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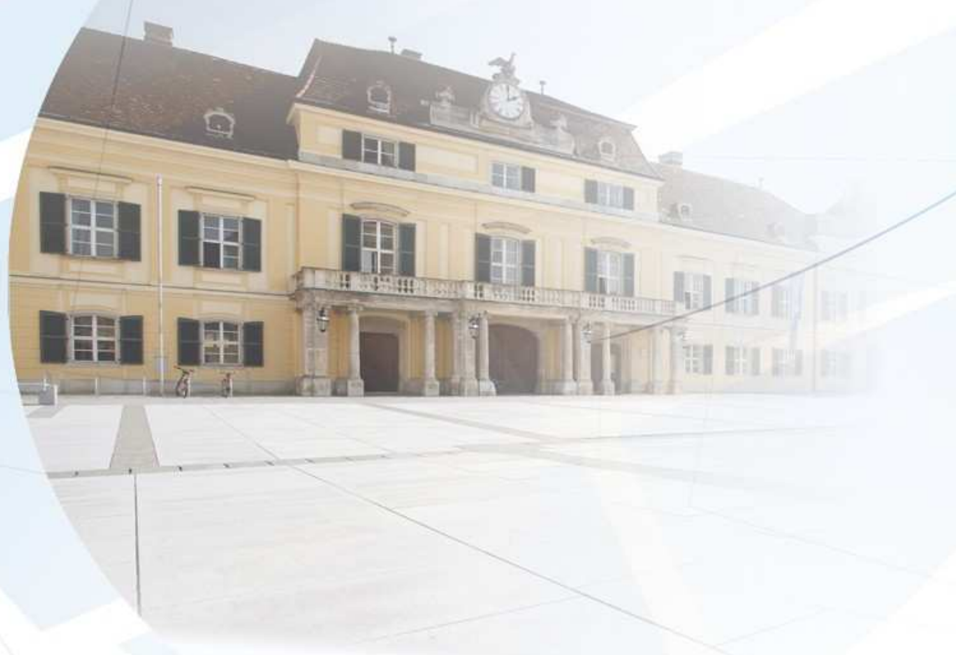

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Interim Report **IR-07-058**

2007 Report of the ICES Study Group on Fisheries-Induced Adaptive Change (SGFIAC)

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Executive summary

There is a growing body of scientific evidence indicating that fisheries can cause evolutionary responses over time periods as short as 10–20 years, in particular in traits such as the onset of maturation. As these changes will most likely result in a reduction of the productivity of a fish stock, management objectives and (precautionary) reference points for sustainable exploitation need to be re-defined, and new objectives and reference points for managing fisheries-induced evolution need to be developed. Current knowledge allows for two generalisations. First, reducing harvest rates will almost always slow the rate and extent of fisheries-induced evolution in most life-history traits. Second, raising a stock's minimum size limit for exploitation well above the size range over which maturation occurs will slow down the rate of evolution in its maturation schedule. To go beyond these generic insights, 'Evolutionary Impact Assessments' (EvoIAs) are proposed to quantify the effects of management measures, through the evolutionary response of specific stocks, on the utility functions defined by managers. The Study Group on Fisheries Induced Adaptive Change [SGFIAC] proposes to further develop this framework in dialogue with fisheries scientists and managers, with the aim of integrating the effects of fisheries-induced evolution into fisheries management advice. Developing EvoIAs in the context of suitable case studies is considered to be the most efficient way for making progress.

1 Opening of the meeting

The Chair opened the meeting on Monday, 26 February, at 14.00 and closed the meeting on Friday, 2 March, at 13.00.

2 Adoption of the agenda

The Terms of Reference for the Study Group on Fisheries Induced Adaptive Change [SGFIAC] are as follows:

a) assemble and review empirical evidence of fisheries-induced adaptive change and its consequences for conservation of biodiversity and sustainable exploitation of marine species, within an ecosystem context, including previous work by WGAGFM and WGECO;

b) evaluate the impact of existing management measures and tools, such as minimum mesh and landing sizes, precautionary reference points and marine protected areas, effort regulations, on fisheries-induced adaptive change;

c) develop appropriate scientific and methodological tools to monitor and respond appropriately to risk to biodiversity and sustainable exploitation posed by fisheries-induced adaptive change;

d) relate consequences of fisheries-induced adaptive change to current management objectives and evaluate possible more specific objectives for managing fisheries-induced adaptive change.

3 Introduction

While traditional fisheries management focuses on the demographic effects of fishing, ecological and evolutionary implications of fishing have received less attention. In particular, even though the earliest discussions about the possible evolutionary implications of fishing (Rutter, 1902) go back to the founding years of fisheries science, evolutionary thinking remained on the sidelines. The current drive towards an ecosystem approach to management recognizes a broader range of values and services of aquatic ecosystems than the classic yield-focused management paradigm (Garcia and Cochrane, 2005), and ecological and evolutionary effects of fishing are receiving increasing attention (Pikitch *et al*., 2004; Olsen *et al*., 2004). The ecosystem approach and the precautionary approach mandate assessing the broader impacts of exploitation. In particular, a precautionary approach “exercises prudent foresight to avoid unacceptable or undesirable situations, taking into account that changes in fisheries systems are only slowly reversible, difficult to control, not well understood, and subject to change in the environment and human values” (FAO, 1996). The ecosystem approach strives “to balance diverse societal objectives, by taking into account the knowledge and uncertainties about biotic, abiotic, and human components of ecosystems and their interactions and applying an integrated approach to fisheries within ecologically meaningful boundaries” (FAO, 2003). However, fisheries scientists are only now beginning to recognize that evolutionary effects of fishing do occur on top of ecological impacts, and that these effects can both ameliorate and aggravate demographic and ecological effects of fishing.

Fisheries-induced evolution is largely inevitable: fishing is essentially always selective (Law, 2000), and breeding programs with cultured fish show that heritable variability is essentially always present. The question then is not whether, but how fast, the induced evolutionary changes are occurring. Recent empirical and experimental evidence summarized later in this report clearly demonstrates that the rate of fisheries-induced evolution can be much faster than was believed earlier on, occurring at time scales directly relevant to fisheries management. In addition, fishing is not the only selective force that fish experience. Environments where fish are living are always changing, be it due to natural fluctuations, local anthropogenic impacts such as eutrophication, or climate change. Thus, fish populations are constantly under evolutionary selection pressures, and will continue to evolve, whether we want this or not.

Based on acknowledging that evolutionary changes are inevitable in exploited and unexploited ecosystems, the consequences of fishing-induced selection must be incorporated into contemporary management to fulfil the goals of the ecosystem approach to fisheries. Echoing Ashley *et al*. (2003), we call this "evolutionarily enlightened fisheries management". It is defined here as management of fishing activities based on knowledge of ecological and evolutionary dynamics to achieve an optimum level of ecological services generated by fish or other aquatic organisms. "Evolutionarily enlightened fisheries management" is the application of "Darwinian fisheries science" as coined by Conover (2000). Darwinian fisheries science emphasizes that basic awareness of evolutionary biology can help fisheries science to better achieve its traditional goals. A theme section edited by H. Browman for Marine Ecology Progress Series in 2000 highlighted these more general ideas.

The call for evolutionarily enlightened fisheries management is not new. Law and Grey (1989) first pointed out that while unmanaged evolution can have detrimental consequences on yield, fisheries managers could also use evolution to their advantage and adopt the harvesting strategy that maximizes yield after evolutionary changes have taken place. Brown and Parman (1993) coined the term "evolutionarily enlightened manager" to describe a stock manager pursuing this very specific goal. Given that this definition implies ignoring the losses of yield that might occur while population is evolving to the state where yield is maximized; this is the most extreme form of evolutionary management. Therefore, the modern usage of the term evolutionarily enlightened management is broader and less extreme: no specific goal is implied, only that the managers are aware that evolutionary changes may take place and have consequences for the utility of the stock for humans. The response to such changes will depend on the specific management objectives, but in keeping with the ecosystem approach and international agreements such as the 1992 Convention on Biological Diversity, one would usually expect attempts at mitigating negative consequences of fisheries-induced evolution.

4 Previous ICES work

Within ICES, evolutionary consequences of exploitation have been addressed since 1995 (Table 1). First, the Working Group on the Application of Genetics in Fisheries and Mariculture (WGAGFM) treated the question of genetic effects of selective fisheries in 1995–1998. The question received substantial coverage in 1997, based on review work by P.J. Smith, which has also been published as a FAO Fisheries Technical Paper (Smith, 1994). At that time, much of the theory underlying fisheries-induced evolution was already in place, but empirical evidence was slim. This bout of activity concluded with the following recommendations, which remain relevant today (ICES, 1998):

- WGAGFM emphasised that stocks should be monitored for relevant traits (e.g. age at maturity, growth rates, spawning period, migration patterns, etc.) so that potential selection effects can be identified as early as possible.
- WGAGFM reviewed recent literature which emphasizes, e.g. the effect of the age composition of the spawning stock as a significant factor for year class strength. In this connection, it was noted that some regulation regimes in current use may have effects on age composition which in fact are not considered beneficial for stock recruitment.
- In the monitoring of biological traits of populations, time series of data which make it possible to sort out effects of environmental changes would be especially valuable, and efforts should be made to identify and/or produce such data (e.g. age at maturity data during medium-term shifts in the temperature regime, e.g. from an upward trend to a downward trend, could make it possible to identify the

variance component due to temperature and thus make it possible to reduce substantial 'noise' in the data sets).

The topic was picked up again by the Working Group on the Ecosystem Effects of Fishing Activities (WGECO) in 2002, although the work in WGECO was focused on genetic effects in general, with fisheries-induced evolution receiving minor attention. This work was partly continued in WGAGFM, where a more specific agenda related to probabilistic maturation reaction norms was followed in 2004–2005.

Two ICES Annual Science Conferences included Theme Sessions dedicated to fisheries-induced evolution, first in Copenhagen in 2002 (Theme Session on "The effects of fishing on the genetic composition of living marine resources" with a total of 16 presentations) and then in Maastricht in 2006 (Theme Session on "Evolutionary effects of exploitation on living marine resources" with a total of 18 presentations).

The aim of the present report is to build on these earlier accounts and extend their management implications. We first present an overview of the available empirical evidence for fisheries-induced evolution. We then show that fisheries-induced evolution has consequences that require attention of fisheries scientists and managers, in keeping with agreed global management approaches and objectives. We then elaborate on how management objectives more specific to fisheries-induced evolution might be defined and introduce Evolutionary Impact Assessments as a tool for tackling this challenge. This will lead to clearer insights about the specific management measures that could be used to mitigate unwanted evolutionary changes.

Terms and abbreviations

- Fisheries-induced evolution (FIE): Genetic change in a population, with fishing serving as the driving force of evolution.
- Fisheries-induced adaptive change (FIAC): Change in the phenotypic characteristics of individuals in a population, caused by fishing and reflecting both genetic changes and changes due to adaptive phenotypic plasticity.
- Limit reference point for spawning stock biomass (B_{lim}): In ICES usage, this benchmark is defined such that below this level, there is a high risk that recruitment will be impaired and on average be significantly lower than at higher spawning stock biomass (*SSB*), or alternatively, the stock dynamics are unknown.
- Limit reference point for fishing mortality (F_{lim}): In ICES usage, this is the fishing mortality that, if maintained, will drive the stock to the biomass limit B_{lim}.
- Maximum sustainable yield (*MSY*): Maximum biological yield that can be harvested from a population in the long run, without driving the population to extinction.
- Precautionary reference points: In general, reference points used to implement precautionary fisheries management. In ICES usage, these have a more specific meaning. The precautionary reference point for spawning stock biomass (B_{pa}) is defined such that if the estimated *SSB* is larger than this benchmark, then the true *SSB* is larger than B_{lim} with a high probability (usually 95%). The precautionary reference point for fishing mortality (F_{pa}) is defined analogously.

5 Empirical evidence

In exploited fish stocks, fishing is the major source of mortality. Life-history theory predicts that an increase in mortality, even when it is uniform, favours maturation at an earlier age and smaller size, as well as increased reproductive effort (Law and Grey, 1989; Stearns, 1992; Roff, 1992; Heino, 1998; Ernande *et al*., 2004). Additional evolutionary pressures may be inflicted on exploited fish stocks through fishing selectivity on size, behaviour, and morphology (Heino and Godø, 2002). These theoretical predictions have been confirmed in experiments showing that, given strong selection pressures, significant evolutionary changes can take place within just a few generations (Silliman, 1975; Edley and Law, 1988; Conover and Munch, 2002; Reznick *et al*. 1990; Reznick and Ghalambor, 2005).

Numerous authors have detected long-term changes in life-history patterns of exploited fish (see reviews by Trippel, 1995 and by Dieckmann and Heino, 2007, and references therein). More seldomly, changes in morphological traits (Izyumov *et al*., 2002; Marshall *et al*., 2004) and in behavioural and physiological traits (Cooke, 2002) have been reported. Reported trends include those in age and size at maturation (Rijnsdorp, 1989; 1993; Jørgensen, 1990; Trippel, 1995; O'Brien, 1999; Engelhard and Heino, 2004; Yoneda and Wright, 2004), somatic growth (Ricker, 1981; Jørgensen, 1992; Sinclair *et al*., 2002; Bolle *et al*., 2004; Engelhard and Heino, 2004a, 2004b; Swain *et al*., 2007), and fecundity (Yoneda and Wright, 2004; Rijnsdorp *et al*., 2005; Wright, 2005). Many of these changes could be attributed to fisheries-induced evolution. However, since the environment readily influences life-history traits, these patterns could alternatively be the consequence of phenotypic plasticity, rather than of genetic change. For example, fishing reduces stock size, which may release intraspecific competition for food resources and result in faster growth and earlier maturation. Therefore, establishing the true nature of life-history changes in exploited stocks requires careful analysis of possible explanations.

The recently developed methodology of probabilistic maturation reaction norms has helped to disentangle growth-related phenotypic plasticity and evolutionary change in maturation (Heino *et al*., 2002a; Barot *et al*., 2004a; Dieckmann and Heino, 2007). A large number of independent case studies utilizing this methodology (Table 2) have revealed that growth-related phenotypic plasticity alone is not sufficient to explain the observed trends in age and size at maturation, suggesting that explanations must be sought elsewhere. The patterns in probabilistic maturation reaction norms are in accordance with the theoretical expectations of fisheries-induced evolution derived from life-history theory. While alternative hypotheses can never be ruled out in single studies, fisheries-induced evolution consistently arises as the most parsimonious explanation for the observed trends and changes.

Similarly, a recent combination of modelling and statistical analyses has suggested that genetic alterations in growth have likely occurred in cod (Swain *et al*., 2007). This implies that such changes could be expected also in other exploited stocks, and calls for further methodological development and empirical investigations.

6 Consequences of fisheries-induced evolution

Fisheries-induced evolution of life-history traits can have repercussions for biodiversity and impact stock dynamics, demography, biomass, and economic yield. Currently, the bulk of empirical and theoretical evidence concerns stock demography and dynamics (Law and Grey, 1989; Trippel, 1995; Heino, 1998; Ernande *et al*., 2004; de Roos *et al*., 2006; Dunlop *et al*., 2007).

Selective fishing affects biodiversity in terms of both within- and between-population genetic composition. Small populations, such as coral reef fish, or anadromous and freshwater species, may suffer from "genetic erosion" through the loss of allelic diversity. This may lead to inbreeding depression and/or the loss of evolutionary potential. In contrast, large populations will mainly be affected by changes in mean genotypic values. Overall, populations will adapt to fishing mortality, which is generally much higher than natural mortality, and therefore the ancestral adaptation to their local natural environment may be lost.

Alterations of stock dynamics — arising through changes in life-history traits — will in general impact stock-level demographic properties such as:

- Spawning stock biomass and recruitment, and thereby related reference points: minimum spawning stock biomass, B_{lim} (with a possibility of overestimating it), its precautionary counterpart, B_{pa}, and associated fishing mortalities, F_{lim} and F_{pa}. Owing to fisheries-induced evolution, these reference points thus require regular updating.
- The likelihood of stock collapse and the potential for, and speed of, recovery (Hutchings, 2005).
- Reproductive potential of a stock, through reduced fecundity and maternal effects (under most current fishing practices, fisheries-induced evolution leads to reduced individual size; Walsh *et al.*, 2006).
- Yield will also be affected, both in biological and economic terms:
- Biomass yield (Edley and Law, 1988; Conover and Munch, 2002), as well as related reference points: maximum sustainable yield, *MSY*, and the corresponding fishing mortality, F_{MSY};
- Loss of biological yield implies decreased economic yield; in addition, current fishing practices typically alter the size composition of catch and favour the evolution of reduced individual size (Heino, 1998), lowering the market (and social) value of individual fish and thus the economic value of the entire stock.

7 Implications of existing management objectives

The overarching guidelines for the general objectives of fisheries management have been codified in a number of policy documents, including

- Chapter 17 of Agenda 21 of the UN Conference on Environment and Development (UNCED 1992),
- The Convention on Biological Diversity (UN 1992),
- The United Nations Fish Stocks agreement (UN 1995),
- The FAO Code of Conduct for Responsible Fisheries (FAO 1995), and
- The Declaration of the World Summit of Sustainable Development (UN 2002).

The resultant guidelines include (i) the precautionary approach, (ii) the ecosystem approach to marine management, and (iii) the goal that fish stocks shall be maintained or restored to levels that can produce the maximum sustainable yield (MSY) by 2015. Although the concept of MSY has been under critique since the mid 1970s (Larkin, 1977), the European Commission recently adopted a Communication on the implementation of the MSY concept in the Common Fisheries Policy (European Commission, 2006a) in agreement with the Declaration of the World Summit of Sustainable Development (UN 2002). This policy is likely to result in the need to reduce current fishing mortality. Fisheries-induced evolution is yet another reason for reducing fishing mortality.

The reference points currently in use within ICES, as well as the future strategies for reaching the stipulated MSY goal, will be influenced by fisheries-induced evolution. If exploitation causes fisheries-induced evolution in productivity-related traits, harvesting may no longer be sustainable and alternative reference points need to be established to take this into account. On the same grounds, the objective of restoring populations to MSY will be influenced by fisheries-induced evolution. Although some parties may still question whether or not fisheries-induced evolution occurs, and rates of fisheries-induced evolution may currently not be estimable with accuracy, the precautionary approach prescribes that the absence of adequate scientific information shall not be used as a reason for postponing or failing to take conservation and management measures (UN 1995).

Based on the concept of sustainable development (UN 2002), the recent Green Paper of the European Commission (European Commission 2006b) aims to unify the multitude of EU maritime policies that were developed separately in the past. The recommended approach is based on maintaining and improving the ocean resource and emphasizes the application of an ecosystem approach to fisheries management. A healthy marine environment is said to include the "size and diversity of the life within [the ocean], including fish stocks". Achieving a good status of the marine environment is a key aim to be achieved by 2021.

It can thus be concluded that

- Existing management objectives and policies with regard to the marine environment require the inclusion of genetic implications of fishing such as fisheries-induced evolution,
- Current fisheries management objectives (reference points and MSY) need to be re-formulated to account for fisheries-induced evolution, and
- Additional objectives need to be developed for managing fisheries-induced evolution.

8 Objectives and resultant utility metrics

Marine ecosystems in general and fish stocks in particular, produce a series of so-called ecological services of direct and indirect utility to society (Holmlund and Hammer, 1999; Carpenter and Folke, 2006). Such services are potentially affected by fisheries-induced evolutionary change and include tangible and intrinsic dimensions. Three categories of ecosystem services provided by aquatic ecosystems and fish stocks directly affect humans:

- *Provisioning services* are the products humans derive from marine ecosystems such as fish yield. These services are most obviously affected by fisheries-induced evolution (Law and Grey, 1989; Heino, 1998; Conover and Munch, 2002; Dunlop *et al*., 2007).
- *Regulating services* are benefits that humans obtain from a natural regulation of ecosystem processes. In particular, ecosystem regulation, fish population resilience, and preservation of genetic biodiversity are prerequisites for adaptive evolution to changing environmental conditions. Fisheries-induced evolution may alter various aspects of regulating services such as predator-prey relationships (Gårdmark *et al*., 2003), with potentially negative impacts on ecosystem structure and functioning.
- The last category of ecological services generated by fish populations is less tangible and termed *cultural services*. This includes the non-material utility humans obtain from fish populations through existence values, spiritual and educational enrichment, and recreational and aesthetic experiences.

A clear identification of the aforementioned ecological services is important because not all of them are readily apparent to fisheries managers and society in general. For example, regulating services could be overlooked in the context of fisheries-induced evolution, even though they are crucial for the long-term resilience of fish populations and ecosystems. Traditionally, fisheries management objectives exclusively or predominantly focused on maximizing provisioning services such as yield. However, as explained above, this is only one dimension of the utility function of operational management: focusing on utility through fish yield falls short of appreciating the multiple components of the utility generated by fish to society. A more holistic approach is needed.

The definition of an operational utility function remains a complex task and is ultimately socially constructed. Identifying utility components and the weights attached to different aspects into operational utility functions necessitates a dialogue between fisheries managers, scientists, politicians, and various stakeholder groups. This is an issue that cannot be addressed by ICES alone. We envision that an integrated utility metric will include the following components:

- Fisheries values such as cumulative yield and the stability of yield.
- Conservation values such as existence values and preservation of genetic diversity.
- Ecological values such as the role of a harvested species in ecosystem functioning.
- Economical values incorporating discounting and time-varying pricing.

Evolutionarily enlightened fisheries management replaces the current management objective of keeping sustaining spawning stock biomass within safe biological limits with yield sustainability based on accounting for evolutionary changes in adaptive traits of fish stocks. This objective must be traded-off against socio-economic values, and the acceptable level of genetic change in exploited stock is therefore dependent on adopted utility function. At one extreme, fisheries selection could be targeted so as to select for trait values that would enhance yields at the expense of compromising other components of overall utility.

9 Evolutionary impact assessments

The preceding considerations have shown that evolutionary impact assessments (EvoIA) are needed for responsibly dealing with the evolutionary implications of fishing. Any EvoIA will typically involve two major translation steps:

$$\text{Fishing} \rightarrow \text{Traits} \rightarrow \text{Utility}$$

First, current or prospective management actions affecting the intensity or pattern of fishing are translated into predicted changes in a stock's traits, in particular its life-history traits. In EvoIAs, this must always include evaluating the consequences of inaction relative to current fishing practices. In a second step, these life-history changes are translated into changes in the stock's utility. While the former translation primarily relies on biological information, the utility function underlying the latter translation must be based on management objectives.

Retrospective EvoIAs can often be carried out based on existent data and without a need for dynamic modelling. Prospective EvoIAs, by contrast, will typically involve models to provide the required quantitative predictions. In EvoIAs, the utility impacts assessed are those that result from changes caused by trait evolution. Once a model suitable for prospective EvoIA is in place, comparisons can be made both between times and between actions:

- *Comparisons between actions.* A primary goal of prospective EvoIAs is to predict how a stock's utility changes within a given time horizon as a result of alternative management actions. Utilities may either be accumulated over the considered time window, or considered at its end. For example, a stock's yield resulting after 20 years of intensive harvesting could be contrasted with its yield after 20 years of low harvesting.
- *Comparisons between times.* Prospective EvoIAs can also be used for estimating costs of inaction. Here one is concerned with a single course of action, defined by the continuation of current exploitation practices. On this basis, a stock's current utility is compared with its predicted utility at future moments in time. For

example, the cost of inaction could be computed as the yield lost over a period of 20 years as a result of fisheries-induced evolution.

In practice, these two dimensions will often be combined.

As demonstrated by recent empirical studies, evolutionary changes in some traits and stocks can happen quickly, while other evolutionary changes may happen more slowly. Further, there are good reasons to expect that recoveries from fisheries-induced evolution (if ever attempted) will take a very long time. Different time horizons will thus be needed for EvoIAs, in accordance with management objectives and stock characteristics.

Since evolutionary changes are complicated reactions to selection pressures that involve many factors, nonlinear analyses are required for comparing the impacts of different actions. In addition, linear sensitivity analyses can be used to assess the impacts of small modifications in actions. In keeping with the two-step approach proposed above, three different sensitivity measures will be relevant:

- *Susceptibility* measures how sensitive the response of a stock's adaptive traits is to changes in fishing (*d* traits / *d* fishing).
- *Desirability* measures how sensitive the response of a stock's utility is to evolutionary changes in its adaptive traits (*d* utility / *d* traits).
- *Vulnerability* combines these two measures and describes how sensitively, as a result of fisheries-induced evolution, a stock's utility responds to changes in fishing (*d* utility / *d* fishing).

Working with these definitions will facilitate discussions among participants with different backgrounds, and assist in the prioritization of actions.

Since evolutionary changes are expected to have affected, and be affecting, all stocks exposed to exploitation, it is recommended that EvoIAs be carried out for all these stocks. Initial EvoIAs can be rough and should be aimed at prioritizing target stocks. On the basis of such initial assessments, detailed EvoIAs should be carried out, focussing efforts on the most vulnerable stocks.

10 Management responses

To date, two evolutionarily enlightened fisheries management measures have been identified that will widely apply in single-species settings. First, reducing harvest rates will slow the rate and extent of fisheries-induced evolution in most life-history traits. Second, raising the minimum size limit well above the size at maturation will slow down the rate of evolution in maturation schedules. Owing to the complex and dynamic nature of fisheries-induced changes, it is simply not feasible based on research to date to draft further management guidelines that could be applied broadly across all species, stocks, and ecosystems.

In the near future, research will reveal the extent to which guidelines for evolutionarily enlightened fisheries management can be devised for specific stocks based on their life-history characteristics and harvesting regime. Resultant predictions that particular stocks are susceptible to undergoing rapid or severe evolutionary change can help set management priorities. The predicted nature of evolutionary change, combined with knowledge about the current fishing regime, might also suggest which management measures will be most effective. Based on broad features of life-history characteristics and fishing patterns, a decision-tree matrix could be developed to guide management in the absence of more detailed stock-specific predictions. This approach can provide a cost-efficient basis for coarse-grained EvoIAs.

Beyond the general guidelines mentioned above, evolutionarily enlightened management decisions will have to be made on a case-by-case basis. For a given action (e.g. reducing fishing effort), one can use EvoIA to assess the expected impact on a chosen utility. A manager who needs to decide between alternative measures – including changing the harvest rate, changing the minimum size limit or minimum mesh sizes, or implementing a marine reserve – could use detailed EvoIA to map these measures onto expected utility changes. Reflecting widely acknowledged features of responsible management, the complete management cycle will need to include steps for implementation, monitoring, and re-evaluation of the chosen management measures.

11 Conclusions

The empirical evidence for fisheries-induced evolution is strong and mounting, its biological and economic consequences are potentially severe, and the resultant needs for precautionary and mitigating actions have thus become compelling. To address these needs, a practical framework for evolutionary impact assessments (EvoIAs) in fisheries must be developed in dialogue between all involved parties. The time horizons on which evolutionary impacts unfold are much shorter than previously believed and are thus compatible with those mandated by the ecosystem approach and precautionary approach to fisheries management. It is recommended that EvoIAs be carried out as soon as possible for as many exploited stocks as is feasible: initial coarse-grained assessments can be used for the prioritization of efforts to be invested into more fine-grained assessments focusing on those stocks that are identified as particularly vulnerable to fisheries-induced evolution.

Enhanced communication

Improved communication will be essential to achieve the evolutionarily enlightened management approach outlined above. A dialogue between managers, fisheries scientists, evolutionary scientists, and fishers is necessary to attain the following five goals; (i) to demonstrate the relevance of fisheries-induced adaptive change to other fields of fisheries science, (ii) to ensure that the knowledge and experience of fishers are suitably represented in these developments and to enable them to stay abreast of research developments in evolutionary fisheries management, (iii) to collaboratively integrate current insights about fisheries-induced adaptive change into the scientific advice supporting fisheries management, (iv) to obtain guidance on research needed to enhance the applicability of fisheries-induced adaptive change to the scientific advisory process and to management, and (v) to collaboratively develop case studies of EvoIAs. These goals all necessitate a dialogue that places the findings of fisheries-induced adaptive change in a context that is easily transferable between disciplines.

Promising approaches for addressing these communication goals are as follows:

- *Goals (i) and (ii)* – Provide information and discussion opportunities for a broader audience. Measures to achieve this include recurring Theme Sessions at the ICES Annual Science Conference, the organization of dedicated international workshops and conferences, dissemination of information leaflets on fisheries-induced adaptive change, and publication of popularised summaries of the Study Group's work, e.g. in the ICES Newsletter.
- *Goals (ii) and (iii)* – Strengthen interface between ICES scientific advisors and evolutionary researchers. Measures to achieve this include exchange with ICES working groups dealing with the topic (WGAGFM, WGECO, WGIAB – respectively, Working Group on the Application of Genetics to Fisheries and Mariculture, Working Group on Ecosystem Effects of Fisheries Activities, and Working Group on Integrated Assessments for the Baltic), invitation into the study group of management experts and advisory scientists, and participation in

the study group of scientists from fisheries research institutes linked to fisheries assessments and/or life-history studies.

- *Goal (v)* – Collaboration with stock-specific scientists and managers. Measures to achieve this include the recruitment of stock-specific experts to participation in the study group and the corresponding intersessional work, to strengthen case studies underlying EvoIAs providing input, and to improve dialogue on relevant processes and utility metrics.

Enhanced research

The European Union's recent Green Paper on maritime policy (European Commission 2006b) emphasizes the importance of staying at the cutting edge of knowledge via marine-related science and research. Evolutionary change in exploited stocks is still a relatively new concept within fisheries science and management and the aim of promoting developments in this burgeoning field would thus be in line with EU priorities. The Green Paper also stresses the importance of innovation under changing environmental circumstances. Like climate change, the evolution of exploited resources is a fundamental, and often still underappreciated, process requiring such innovation. For future progress, the Green Paper strongly encourages the development of processes and methods that help reduce uncertainties in impact and scale of environmentally unfriendly practices through the use of risk assessment methods.

Promising research approaches for addressing the four main goals set out in the Study Group's terms of reference are as follows:

- *ToR (a)* – Assemble and review empirical evidence. Measures to achieve this include the taxonomic and geographic extension of empirical studies of fisheries-induced evolution; the exploration of molecular evidence of fisheries-induced evolution; and the examination of fisheries-induced evolution in behavioural traits such as gear avoidance and mating preferences.
- *ToR (b)* – Evaluate the impact of existing management measures. Measures to achieve this include empirical and theoretical studies of the evolutionary effects and utility consequences of common management measures; understanding the evolutionary determinants of probabilistic maturation reaction norms; identification of fisheries-induced evolution syndromes resulting from multi-trait evolution; understanding the evolutionary dimensions of stock collapse and recovery processes; identification of the utility functions implicitly or explicitly applied in current management practices; and closer integration of eco-genetic models with bio-economic approaches.
- *ToR (c)* – Develop appropriate scientific and methodological tools. Measures to achieve this include the development of a decision-tree approach to evolutionarily enlightened fisheries management; adoption of risk assessment methods suitable for tackling fisheries-induced evolution; and the development of standardized approaches for removing phenotypic plasticity from life-history traits such as growth rates and reproductive efforts.
- *ToR (d)* – Relate consequences of fisheries-induced adaptive change to current management objectives. Measures to achieve this include the specification of practical measures and protocols for assessing susceptibility, desirability, and vulnerability to fisheries-induced evolution; development of new indicators and reference points suitable for monitoring and mitigating fisheries-induced evolution; and propositions for integrating requirements resulting from fisheries-induced evolution into current practices for monitoring, assessment, and advice.

It is hoped that the aforementioned agenda of enhanced communication and research will help overcome the current status of fisheries-induced evolution as a blind spot of contemporary fisheries management.

12 Next steps

The Study Group has agreed on the following targets for intersessional work until the group's next meeting:

- *Communication targets.* Dissemination of information to a broader audience through a short article in, e.g. Science's Policy Forum (or alternative publication outlets such as a forum article in BioScience or an essay in Trends in Ecology and Evolution) and/or the ICES Newsletter. Liaison with WGECO, WGAGFM, WGIAB, and SGBIODIV. Personal interaction with committee chairs and assessment scientists. Meetings during the 2007 Annual Science Conference with committee chairs and DG Fish representatives.
- *Research targets.* One or more worked-out examples of EvoIA. Additional case studies based on empirical data analyses and on the application of eco-genetic and evolutionary energy allocation models. Steps towards establishing a decision-tree matrix for coarse-grained EvoIA.

The Study Group's next meeting is planned to be held at the ICES headquarters in Copenhagen, Denmark, from 21 to 25 January, 2008 (with the preceding week serving as a fall-back option). Specific items envisaged for the agenda of this meeting include the following:

- Presentation and discussion of specific case studies.
- Steps towards establishing a decision-tree matrix for coarse-grained EvoIA.
- Drafting of a first specification of the EvoIA protocol.
- Discussion of how best to integrate FIE-related considerations into ICES assessment working groups (addressing standard issues such as maturity ogives, reference points for sustainable exploitation, and the relationship between recruitment and spawning stock biomass).

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Table 1. Overview of previous ICES work related to fisheries-induced evolution.

YEAR	EXPERT GROUP	TERMS OF REFERENCE	COVERAGE IN REPORT
1995	WGAGFM	Review the question of selective fisheries with a view to proposing studies to identify possible long term genetic effects.	Overview of theoretical expectations (2 pages).
1996	WGAGFM	Continue the review of knowledge of basic population genetic topics in fisheries and mariculture, including the questions of selective fisheries and GMOs (genetically modified organisms) with emphasis on a combination of qualitative and quantitative genetics.	Presentation of modelling work on North Sea cod by K. Stokes and A. Thompson, summarized in the report (1.5 pages).
1997	WGAGFM	Continue the review of population genetic topics in fisheries and mariculture, including the questions of selective fisheries and GMOs (genetically modified organisms), with emphasis on a combination of qualitative and quantitative genetics.	Review of empirical evidence and modelling based on the position paper by P. Smith (15 pages).
1998	WGAGFM	Continue the review of population genetic topics in fisheries and mariculture, including the questions of selective fisheries and GMOs (genetically modified organisms), with emphasis on a combination of qualitative and quantitative genetics.	Overview of the treatment of the selective fisheries topic in WGAFGM, with summary of recommendations (1.3 pages).
2002	WGECO	Propose a process to be able to obtain information to develop advisory forms appropriate to the preservation of genetic diversity, beginning with the initiation of an evaluation of the advisory forms and management approaches that would be necessary and sufficient for the protection of genetic diversity of exploited stocks, and stocks suffering substantial mortality as by-catch.	Overview of genetic diversity and processes affecting it, with about 2 pages on fisheries-induced selection; some procedural recommendations (10 pages in total).
2003	WGECO	Continue work on the development of advisory forms appropriate for the preservation of the genetic diversity of exploited stocks and stocks suffering substantial mortality as by-catch.	Overview of management measures to preserve genetic diversity, with fisheries-induced selection mentioned in passing (3.5 pages in total).
2004	WGAGFM	Evaluate the use of reaction norms to evaluate the genetic impact of selective fishing.	Overview of empirical evidence and theoretical developments based on a position paper prepared by U. Dieckmann, B. Ernande. M. Heino, and P. Boudry (4.5 pages).
2005	WGAGFM	Evaluate the usefulness of probabilistic maturation reaction norms as ecological quality objectives (EcoQOs) as an early warning signal for the negative impact of fishing and other anthropogenic activities.	Evaluation based on a working paper by P. McGinnity, B. Ernande, and E. Kenchington (1 page).

Table 2. Overview of studies in which probabilistic reaction norms have been used to detect likely evolutionary trends in maturation. With only few exceptions, these studies suggest that significant evolutionary changes are occurring in exploited fish stocks. Where exceptions occur, they can be explained by the nature of fishing selection (herring: fishing primarily targeting mature fish does not favour earlier maturation) or by natural selection countering fisheries-induced selection (smallmouth bass: nest-guarding behaviour favours large individuals).

Species	Population or stock	Period with data	Evolutionary trend towards earlier maturation at smaller size?	Reference
Atlantic cod *Gadus morhua*	Northeast Arctic	1932–1998	Yes	Heino *et al*., 2002b
	Eastern Baltic	1991–2005	Yes	Vainikka *et al*., in prep.
	Georges Bank	1970–1998	Yes	Barot *et al*., 2004b
	Gulf of Maine	1970–1998	Yes	
	Northern (2J3KL)	(1977–)1981–2002	Yes	Olsen *et al*., 2004
	Southern Grand Bank (3NO)	1971–2002	Yes	Olsen *et al*. 2005
	St. Pierre Bank (3Ps)	1972–2002	Yes	
Haddock *Melanogrammus aeglefinus*	Georges Bank	1968–2002	Yes	O'Brien *et al*., in prep.
	North Sea	1976–1999	Yes	Wright, 2005
Plaice *Pleuronectes platessa*	North Sea	1957–2001	Yes	Grift *et al*., 2003
American plaice *Hippoglossoides platessoides*	Labrador–NE Newfoundland (2J3K)	1973–1999	Yes	Barot *et al*., 2005
	Grand Bank (3LNO)	1969–2000	Yes	
	St. Pierre Bank (3Ps)	1972–1999	Yes	
Sole *Solea solea*	Southern North Sea	1958–2000	Yes	Mollet *et al*., 2006
Atlantic herring *Clupea harengus*	Norwegian spring-spawning	1935–2000	Yes (weak)	Engelhard and Heino, 2004b
Small yellow croaker *Pseudosciaena polyactis*	Yellow Sea	1985–2001 (4 years)	Yes (research in progress)	Heino, Yin and Dieckmann, in prep.
Grayling *Thymallus thymallus*	Lake Lesjaskogsvatnet, Norway	1903–2000 (ca. 15 years)	Yes	Haugen and Vøllestad, 2007
Smallmouth bass *Micropterus dolomieu*	Opeongo Lake, Ontario, Canada	1936–2002	No (or not detectable)	Dunlop *et al*., 2005

Annex 1: List of participants

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Annex 2: SGFIAC Terms of Reference

The **Study Group on Fisheries Induced Adaptive Change** [SGFIAC] (Co-Chairs: M. Heino, Norway, U. Dieckmann, Austria, A. Rijnsdorp, The Netherlands) will meet at the ICES Headquarters in Copenhagen, Denmark, 21–25 January 2008 to:

a) assemble and review empirical evidence of fisheries-induced adaptive change and its consequences for conservation of biodiversity and sustainable exploitation of marine species, within an ecosystem context, including previous work by WGAGFM and WGECO;

b) evaluate the impact of existing management measures and tools, such as minimum mesh and landing sizes, precautionary reference points and marine protected areas, effort regulations, on fisheries-induced adaptive change;

c) develop appropriate scientific and methodological tools to monitor and respond appropriately to risk to biodiversity and sustainable exploitation posed by fisheries-induced adaptive change;

d) relate consequences of fisheries-induced adaptive change to current management objectives and evaluate possible more specific objectives for managing fisheries-induced adaptive change.

SGFIAC will report by 1 March 2008 for the attention of RMC, ACFM and ACE.

Terms of reference: supporting information

PRIORITY:	The activities of the Study Group will provide ICES with a basis for advice on whether and how the adaptive effects of fisheries need to be taken into account in future management. Such advice is needed in relation to the Precautionary Approach, the Ecosystem Approach, Biodiversity and Evaluation of Risk and Uncertainty. Consequently, these activities are considered to have a very high priority.
SCIENTIFIC JUSTIFICATION AND RELATION TO ACTION PLAN:	Action Plan No: 2.5 (assess and evaluate the genetic consequences of human-induced selective factors) **Term of Reference a)** Several countries are conducting or have recently completed significant studies in this area and the subject would benefit from a review of progress and an evaluation of the results obtained.

SCIENTIFIC JUSTIFICATION AND RELATION TO ACTION PLAN: CONTINUED	**Term of Reference b)** Managing fisheries-induced adaptive change is implicitly included in management objectives under the precautionary approach as sustainable harvesting must be understood to include evolutionary sustainability. However, explicit attention on fisheries-induced change raises some new issues. For example, the World Summit on Sustainable Development (2002) stipulated that fish stocks shall be maintained or restored to levels that can produce the maximum sustainable yield by 2015, but MSY itself may be eroded because of fisheries-induced adaptive change. It is therefore important to assess the degree to which fisheries-induced adaptive changes are properly accounted for by the existing management objectives, and to what degree specific considerations are warranted. **Term of Reference c) and d)** Frame work is needed to evaluate which stocks are most at risk, what level of monitoring is needed, and how to respond where fisheries-induced adaptive changes are likely to have significant negative impacts. Where management measures to mitigate such changes are required, it is in our best interests that most cost-effective management measures are found. **Term of Reference e)** As this is a relatively new field, methods for observing and monitoring fisheries-induced evolution as well as its consequences and evaluating possible management targets and thresholds are still under development. Timeframe: 2-3 years
RESOURCE REQUIREMENTS:	No financial requirements for ICES. The research programmes which provide the main input to this group are already underway, and resources are already committed (see 'Participants' below). The additional resources required to undertake additional activities in the framework of this group are negligible.
PARTICIPANTS:	Ca. 15–20 participants. Closely related EC-funded projects *Fisheries-induced Adaptive Changes in Exploited Fish Stocks* (2005–2009) and *Fisheries-induced Evolution* (2007–2010) as well as *Marfish* project within EU Network of Excellence *Marine Biodiversity and Ecosystem Functioning* (2005–2009) will secure participation from both fisheries research institutes and universities.
SECRETARIAT FACILITIES:	None.
FINANCIAL:	No financial implications.
LINKAGES TO ADVISORY COMMITTEES:	ACFM, ACE
LINKAGES TO OTHER COMMITTEES OR GROUPS:	For management implications: Resource Management Committee (RMC), Living Resources Committee (LRC), Working Group on Fishery Systems (WGFS), possible follow-up group of Study Group on Management Strategies (SGMAS) For more fundamental aspects: WGAGFM
LINKAGES TO OTHER ORGANIZATIONS:	