Implications of fisheries during the spawning season for the sustainable management and recovery of depleted fish stocks: a conceptual framework

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Contents

Summary

Fishing during the spawning season may negatively affects the reproductive potential and reproductive dynamics of exploited fish stocks due to a variety of mechanisms such as the disturbance of the natural spawning behaviour, effects on the age, size and sex composition of the spawning population and effects on the population genetics. The effect may differ between species in relation to the spawning strategy and population dynamic characteristics. Based on first principles of reproductive biology, population biology and fishing methods, a theoretical framework is developed on the effects of fishing during the spawning period. This framework is used to structure a review of the available scientific evidence. Implications of the findings on the recovery of depleted fish stocks and the sustainability of exploitation will be discussed and illustrated for a selection of North Sea fish stocks (flatfish, roundfish and pelagic).

Keywords: seasonal management, spawning fisheries, spawning behaviour, reproductive potential

1 Introduction

Great concern about the poor status of marine fish populations world wide due to severe overfishing (Jackson et al., 2001; Pauly et al., 2002; Worm et al., 2009). Fisheries management has been unsuccessful in many areas due to a variety of reasons such as poor governance, poor enforcement, erroneous scientific advice, inconsistent management regulations (Rijnsdorp et al., 2007; Rice et al., 2005). NGO's are vocal critics of the failures of fisheries management and increasingly gain influence. A major achievement is the promotion of eco-labeling such as the marine Stewardship Council which allow consumers to choose products from sustainable fisheries. An idea proposed by NGO's and fish traders is to stop fishing during the spawning period in order not to disturb the spawning process and hence improve the reproductive success of the population. Although the idea may be appealing to the general public, and spawning time closures are used widely in fresh water systems, the scientific underpinning is lacking.

Here we attempt to provide a analysis of the effects of fishing during the spawning period and its implication for sustainable management. Our approach is to analyse the physiological, behavioural, ecological and genetical mechanisms that result in successful reproduction and explore how fishing interfere with these.

2 Population dynamics

A natural population can be sustainably exploited by only harvesting the surplus production (Beverton and Holt, 1957; Ricker, 1954). Surplus production is determined by the excess of offspring produced. In absence of fishing, the number of offspring is controlled by density-dependent processes. Moderate exploitation will harvest only part of the access production that would otherwise have died due to density-dependent processes. At a certain level of exploitation (Fmsy), the harvest rate is equal to the maximum productivity of the stock. A further increase in exploitation will bring down to biomass of the adult stock to a level at which the production of young fish is jeopardized.

The number of offspring is determined by three parameters: (i) the size of the adult population; (ii) the proportion of the potential egg production that will be fertilized; (iii) the survival of the offspring till maturation. These parameters will differ greatly across fish species due to the rich variety of life history characteristics and reproductive strategies that have evolved (Wootton, 1990). An important point that determines the dynamics of a population and the susceptibility for fishing is the question during which life history phase the density-dependent process(es) take place, and how many offspring the population produces. Hence, fish species like cod and sole which produce millions of eggs, are less susceptible for fishing than species like sharks and rays that produce only a dozen of offspring.

2.1 Size of the adult population

Fishing increase the mortality rate of the fish that are retained in the net and will lead to a decrease in the adult biomass, the proportion of older and larger fish in the spawning population. If fishing mortality differs between the sexes, it may also lead to a distortion of the sex ratio in the spawning population (Rijnsdorp, 1994).
The number of eggs or young produced increase with body size. In many fish species, the relative fecundity (egg per gram body weight) increase with age and size. Hence, older and larger fish contribute disproportionally to the potential egg production of the population (Kjesbu, 2009; Trippel et al., 2005). There is also evidence that older and larger females produce higher quality eggs (Marteinsdottir and Steinarsson, 1998; Trippel and Neil, 2004) and that older and larger males have higher sperm counts (Trippel and Neilson, 1992; Rideout et al., 2004; Rakitin et al., 1999). Hence the population egg production is determined by the number of adult females in the population, their size and age structure. (Marteinsdottir and Thorarinsson, 1998) showed that the diversity of the age composition of the spawning population influenced the strength of the recruitment. A spawning stock comprising of many age groups produced on average a larger number of recruits than a spawning stock that was dominated by 1 or 2 age groups.

2.2 Proportion of the potential egg production that will be fertilized

Whether the potential egg production will lead to fertilization will depend on the ability of the male and females to find each and mate successfully and the quality of the spawning products. Here, the quality of the male and female is important, as well as the mating strategy and the behaviour. In the scientific literature there are only few studies which have addressed these questions. Experiments with tanks comprising of one female cod and a number of males revelaed that the fertilization success increased with the number of males (Rowe et al., 2004). One aspect which is very well supported by data is the fact that eggs can only be fertilized during a limited time window. During the final maturation of the oocytes, the oocytes are brought into a stage during which they can be fertilized and develop into capable embryos. If this maturation process is disturbed, or if the female is not able to spawn the oocytes in time, the quality drops and the fertilization rates decline (McEvoy, 1984). This implies that spawning fish are potentially sensitive for disturbance, which may prevent a batch of eggs to be spawned successfully.

2.3 Survival of the offspring till maturation

Survival of the offspring till maturation will very much depend on the reproductive strategy of the species and the environment in which it has to close its life cycle. Ecological theory generally distinguish between three type of survival curves (Krebs, 1972). The first curve is characterized by a very high mortality in the early life history stage which quickly decrease to a low leveled plateau for the later stages. The second type is a constant survival and the third shows a low mortality in early life and an increasing mortality rate late in life. In the marine environment where size structured processes dominate (Rothschild, 1986), survival curves are typically of type 1, except for marine mammals which show a type 3 curve. In fish, which generally produces offspring that are many orders of magnitude smaller than their parents and show an ontogenetic shift between habitats, will show a very high mortality during the early life history stages and therefore be characterized by a type 1 survival curve.

2.3.1 Survival between fertilization and metamorphosis

Fish often show a shift in habitat around the time of metamorphosis. Demersal fish spend their egg and larval phase in the pelagic habitat and become demersal around metamorphosis. Pelagic fish, although bound to the 3-dimensional habitat, may show habitat changes for instance in terms of salinity of temperature (Sinclair and Iles, 1989). As a result, the mortality experienced may change with the change in habitat. Fish are characterized by a type 1 curve and show a mortality rate that decrease with size / developmental stage (Bailey and Houde, 1989; Leggett and Deblois, 1994). However, the rate of decline of the mortality with body size will differ between fish species (Koslow, 1992). Hence broadcast spawners will suffer a very high mortality in the egg and larval stage (McGurk, 1986), while fish species producing larger young or that show parental care will show lower mortality rates. The differences in the number of offspring produced and the mortality rate are linked to the life history of the species which is an adaptation to the environment in which they live. Hence, fish species that show parental care will reduce the mortality rate of their offspring at the cost of the time and energy needed to product their young.

For fish species in which the larvae inhabit the water column and feed on plankton, the reproductive success is dependent on the match between the production of larvae and the production cycle of their food (match-mismatch hypothesis of (Cushing, 1990). As the occurrence of food patches in unpredictable, fish have evolved to spawn multiple batches that can be seen as an adaptation to enhancing the probability that a batch may hit a rich food patch. Although it is generally believed that the number of batches will increase the reproductive success and reduce the variability in recruitment, it has been notoriously difficult to prove this empirically. Only a few studies have provided evidence for this effect (Lambert, 1990; Marteinsdottir and Thorarinsson, 1998). The best evidence stems from a comparative analysis of the variability in the abundance of fish eggs and larvae of exploited and non-exploited species off California (Anderson et al., 2008). This study provided unequivocal evidence that exploited species were more variable than non-exploited species.

2.3.2 Survival between metamorphosis and maturation

Survival between metamorphosis and maturation will be determined by the mortality rate as well as duration of this stage. If due to density-dependent processes the duration of this stage increases the overall survival. There is ample evidence for density-dependent reductions in the juvenile phase (van der Veer et al., 1994; Myers and Cadigan, 1993). In relation to the question – how fishing during the spawning period may affect the reproductive success – the processes occurring after the spawning period are of no direct relevance.

2.4 Spawning mechanisms

In order to evaluate the potential impact of fishing on successful reproduction, we will now analyse the various mechanism that operate.

2.4.1 Physiological

(i) Bio-energetic considerations. Fishing disturbance may lead to energy cost that cannot be allocated to reproduction (behaviour, spawning products). If spawning requires full utilization of the metabolic scope, any disturbance will not only affect the spawning activity at the time of the disturbance, but may negatively affect the spawning performance during a certain period following the disturbance due to the physiological recovery such as oxygen debt (Brett and Groves, 1979; Portner et al., 2001).
(ii) Over-ripening of eggs (McEvoy, 1984).
(iii) Reproductive physiological consideration. Disturbance during the spawning period, by increasing stress hormones, could potentially influence the final maturation of the gametes, and hence reduce the reproductive potential.

2.4.2 Behavioural

Fishing may interfere with the following components of the behaviour related to reproduction
(i) Spawning migration. Some species may form pre-spawning or spawning aggregations during which they are particularly vulnerable for fishing and the potential disturbing effects of fishing activities.
(ii) Pair formation. If in the breeding system of fish, the male and female invest in pair formation, the time and energy cost of forming a pair bond may make the species more vulnerable for fishing disturbance, because a distortion of the pair bond will not be immediately restored.
(iii) Spawning behaviour. Species may synchronise their spawning activities at certain times of the day or tidal cycle, which may make them more vulnerable for disturbance during these spawning windows.

2.4.3 Ecological

The ecological mechanism of the importance to spawn at the right place and at the right time has already been mentioned. The match-mismatch is particularly important for batch spawners that produce small larvae that are very dependent on exogenous food resources. Another match-mismatch may occur between the occurrence of the fish larvae of early juveniles and their predators. After a cold winter, the predatory shrimps return later in spring to the coastal waters, whereas the arrival of the juvenile plaice is less affected. The later arrival of the predators following a cold winter reduces the mortality and result in an increase in the recruitment.

2.4.4 Genetical

Fishing during the spawning period may affect not only the reproductive success, but may also affect which parents can be successful. Although commercial fish populations comprise of millions of fish, even the overexploited ones, genetic research has revealed that only very few of the adult fish actually contribute to the next generation. The effective population size of exploited populations can be as low 10 - 1000 of adult fish (Hoarau et al., 2005; Hauser et al., 2002; Hauser and Carvalho, 2008), which may have implications for the sensitiveness for fishing disturbance.

Another aspect relates to the possibility that fishing leads to evolutionary changes in exploited stocks (Jorgensen et al., 2007). It is yet not yet clear how the evolutionary effect of fishing during the spawning period compares to the effect of fishing during the feeding period.

3 Conclusion

With the above conceptual framework, a structured literature analysis can be carried out to objectively review the scientific literature for the processes that may occur and will determine how fishing during the spawning period may impact the reproductive success of a fish stock. Based on the literature review we then can explore the effects of different management regimes on the reproductive success.

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