite behavior; increased catches in gillnets are likely caused by increased swimming behavior, while reduced longline catches indicate less feeding motivation. Another study showed that schools of young herring in the area did not respond to the seismic blasting with changes in swimming direction, speed, or vertical position in the water column [64].

Conflicts between seismic activity and fishing have occurred now and then and have at times become quite harsh. This has also occasionally initiated research to clarify whether there is any scientific basis for such claims. In Norway, a sandeel (*Ammodytes marinus*) fishery in the North Sea, close to several oil and gas fields, is such an example. Fishermen claimed to have reduced catches and explained this with the sound from seismic surveys causing sandeel to migrate away, or to bury themselves in the sand during seismic exposure. Video of caged sandeel during seismic exposure did reveal some alarm responses to the sound, but no burrowing into the sand [65]. Similar claims have also been posed for mackerel (*Scomber scombrus*), initiating a study where mackerel were kept in net pens and exposed to a small, approaching air gun, with gradually increasing sound exposure. Neither of these studies showed any particular reaction in terms of diving, startling, or increased swimming speed in mackerel [66]. Similar conflicts have been reported elsewhere in the world; scientific studies on seismic exposure in a redfish (*Sebasteds* sp.) fishery in California revealed that fish elicit alarm responses [59] and reduced longline catches [67]. However, it should be noted that studies were conducted with caged fish, which may influence the observed behavior, as well as inhibit larger-scale movements such as flight or avoidance, although this depends on the size and design of the enclosure [18,68].

These studies, as well as other studies conducted in other countries (e.g., [69–71]), show that a behavioral response is not always present, and, by nature, will vary in characteristic and strength. Some studies showed that the fish did not move away, while other studies showed that the fish left the area of exposure. Hence, responses may depend both on the species and the context. Throughout the first 10–15 years of the millennium, new knowledge was evaluated as it emerged to improve management recommendations. Despite the variable nature of how fish respond behaviorally during exposure to sound from seismic surveys, there was still a core knowledge-based conviction that fish could abandon their spawning sites if exposed to seismic blasting, so the advice to protect these areas and periods was not changed.

2.4. The 2010s: Towards Better Basis for Exclusion Zones (Refining Spawning Maps)

To effectively protect spawning areas, good knowledge of the actual spawning areas and periods of those species is crucial. An extensive report describing the spawning habitats and periods with drifting eggs and larvae from historic and recent data acquisition was published in 1991 [72]. These data were used to pinpoint areas and periods where seismic surveys should be avoided. Spawning areas are, however, dynamic habitats and change over time with changes in environmental variables, such as temperature (e.g., [73]). To better ensure that the recommendations reflect the actual spawning habitats, as well as to give more precise estimates of the relative importance of different spawning areas and periods, two projects were initiated to improve existing information on spawning areas and periods for the Norwegian and Barents Sea [41] and the North Sea [42]. These reports also took into account both historic and new knowledge from spawning surveys, as well as data from scientific surveys. Furthermore, data from fisheries on sampled egg and fish larvae were back-calculated to their spawning position using drift models. The results of these studies produced updated spawning maps, and, importantly, pinpointed those areas where the most significant and concentrated spawning occurred in time and space. For many species, restriction areas could be narrowed down to those most concentrated areas, without jeopardizing the links to recruitment. In addition to the species of greatest commercial importance that until now had been included in the advice, these projects also provided data to map spawning areas of other fish species. New questions, therefore, arose concerning which species to include in the advice in addition to those already included. Based on the evaluation of ecological importance, stock condition, and data basis, several species of less commercial importance, such as Greenland halibut (*Reinhardtius hippoglossoides*) and golden redfish (*Sebastes norvegicus*) were also included in the recommendations given from around 2015.

2.5. 2015 Onwards; New Technical Achievements Require New Advice

Another emerging trend since the 2000s was the use of electromagnetic (EM) surveys to more precisely locate and verify oil and gas deposits in the seabed. With this technique, electric and magnetic fields are generated within the water column. Several species of marine animals use electric and/or magnetic fields for orientation, migration, and prey or predator detection [74–76] thus with the potential of disturbing that behavior. During the first years of EM surveys, the recommendations from IMR for such surveys were the same as for a seismic survey, and the same areas were restricted, only without a buffer zone. This was, however, a highly questionable practice, as was pointed out by both the industry and the scientific community. A literature study was initiated and the results indicated that the main EM disturbances to fish species are likely to occur during their navigation during migration [43]. In accordance with the general goal of the recommendations: to prevent recruitment failure, the migration towards spawning grounds was considered to be most important to protect. From 2019, recommendations for EM surveys were to avoid known spawning migration routes during the migration periods.

Further studies on how the EM field induced by these surveys affect orientation and behavior of early-stage fish are currently (spring 2021) ongoing and the results thereof will be implemented within the advice as they emerge.

2.6. The Late 2010s: Inclusion of Marine Mammals

While Norway may have been very early to include fish in management advice, recommendations with respect to marine mammals have largely been lacking, and in contrast to most other countries, no restrictions were made to protect this group from potential effects from seismic blasting. The question of whether to include marine mammals in management advice has been regularly raised, e.g., by environmental organizations, the scientific community, and the general public. A challenge with including marine mammals in management advice is that Norwegian waters have many species, which are distributed over large areas, and that data on distribution, and, in particular, data on the relative importance of different habitats, is largely lacking. In response to the increasing amount of seismic activity in the Barents Sea, the demand for better management of seismic activity in these important mammal habitats increased [77]. From 2018, a new regulation made ramp-up procedures prior to seismic blasting mandatory by law to protect marine mammals from hearing injuries. In this respect, IMR also saw the need for marine mammals to be included in their recommendations. In the absence of specific studies on the impact of seismic exposure on mammals in Norway, the evaluation of seismic exposure studies elsewhere, as well as an extensive amount of scientific publications on exposure experiments of low-frequency naval sonar, another high intensive sound source, in Norwegian waters with different mammal species were considered as the basis for giving advice. Exposure to such low-frequency sonar has been documented to reduce foraging in several common species in Norwegian waters for humpback whales (*Megaptera novaeangliae*) [78], blue whales (*Balaenoptera musculus*) [79], bottlenose whales (*Hyperoodon ampullatus*) [80], sperm whales (*Physeter catodon*) [81], and killer whales (*Orcinus orca*) [82]. In particular, species that feed intensively within a season and depend on dense prey concentrations can experience severe consequences [79,83]. Baleen whales migrate to the Barents Sea to feed intensively during summer and early autumn to feed on the large concentrations of zooplankton and small fish [84]. Based on this knowledge, from 2019, areas and periods with intensive feeding of baleen whales were included in the recommendations of where to restrict seismic activity.

2.7. Into the 2020s: Increasing Scientific Effort

Since the first advice was given, spawning habitats for fish have been recommended to be avoided. As described above, the rationale for this recommendation is that if the sound from seismic airguns causes fish to avoid these habitats, this can lead to failure of reproduction and stock recruitment. However, the question of whether spawning behavior is actually hampered by the sound from seismic surveys has been raised repeatedly. Some argue that the "drive" to reproduce is so strong that other behaviors, such as avoidance, are depressed, and that they thus may likely ignore the seismic disturbance. If so, the need for strong protection of spawning habitats may not be the most efficient advice to prevent potential negative impacts on fish stocks. Therefore, a large project investigating the effects of seismic on spawning behavior and spawning performance as well as avoidance was initiated in 2018; "Effects of sound on spawning behavior and reproductive success of cod" (SpawnSeis) (https://prosjektbanken.forskningsradet.no/project/FORISS/280367?Kilde=FORISS&distribution=Ar&chart=bar&calcType=funding&Sprak=no&sortBy=score&sortOrder=desc&resultCount=30&offset=0&Fritekst=SpawnSeis, accessed on 17 April 2021) From this project, there are indications that continuous noise may be more hazardous for fish reproduction than intermittent blasts [18]. However, loud impulsive noise has been shown to produce stress, which could affect the spawning output. While the general literature on fish reproduction shows that stress should be avoided during spawning, the buffer zones, particularly, could be adjusted if the sound from seismic air guns does not seem to affect spawning behavior at the levels of exposure in SpawnSeis. Results from three years of experimental work in net pens and in the field are currently being analyzed and will be used to update advice.

Areas with drifting planktonic organisms have been excluded from the protection zones since the mid-1990s. Despite some documented effects on increased mortality and damage to zooplankton and other invertebrates, a large number of studies demonstrate the lack of effects unless in the very vicinity of the air gun [30–33]. However, in 2017, McCauley et al. [45] presented some noticeably contradictory results from Australian waters. Here, the abundance of zooplankton exposed to experimental airgun signals decreased by more than 50% in comparison with the control groups, and effects were observed up to 1.2 km from the airgun source. They concluded that seismic surveys have a highly negative impact on zooplankton, particularly, small copepods [45,85]. Thus, attention was created, as these organisms constitute the basis of the food web and support many of the most important fish stocks worldwide [86]. In contrast, a Norwegian study published in 2019 [46] found such effects to occur only at distances of five meters or closer to the air gun on larger copepods, and the increase in mortality did not exceed more than 30% at any distances from the airgun. In addition, no effects on escape response nor important changes in genes were detected. Together with previous similar results, these contradictions lead to the initiation of a research project on understanding the mechanisms of potential impact from the pressure and particle motion associated with seismic shooting (ZoopSeis). The project started in 2020 and will continue until 2023 and the results will inform recommendations as they emerge.

3. Advisory Tools

As described above, the recommendations from IMR on the regulation of seismic activity have always been provided in the form of geographical and seasonal restrictions to avoid sound exposure of sensitive habitats and periods. Such management rules are easily expressed in a map, and maps of sensitive habitats have always been used as tools.

In parallel to the scientific investigations described in the previous sections, advisory tools have been improved from relatively static maps in paper format to digital maps, so-called restriction maps, showing the exact area to avoid in two-week periods throughout the year (Figure 2). These maps include all the recommendations (spawning grounds, spawning migration areas, and feeding areas for marine mammals as well as buffer zones) in one map, and the operator can choose the type of survey (2D/3D seismic surveys, site survey, or EM survey) and obtain a full overview of when and where advice not to conduct seismic activity will be given. This approach simplifies planning for commercial seismic companies, and may have increased the acceptance of the recommendations. The areas and periods that are included in the restriction maps are evaluated once a year by experts on the different species of fish and marine mammals. The latest ongoing development is that these restriction maps are included in the online application process for seismic surveys. If the planned surveys overlap with a restriction area, an automatic warning will be given when either the area or the time period must be changed for the survey to be approved. Since 2018, IMR has published an annual report describing the restriction maps for that year and the scientific background behind the recommendations. The newest report can be found at https://www.hi.no/hi/nettrapporter/rapport-fra-havforskningen-2021-4 (accessed on 17 April 2021).

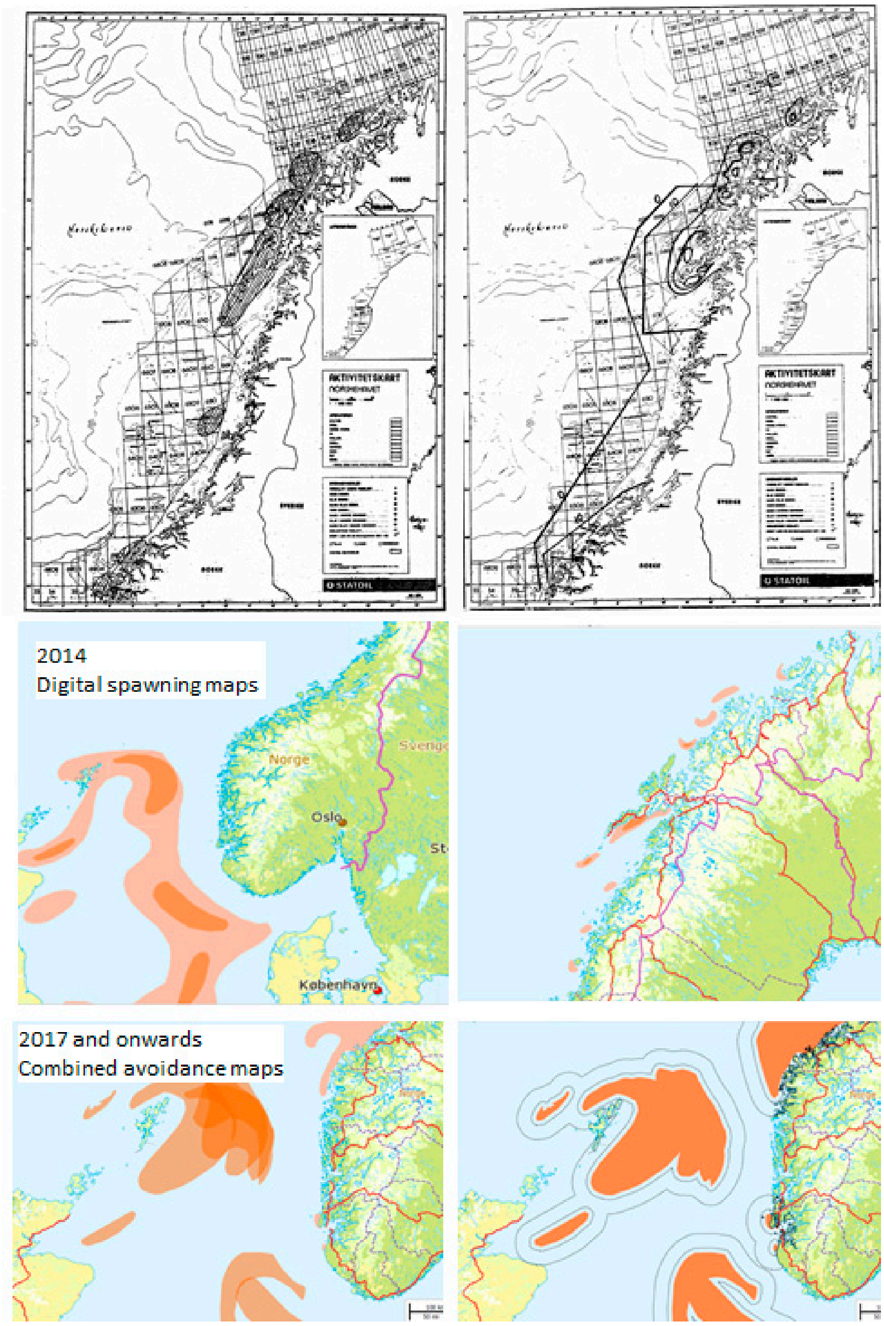

Figure 2. **Upper panel**: Examples of maps of spawning areas of and of areas of drifting eggs and larvae, as used to give advice in the period 1991 to 2014 [72]. These maps only existed in paper format. **Left**: Spawning areas for cod, with restriction periods between 15 March and 15 May. **Right**: Drifting cod eggs. Restriction periods between 1 April and 30 April. The restriction on drifting eggs and larvae ended in 1996, while the restrictions on the spawning areas still hold, but the exact area and period have been updated. **Middle panel**: Digital spawning maps available from 2014. Areas divided into important and less important spawning areas. This example is for cod, with darker areas being the most important ones. The important restrictions are applied in(dark) areas. **Right**: North Sea cod. **Left**: Northeast Arctic cod. **Lower panel**: Spawning maps for each 2 week period of the year merged into maps with restriction areas. **Left**: Important spawning maps for different North Sea fish species (cod, Norway pout, saithe, herring). **Right**: Avoidance map for period 1 to 15 March. These are made by combining all the maps for important spawning areas for those fish that spawn in this period (which are those shown on the map to the left), as well as two buffer zones (dotted lines) of 5 and 20 nmi, and the advised restrictions for site surveys and regular seismic surveys, respectively.

In parallel to advice from IMR on biological implications, the Norwegian Directorate of Fisheries gives advice to all seismic surveys on potential conflicts with ongoing fishery activity. In areas with traditional seasonal fishing grounds, such as those for herring and mackerel, it is advised that seismic surveys are conducted either before or after the fishing season. Additionally, their advice includes a requirement to always have a fishery liaison officer on board the seismic vessel, to handle all communication between the seismic vessel and fishing vessels in the area to ensure cooperation. The fishery liaison officer will inform the captain on the seismic vessel, e.g., about the specifics of the fishing tools used in the area and how to best avoid them, as well as talking to the fishers and telling them about the seismic production and how they can best conduct their activity without being in the way of the seismic vessel.

4. The Way Forward—The Science Needed to Make Good Management Decisions

The above example from Norway shows that scientific input can be routinely used in management decisions by including scientific institutions in the management process. To ensure that scientific research in the field is applicable to management, Prewlaski et al. [87] highlight some important issues, including identifying useful metrics and species, and the ability to generalize results to a certain degree among species and regions. Further, to ensure that regulations are applicable, recommendations should be balanced between highly restrictive regulations and the loss of resource benefits. Effective research-based management, therefore, requires close collaboration between scientists, industry, and regulators to frame scientific results into applicable regulations. For example, in theory, there may always be one or more species spawning, mating, or feeding in an area that can be argued as a reason for avoiding disturbance, and, hence, closing the area year-round. However, such a strict regulation will never be applied by managers. Therefore, instead of the manager taking a potentially arbitrary decision on where and when to allow seismic survey, the scientist should help identify those areas and time periods that are most important to protect.

During the past 20 years, several guidelines have proposed certain sound threshold levels that should not be exceeded both for marine mammals [88,89] and fish [7,90]. Such criteria are useful and relatively easy to apply. Such thresholds are effective to prevent physical injury, as these are likely to arise when the animal is exposed to sound levels exceeding a certain level. Behavioral responses, however, are far more complex and a response may also depend on factors such as time of day [91], season [92,93], context [94,95], and previous exposure (e.g., [96,97]). Hawkins et al. [98] highlight the need for research on how fish respond to sounds at different levels and changes during the course of sound presentation while the sound characteristics (pressure and particle motion) are carefully measured. Further, Duarte et al. [19] emphasized that a new, globally binding agreement on the regulation of anthropogenic sound in the sea is needed, e.g., by inclusion into the UN Law of the Sea.

Some issues of high importance for better management decisions that remain unsolved include the extent and duration of displacement, as well as the thresholds of received sound levels or distances from the source that lead to avoidance of essential habitats, such as spawning, mating, or foraging sites for various species and animal groups. Additionally, studies should preferably enable an evaluation of how the measured effects could disturb the population, stock, or habitat as a whole, as this is usually the main unit that is managed.

In Norway, management has focused on commercially important fish stocks. This was related to a focus on sustainable management of fish stocks at IMR and a focus on coexistence between oil exploration and fisheries at a government level. Currently, an ecosystem-based approach is called for, as a more productive approach for the management of sustainable harvest [99–101]. To reach this goal, a wider range of species should be included in future management advice, including key species for the ecosystem and threatened species. Because data availability is a limiting factor for many such species, this requires a continued effort to collect data on the reproductive behavior of such species in relation to noise.

Furthermore, noise is not the only stressor that affects reproduction, and multi-stressor approaches could provide more insight into anthropogenic effects on underwater life. Thus, future management should also focus more on the overall effects of human impact on the ecosystem, by integrating different types of pressures instead of managing them one by one.

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