Evaluation and management of the Finnish herring fishery

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Academic dissertation in Fisheries Science

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Contents

Summarized publications

This thesis is based on the following articles, which will be referred to in the text by their Roman numerals:

I Stephenson, R., Peltonen, H., Kuikka, S., Pönni, J., Rahikainen, M., Aro, E., and Setälä., J. 2001. Linking biological and industrial aspects of the Finnish commercial herring fishery in the northern Baltic Sea. In: Funk, F., Blackburn, J., Hay, D., Paul, A. J., Stephenson, R., Toresen, R. and Witherell D. (*Eds*.). Herring: Expectations for a new millennium. University of Alaska Sea Grant, AK-SG-01-04, Fairbanks. pp. 741-760.

II Rahikainen, M. and Kuikka, S. 2002. Fleet dynamics of herring trawlers - change in gear size and implications for interpretation of catch per unit effort. Can. J. Fish. Aquat. Sci. 59: 531-541.

III Rahikainen, M., Peltonen, H. and Pönni, J. 2004. Unaccounted mortality in northern Baltic Sea herring fishery – magnitude and effects on estimates of stock dynamics. Fish. Res. 67: 111-127.

IV Rahikainen, M., Kuikka, S. and Parmanne, R. 2003. Modelling the effect of ecosystem change on spawning per recruit of Baltic herring. ICES J. Mar. Sci. 60: 94-109.

V Rahikainen, M. and Stephenson, R. L. 2004. Consequences of growth variation in northern Baltic herring for assessment and management. ICES J. Mar. Sci. 61: 339-351.

Author's contribution in the articles

I The article is a product of team work in which the author contributed some ideas about relevant externalities to herring fishery and carried out some calculations of indicator data.

II The idea of modeling the dynamics of the trawl population was developed jointly. The author acquired the data, was responsible for developing and implementing the methodology, and wrote the article.

III The original idea was developed jointly. The author designed the study and carried out the analysis, and wrote the majority of the article.

IV The author designed and performed the analysis and wrote the article.

V The original idea of the study was the author's. The author analyzed the data and had the lead role in writing the article.

ABSTRACT

Changes in the driving bioeconomic factors are largely unpredictable and uncontrollable by catch-oriented fisheries management in the northern Baltic Sea herring fishery. Changing biological and market conditions and catch quotas have resulted in significant changes in the location, composition and behavior of the herring fisheries. Fisheries assessment and management have failed in maintaining the fishery in the Gulf of Finland. Northern Baltic herring stocks are unique in the magnitude of temporal and spatial variation in growth: weight-at-age of adult herring in some areas has fluctuated by as much as 60% over the past three decades. This has implications for stock assessment and management. The differences suggest a need to consider a smaller spatial structure, at least at the scale of the ICES subdivision. Ecosystem considerations are essential.

Most trawlers have increased the size of trawls being used and changed areas of operation. The increase in the technical efficiency in the fleet has been considerable since the average gear size has virtually tripled in 20 years. This has had a major influence on the assessment output of the Gulf of Bothnia herring stocks where catch per unit effort data are used to calibrate sequential population models. Low survival of herring escaping from trawls causes additional unseen mortality. Herring at the ages of 0 and 1 are discarded underwater in larger numbers than are landed. Unaccounted mortality also involves a marked seasonal pattern. However, the practical effect of underwater discarding is minor on evaluation of stock status, the stock-recruitment function, and reference points.

Assessments for northern Baltic herring stocks have been judged to be unreliable, therefore, biological reference points which are less dependent on those assessments would be useful. There are ways to develop assessment benchmarks for recruitment overfishing that do not require full development of stock and recruitment functions. Spawning per recruit analysis provides a useful framework to define such reference points. However, dramatic changes in growth have an impact on the calculation and the use of these reference points, and erode the applicability of yield projections beyond the short term. In the presence of large growth variation, $F_{0.1}$ was a robust reference point whereas $F_{x\%SPR}$ (e.g. $F_{35\%SPR}$) was less robust. Additionally, the calculation of $F_{x\%SPR}$ is more complicated than so far appreciated, and defining maximum spawning per recruit has a significant influence on the interpretation of this fishing mortality based reference point. Herring in different areas of the northern Baltic Sea probably require different reference points and possibly different management strategies, as a consequence of differences and variability in growth characteristics.

Stock assessment and management would benefit from use of Bayesian statistics and decision analysis as they account explicitly for uncertainty. Socioeconomic viability of the fishery has been inadequately considered so far. Explicit management objectives should be developed in the context of biological, economic, and social constitutions.

1. Introduction

Clupea harengus has perhaps been the subject of more research than any other fish species, partly due to its commercial importance and partly to its complex biology (Blaxter and Holliday 1963). Research on herring has contributed significantly to fisheries science, by the development of population thinking, and to the advancements in fisheries management by promoting an increased role of industry in assessment and management (Stephenson 2001). Clupeoid populations have exhibited a general tendency to collapse under heavy fishing pressure (Murphy 1977, Saville 1980, Hay et al. 2001) often in conjunction with environmental changes (Csirke 1988) creating social, political, and ecological problems and dissipating large amounts of economic rent (Garcia and de Leiva Moreno 2003). Already Gordon's (1954) model explained how economic overfishing would be expected to occur in any unregulated fishery (the bioeconomic equilibrium level of effort will equal exactly twice the optimum level), while biological overfishing would occur whenever price/cost ratios were sufficiently high. This "tragedy of the commons" (Hardin 1968) is difficult to overcome. Indeed, maximum production from marine capture fisheries has been reached, indicated by a slow decline in overall landings since the early 1990s (Watson and Pauly 2001).

Global overfishing of pelagic and demersal fish stocks (Clark 1985, Pimm et al. 2001) has received a significant contribution from the practice of ignoring or underestimating uncertainty in stock assessment and fisheries management (Hilborn and Walters 1992, Walters and Maguire 1996). Stock assessments can be substantially inaccurate. For instance, simulated fishery catch per unit effort (CPUE) data contrasted with simulated survey indices revealed that assessment models may perform pathologically using fishery information as tuning series (National Research Council 1998). Even combining fishery and survey data may cause methods to deviate by 200-300% from true values in the few last estimated years (National Research Council 1998). Obviously, the uncertainty in the stock assessment can be considerable. It has even been argued that no fishery has ever been properly understood or managed (Pitcher et al. 2001).

Modeling the impacts of fishing is constrained by both the inherent complexity of the systems, and our lack of understanding of the interactions (Hildén 1997). Though uncertain and insufficient, models interpreted by scientists represent a key source of information for policy-makers, i.e. fisheries managers, whose decisions should ideally reflect the most up-to-date and accurate state of knowledge. Sustainable management of commercially exploited fish stocks requires an understanding of the resource, i.e. stock growth, recruitment and migration dynamics as well as knowledge of the value-based motivation and capacity of the resource harvesters (Sinclair 1988).

The apparent decline of fisheries, caused by assessment and management failures, has catalyzed more risk averse harvesting policies and management goals (FAO 1995). A prudent management approach seems pivotal, because the possibility of achieving scientific consensus concerning resources and the environment is remote and therefore, initial overexploitation is not detectable until it is severe and often irreversible (Ludwig et al. 1993). Consequently, a concept of precautionary approach (PA) has been launched to safeguard stocks from recruitment overfishing and subsequent collapse (FAO 1995; 1996; 1997). Biological reference points (BRP) are used as signposts in implementing the precautionary approach.

Moving from the global statements above to the theme of this thesis, the Finnish herring fishery, includes analysis of some key problems in evaluation and management of the northern Baltic Sea herring stocks. Past fishery evaluations focusing on traditional biological aspects of stock assessment have had little predictive capability largely due to the impact of changing biological and industrial aspects of the fishery that are currently not incorporated into evaluation and management. Stock assessments have been judged as being highly uncertain and useless for a quantitative statement on the status of the stock (e.g. ACFM 1998), indicated by the fact that assessments for the Bothnian Sea herring stock have not been accepted in the peer review process prior to 2000 (ACFM 2000). Regulation and management are also complicated by the multinational jurisdiction over management units of the Baltic Sea, but even more by major perturbations in the Baltic ecosystem (Sparholt 1994, Flinkman et al. 1998, Hänninen 1999), and by market factors. There is a need for not only improved understanding of the underlying biology, but also a greater understanding and appreciation of the bio-economic context, issues and constraints influencing this fishery.

In article I, the driving bioeconomic factors of Finnish herring fishery in the northern Baltic Sea have been formulated and the magnitude of changes in them has been demonstrated. The article descriptively summarizes and links the key ecological, biological, and industrial aspects of the fishery.

In article II, the change in average trawl size was estimated. It is widely acknowledged that CPUE can be a misleading index of abundance due to increase in catchability over time caused by improvement in fishing technology (Gordoa and Hightower 1991, Pascoe and Robinson 1996, Marchal et al. 2001). Based on information concerning the size of herring trawls manufactured in Finland since 1980, an increase in fishing power of the fleet was postulated. While we were lacking direct information about the size of trawls aboard, we applied a model to estimate the changes over time. In the analysis an analogy between fish and trawls was created by adopting the concepts and algorithms from fish stock assessment into assessment of “the trawl population”, where both the total number of trawls and the size of individual trawls were being analyzed.

In article III, the magnitude of fishing induced mortality, i.e. selection by gear and subsequent escapee mortality, in the Bothnian Sea herring fishery was analyzed. It is previously known that unlanded juveniles make a large fraction of catches in the herring fishery (Suuronen et al. 1991), and that their survival is low (Suuronen et al. 1996a; 1996b), causing additional unseen mortality and flawed catch estimates. Because correct catch data are necessary for age-structured assessment models, the magnitude of this underwater discarding is relevant as well its impact on estimates of stock abundance, recruitment, and fishing mortality.

In article IV, the main objective was to explore the benefits of incorporating causal biological assumptions into an analysis of a precautionary reference point. Specifically, we hypothesized that knowledge of correlation among input variables of spawning per recruit analysis would reduce uncertainty of $F_{30\%SPR}$. Biological reference points, based on stock-recruitment data, have gained importance under a precautionary approach (Caddy and Mahon 1995). An alternative method for establishing thresholds for recruitment overfishing is spawning per recruit analysis (Mace and Sissenwine 1993). Within this context, understanding the effects of highly variable natural mortality and growth rate on the fishing mortality reference point is important.

In article V, changes in weight- and length-at-age of herring in the northern Baltic Sea (ICES subdivisions 29, 30, and 32) over the period 1974–1997 were described along with the differences in these life history parameters among areas. The relevance of growth variation in the perception of stock structure, stock assessment indices, and the choice of appropriate biological reference points was highlighted, and the implications for management of Baltic herring considered. The analyses were intended primarily to illustrate the potential impacts of growth variability on biological reference points, and to encourage improved assessment and management of northern Baltic herring.

2. The realm of the Finnish herring fishery

2.1 Fishery and the fleet

Baltic herring stocks provide a vital resource to Finnish harvest fisheries as they supply the most valuable fishery in terms of size and value of landings in the northern Baltic Sea. Approximately 75 000-90 000 metric tonnes of herring have been landed annually in recent years (Finnish Game and Fisheries Research Institute 2004) and in 2000 herring made up 73 % by weight and 45 % by value of marine commercial fishery in Finland (Finnish Game and Fisheries Research Institute 2001). This represents by far the largest landings of a single species in Finland, and makes up over 50% of the total marine and freshwater landings. Recent landed value in the herring fishery has been in the order of 10 million € (http://www.rktl.fi/english/statistics/fishing/commercial_marine_ fishery/). The net profit of the Finnish fishery has been close to zero implying bioeconomic overcapacity of the fleet (Anon. 2002). See Clark (1985) and Hannesson (1993) for fisheries bioeconomics.

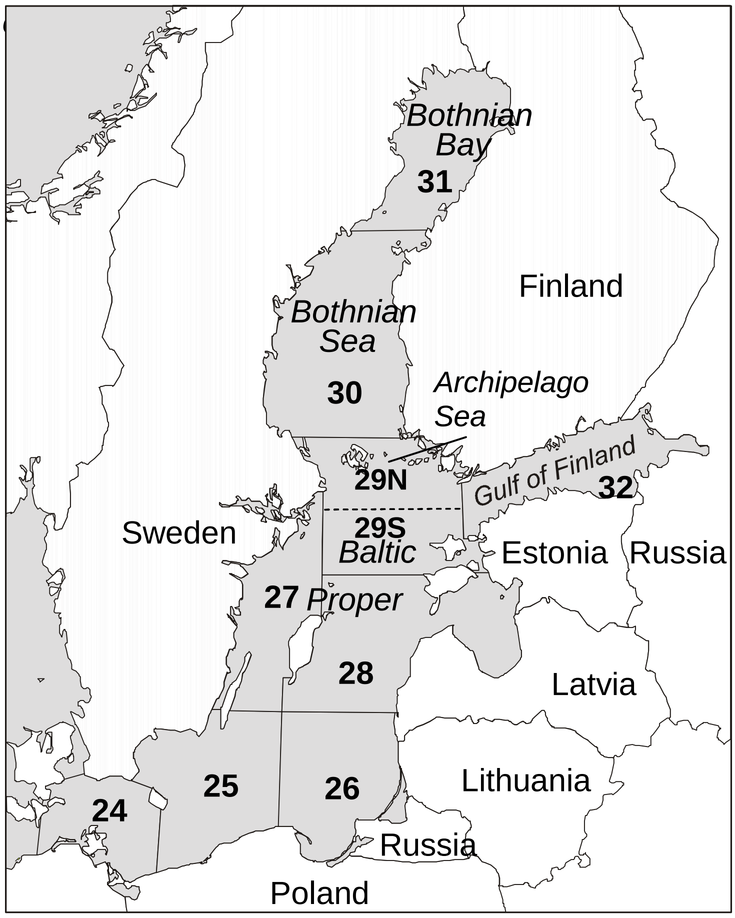

Figure 1. ICES (International Council for the Exploration of the Sea) subdivisions in the Baltic Sea. See the text for the description of assessment areas. The ”Central Basin” management unit contained subdivisions 22-29S and 32 (excluding Gulf of Riga) until 2004. Management unit 3 (MU3) contained subdivisions 29N, 30, and 31 until 2004, and since 2005 contained only the two last ones.

Almost all of the Finnish commercial herring fishery takes place in the northern Baltic Sea (subdivisions (SD’s) 29, 30, 31, 32) (Fig. 1), but is currently concentrated in the southern part of the Gulf of Bothnia, (subdivision 30) and the Archipelago Sea (subdivision 29N) (I). There have been substantial changes in the relative contributions of various areas along the coast.

Landings from the Bothnian Sea have increased over most of the 20 year period but have leveled out since 2000 (Fig. 2). There has been substantial reduction in landings from subdivisions 29 and 32 particularly in the early 1990's. The herring fishery in the Gulf of Finland has collapsed recently so that the landings in the two last years have been about a quarter of the average landings during the 5 previous years (Fig. 2).

An increasing share of landings has been taken by large trawlers while landings by the trapnet fishery have declined without recovery, as yet (I). Vessels that catch large herring for filleting and other human consumption markets deploy considerably larger codend mesh sizes (36 mm) than the minimum (16 mm) defined in the fishery rules, thus avoiding laborious size-sorting onboard (Suuronen et al. 1991).

In the late 1990s about 150 trawlers landed herring. The mean age of the vessels was 28 years. The total crew of these vessels was about 360 producing 120 man-years. Fishing effort, defined as fishing days during a year, varied between 4 and more than 300 among vessels. Fishing effort was positively correlated with vessel size (Virtanen et al. 1999) and also with trawl size (II). Fishing power has increased in concordance with average trawl size (II).

Landings varied strongly among vessels. The most active 20 vessels landed more than 50% of the total catch while 50 least active vessels landed less than 5% of the total catch. Moreover, in the vessel registry there are over 100 trawlers which did not land at all indicating large overcapacity within this fishing segment (Virtanen et al. 1999).

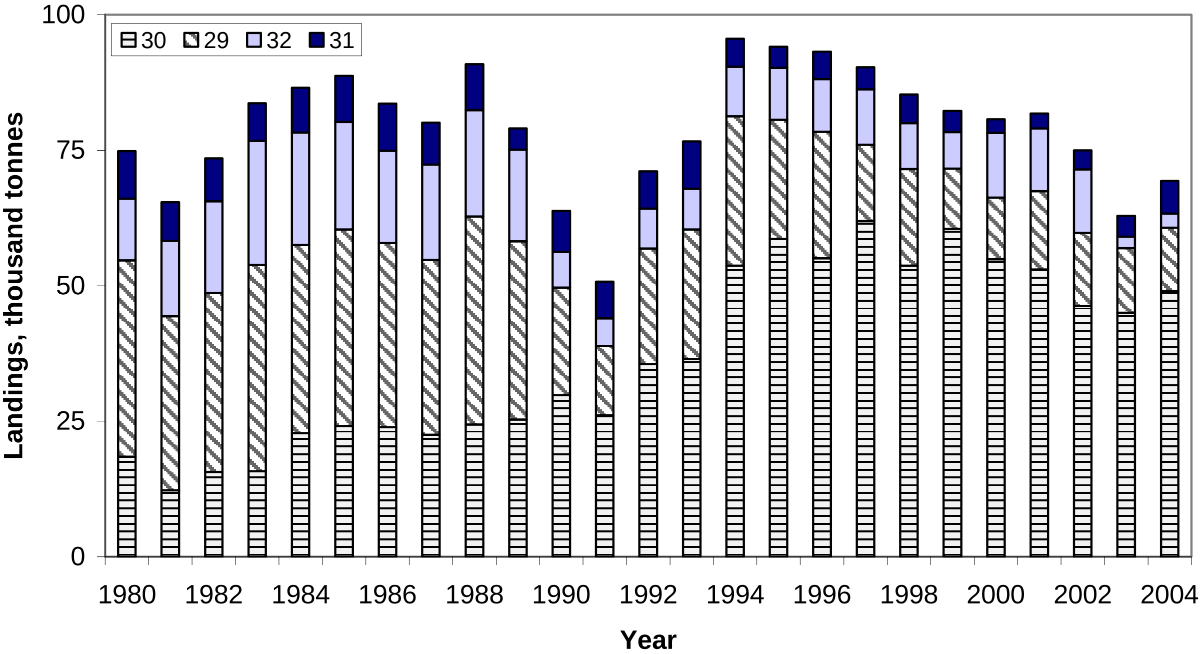

Figure 2. Landings by the Finnish fleet in ICES subdivisions 29-32 in 1980-2004 (2004 is preliminary). Note the sequence of the subdivisions.

The Finnish herring fleet is therefore heterogeneous and thus management decisions impact distinct fisher groups to different extent. The dismantling of subsidies was predicted to seriously affect small enterprises and lower the living standards of individual workers in the herring business (Hildén and Mickwitz 1991), but these impacts have not been monitored since the removal of the system in 1995.

2.2 Current assessment scheme in the Baltic Sea herring fishery

Baltic herring assessments are conducted annually within the ICES Baltic Fisheries Assessment Working Group. Currently, the herring in the Central Baltic is assessed as two units, 1) herring in ICES subdivisions 25-29 and 32, excluding Gulf of Riga herring, and 2) Gulf of Riga herring. In the Gulf of Bothnia the herring is assessed as two stocks, 3) Bothnian Sea (subdivision 30), and 4) Bothnian Bay (subdivision 31) (Fig. 1, ICES 2004). The pooling of herring stocks in the Baltic proper (subdivisions 25-28) and in the Archipelago Sea and the Gulf of Finland (subdivisions 29 and 32) as one assessment unit is a compromise between assessment of biologically relevant unit stocks and practical management purposes. As a result, the assessment is uncertain in part due to the complexity of the stock structure in the area (ICES 1999).

The assessments are peer reviewed by the ICES Advisory Committee on Fisheries Management (ACFM). Biological advice is provided annually to the International Baltic Sea Fishery Commission (IBSFC) by the ACFM. The ACFM regularly rejected assessment for subdivisions 30 and 31 due to high uncertainty in the estimates during 1980s and 1990s (e.g. ACFM 1984, 1998). Separate trial assessments of the Gulf of Finland and Archipelago Sea units in 1998 together with the Bothnian Sea assessment (ICES 1998) indicated, however, that these units which are of particular relevance to the Finnish fishery are of different size (in area and in resource) and that the abundance of herring has fluctuated differently in the three areas over the past two decades.

Assessment strategies are different for the Central Basin stocks and the Gulf of Bothnia herring stocks with respect to evaluation of natural mortality rate and maturation schedule, and calibration of sequential population analysis (SPA) (Table 1.)

Table 1. Key differences in estimation approach for the Baltic Sea herring assessment units.

Assessment unit	Central Basin (subdivisions 25-29 and 32)	Gulf of Bothnia (subdivisions 30 and 31)
Natural mortality rate	Variable by year and age (from multispecies virtual population analysis (MSVPA))	Constant over year and age (0.2 except 0.15 in the assessment conducted in 1999)
Maturation schedule	Constant over years	Observed maturity ogives (variable by year and age)
Calibration data	Acoustic surveys	Commercial CPUE (trawl and trap net fleets)

Validity of CPUE information is of special concern in the assessment of the Gulf of Bothnia herring stocks because commercial CPUE data have been applied as an index of stock abundance to tune SPA (e.g., ICES 2000). CPUE data from commercial fisheries, if not properly standardized, do not usually provide the most appropriate index of abundance (National Research Council 1998) and violation of the assumption of constant catchability due to increased fishing power with time is a general concern (Marchal et al. 2001). Technical advancement is obvious in any commercial fishery characterized by increasing vessel size, engine power, and gear size (II). Even more generally, improved efficiency is a global feature in industrial production and the fishing industry is certainly not an exception.

2.3 Current management scheme

Since 1974, an international convention of the IBSFC in Warsaw has provided a forum for national managers to establish catch limits for all Baltic Sea major fisheries. In IBSFC contracting parties "co-operate … to preserving and increasing the living resources of the Baltic Sea … and obtaining the optimum yield." Contracting parties (Finland as a member of EU delegation) consider the biological advice by ACFM to deal with this target. The target of management advice by ACFM implies matching fishing activities with natural fluctuations so as to avoid unsustainable harvests and stock collapses but the concept of optimum yield remains undefined and unoperationalized. Management strategy has been based on catch limits, i.e. total allowable catch (TAC). IBSFC recommends each year TACs for the following year for the main four commercially exploited species: cod, salmon, herring and sprat. These TACs take into account the biological status of the stocks as described by the ACFM and the economic needs of the fishing industry in the coastal states of the Baltic Sea. TACs were introduced first in 1977 for cod, sprat and herring, and then in 1988 for salmon. The actual control measures to limit landings within the agreed catch quotas are decided and implemented by national governments, in Finland by the Ministry of Agriculture and Forestry.

Management units for herring fishery have been revised from time to time. Generally, herring has been managed by two TACs, the "Central Basin quota" (ICES subdivisions 22-29S and 32) and the Management Unit III quota" (ICES subdivisions 29N, 30, and 31, i.e. MU3) (Fig. 1). From 2005 onwards subdivision 29N is reassigned in the "Central Basin" management unit. After this change the fishery in subdivision 29N will be managed within the same geographical boundaries as it has been assessed.

To accommodate sharing arrangements in these multinational fisheries, herring quotas have in many cases been set well above the scientific advice from ACFM, and have been so high that they have not restricted the fishery until recently (Fig. 3). The lurch of TAC of the Central Basin herring stock (Fig. 3a) in 1993 was catalyzed by a stock estimate which was very high compared to the previous year (ACFM 1992). Later, that estimate appeared to be an artifact (Fig. 5). Regarding MU3 herring (Fig. 3b), the TAC jump in 1995 was induced by the conclusion by ACFM (1994) which considered that a 40% increase in fishing mortality would be within safe biological limits. Quotas of both management units have decreased considerably only few years after the peak levels.

Aside from the national quotas, there have been few management measures in Finnish herring fishery. The first ones were implemented in 1980's when trawling was restricted in the archipelago in the Gulf of Finland to conserve age 1 and 2 herring from excessive harvesting (Ministry of Agriculture and Forestry 1986; 1987). In the beginning of 1990s, mesh size regulations were planned to allow only the use of the 36 mm codend. The objective was the cessation of fishing for animal fodder while ensuring supply for human consumption. Plans concerning mesh size regulations were rejected as it was shown that increased codend mesh size would reduce the value of catch per recruit due to low survival of the escapees (Kuikka et al. 1996).

Weekly trawling restrictions combined with cessation of fishing operations during summer have been implemented in Finland since 2001 (Ministry of Agriculture and Forestry 2001; 2002; 2003; 2004) to avoid exceeding the quota before end of the management season. In addition, mesh size regulations came along in 2003 and 2004 (Ministry of Agriculture and Forestry 2003; 2004) in a form of more strict temporal restrictions concerning trawling for animal fodder markets. Trawling is categorized as fodder fishery when stretched mesh size is less than 32 mm.

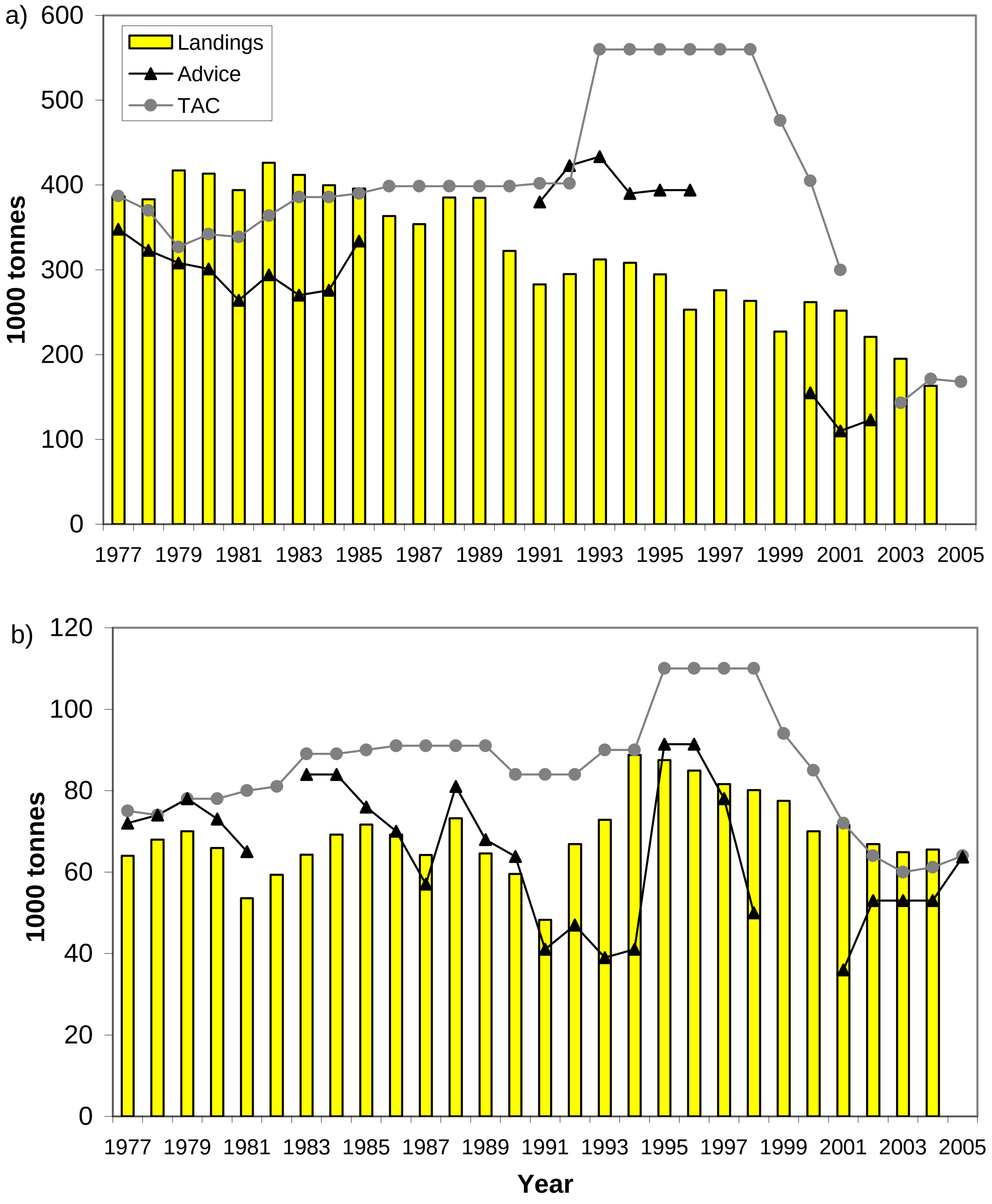

Figure 3. Total allowable quotas (TAC), predicted catch corresponding to advice, and realized landings in the a) Central Basin (subdivisions 22-29S and 32) and b) in MU3 (subdivisions 29N, 30 and 31) in 1977-2005. Predicted catch corresponding advice includes only subdivisions 30 and 31 after 1990 and subdivision 30 only during 1997-2002.

2.4 Biological framework for fisheries management advice

Foundation of precautionary approach

The concept of sustainable development has influenced fisheries management for more than a decade. The goal of sustainable development has been defined on a general level as ensuring continued satisfaction of human needs for present and future generations (UN Conference on Environment and Development, Rio de Janeiro 1992). The Code of Conduct for Responsible Fisheries (FAO 1995) establishes principles and provides guidance for implementation of the Rio Declaration in the fisheries sector in the form of 'precautionary approach' (PA) which was introduced into the scientific advice some years ago (Garcia and de Leiva Moreno 2003).

The probability of an undesirable event is a common interpretation of risk. The precautionary approach links risk assessment and risk management to the quality of knowledge and quality of available management measures (FAO 1995). Thus, the key feature of precautionary approach is to adopt more conservative management actions with increasing uncertainty about fish stock status. Precautionary approach also involves reversing the burden of proof built into scientific analysis and fisheries management (Charles 2001a): instead of requiring that scientists to 'prove' that harvesting levels are harmful, the FAO (1995) has noted that "human actions are assumed to be harmful unless proven otherwise". The PA should consequently create an economic incentive for investment in improved data gathering and assessment procedures to reduce uncertainty, because application of risk-adjusted biological reference points would immediately lead to reduced total allowable catch.

Principles of PA also include clear definition of responsibility, actions based on sound scientific advice, and broad involvement of stakeholders. Moreover, the need to identify significant sources of biological waste associated with commercial capture technologies became increasingly important in conjunction with precautionary fishery management strategies (Chopin et al. 1997, III). Hilborn et al. (2001) criticize scientists and managers for putting much too much emphasis on developing biological aspects of precautionary approach whilst its application to the protection of fishing communities lags considerably. Further, they argue that implementing policies that reduce the risk to the communities exploiting fish stocks would be consistent with the early description of the precautionary approach provided by FAO (1996), i.e. to meet the objective of the intergenerational equity. Certainly, resilient social choices must be tracked down (Ricci et al. 2003) in concert with considerations related to biological resiliency – without ignoring the fact that commercial fishery is business where welfare will not be distributed equably.

Precautionary approach has imperative status in the Common Fisheries Policy in the European Union (Council Regulation 2002). Precautionary approach, thereby, provides a legislative and political framework to be adopted to promote a sustainable fishery. Environmental, economic and social aspects should be taken into account in a "balanced manner" in the fisheries policy (Council Regulation 2002).

At the international level the conservation objectives have been broadened to include ecosystem features in addition to protection of the target species (Oceans Act of Canada 1996, Environment Australia 1998a, 1998b). Also the Common Fisheries Policy (Commission of the European Communities 2001) and the United Nations Fish Stocks Agreement adopted in 1995 are explicit about protecting the marine environment in general. According to the agreement, the impacts of fishing must be assessed on target species, species that are part of the same ecosystem, and species that are associated with or dependent upon target species. Murawski (2000) suggests that even social and economic benefits should be considered to define overfishing from an ecosystem perspective.

Biological reference points

Biological reference points (BRP) are a key concept in implementing a precautionary approach (ICES 2001a). The fundamental management target is to avoid recruitment overfishing and reference points are applied as long term objectives for maintaining renewable resources. They are increasingly used for fisheries management, forming a link between management objectives and the characteristics of the fishery (Caddy and Mahon 1995).

Management has been based on a variety of biological reference points. They are usually expressed as fishing mortality rates (e.g. F_{med}, $F_{x\%SPR}$, $F_{0.1}$, F_{msy}) or as critical levels of spawning or recruited biomass (e.g. B_{loss}, B_{mbal}, $B_{20\%\ b\text{-}virg}$) (Maguire and Mace 1993). The rules to calculate biological reference points are usually based on the perception of risk of stock collapse or of "safe" harvest level. For instance, Francis (1993) has proposed the definition that a level of harvesting should be considered safe if it maintains a spawning stock biomass above 20% of its mean virgin level at least 90% of the time. Often a reference point is a threshold that delineates the boundary between acceptable and unacceptable states of the performance indicator. As a convention, a stock status can be labeled "good" when both indicators of spawning biomass and fishing mortality are better than the precautionary limits, "bad" when both indicators are worse than precautionary limits, and in the buffer area when only one of the indicators is adequate (Garcia and de Leiva Morano 2003).

The objectives are made operational through strategies. Strategies are typically designed to limit the impact of a human activity on the target resource in particular and on the ecosystem in general. Reference points thus make the objective of not causing "unacceptable" outcomes operational (Gavaris et al. 2005) and BRPs are applied as thresholds with specified consequences of exceeding them. The status of a fish stock is often determined by comparing an indicator reference point estimated from stock assessment (usually current stock biomass and current fishing mortality rate) with a management reference point (F_{pa} and B_{pa}) (Caddy and Mahon 1995). In the Baltic Sea herring fishery, the current reference points (fishing mortality rate and spawning stock biomass) are put into operation by defining TAC which reduces F below F_{pa} and ensures that the spawning stock biomass (SSB) increases toward B_{pa} (ACFM 1998c). This is attractive to common sense but Walters (2001) has pointed out that the precautionary approach may give a false impression of safe harvest policy. PA can in fact be utterly destructive if it is based on assumptions and analyses that are not even in the right general ball park in the first place.

The precautionary levels of mortality and spawning biomass (F_{pa} and B_{pa}) are usually developed from the estimated minimum safe levels of these indicators (F_{lim} and B_{lim}). Much effort has been devoted to defining overfishing thresholds (F_{lim}, B_{lim}). Noteworthy, they should not be used as targets because they do not optimize the fishery, nor leave any buffer to accommodate occasional overestimates of stock biomass or negative environmental factors.

Many of the BRPs essentially rely on a reliable stock-recruitment function. For various fish stocks, including Baltic herring (ICES 1999), derived stock-recruitment scatterplots are uninformative (noisy). In such cases, alternative criteria or information sources must be considered to determine threshold of sustainable harvesting. Spawning per recruit (SPR) analysis has received some attention in establishing thresholds for recruitment overfishing (Sissenwine and Shepherd 1987, Mace and Sissenwine 1993, Goodyear 1993, Myers et al. 1994, Caddy and Mahon 1995, Cook 1998). In this analysis, growth, maturity and natural mortality are the input variables in conjunction with stock-recruitment data (Fig. 4). Stock-recruitment function needs not to be "known" because by meta-analyses it has been explored how taxonomic affiliation affects the resilience of a stock so that life history parameters can be used to select preliminary %SPR estimates (Mace and Sissenwine 1993, Myers et al. 1995).

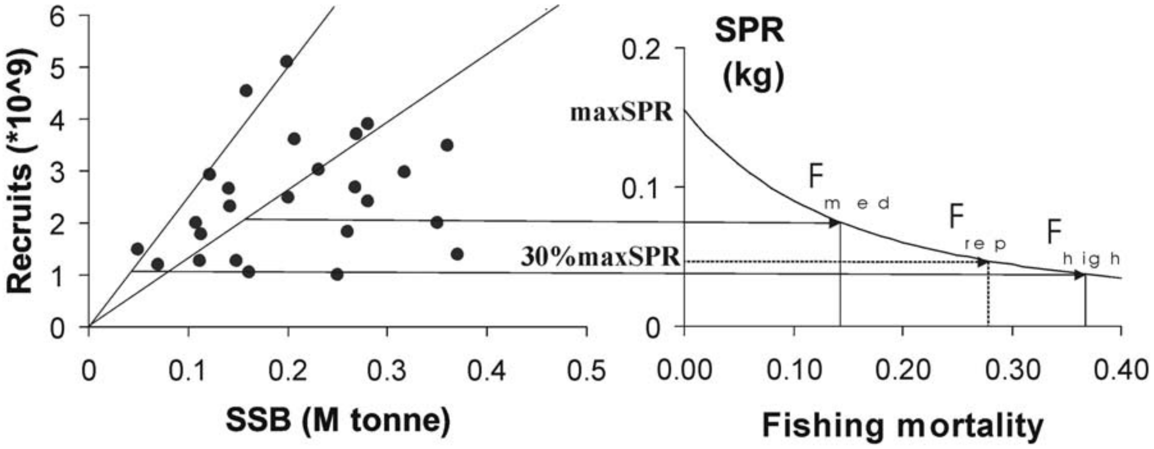

Figure 4. Linkage between stock-recruitment data and spawning per recruit analysis. SPR corresponds to the inverse of the slope of a replacement line (in the left hand panel).

The important advantage in applying %SPR reference point is that it is linked to the ecosystem state and to productivity of the population and, therefore, to resilience of a fish stock. Change in externalities will thus be reflected by %SPR approach. This link is lacking from the majority of the reference points (e.g. F_{loss}) but the need for ecosystem considerations is obvious for Baltic herring stock which has experienced large fluctuations in growth and natural mortality rate. Consequently, spawning per recruit analysis gives a framework for generating biologically valid reference points under uncertain spawning stock-recruitment function and changing life history parameters.

Cautious use of reference points has been called for in the Baltic Sea because for herring they depend on species interactions (ACFM 1998). Reference points differ in single and multispecies models and reference limits for forage fish cannot be defined without considering changes in the biomass of their predators. When predation increases, the prey stock can sustain less fishing mortality before dropping below B_{lim} (Gislason 1999). However, this is not necessarily the case, since increased natural mortality may be compensated for by increased growth rate (IV).

Since 1998, ICES has used reference points linked to spawning stock biomass (SSB) and fishing mortality rate (F) to provide biological advice for Baltic Sea herring that is considered to be consistent with a precautionary approach (ICES 1998; 1999; 2000; 2001). BRPs, by definition, are ecological conservation objectives which do not consider socioeconomic needs of a fishery. Implicit precautionary catch quotas were recommended already in the 1970s for the Baltic Sea herring stocks (ICES 1976).

Biological reference points have been proposed for F, but have not been defined for SSB regarding the Central Basin assessment unit. Both SSB and F reference points have been defined for the Bothnian Sea (subdivision 30) unit. The technical basis for fishing mortality reference points is the same in both assessment units. A limit reference point (F_{lim}) has been defined as the value of F associated with spawning per recruit at the lowest observed spawning stock biomass (F_{loss}). A more conservative functional reference point (F_{pa}) has been developed from F_{med}, using stock-recruitment observations and spawning per recruit analysis (ICES 2001). Biological and economic objectives have not received as much attention and explicit management targets for the fishery are lacking.

2.5 Herring in the Baltic Sea ecosystem

Northern boreal shelf ecosystems are characterized by relatively few dominant species with strong interactions (Livingston and Tjelmeland 2000). This description is also valid for the Baltic Sea where cod is the dominant piscivore and herring and sprat are the major pelagic fish species (Sparholt 1994). Hydrographically the semi-enclosed Baltic Sea is a unique brackish water ecosystem. Annual variations in the intrusions of saline water from the North Sea have caused periods of relatively higher and lower salinity (Alenius and Haapala 1992). There was some decline in salinity during 1960s but in the 1970s another increase occurred particularly in the Gulf of Bothnia (Samuelsson 1996). In the1980s and 1990s salinity has decreased almost continuously and reached low levels compared to the earlier decades of the 20th century (Matthäus and Franck 1992, Matthäus and Lass 1996, HELCOM 1996, Alenius and Haapala 1992, Samuelsson 1996, Vuorinen et al. 1998, Hänninen et al. 2000). Persistent low inflow of saline water in recent years has led to an increase in stagnation and a depletion of oxygen resources in the lower layer of the Baltic Main Basin, with a major impact on the Baltic food web. Climate variability has been suggested to be a driver of ecosystem change in the Baltic Sea (Hänninen 1999) but Caddy (2000) has concluded that eutrophication is the major cause of ecosystem change in semi-enclosed seas.

Diverse marine ecosystems function in different ways depending on a wide range of types of energy flow. Consequently, no general theory of the functioning of marine ecosystems is available (Cury et al. 2003). This lack of explanatory power within marine ecology imposes severe limits to our ability to explain and predict the impacts of fishing on the functioning of ecosystem. It follows that fisheries management is and will be fraught with uncertainty (Sinclair et al. 2002).

Northern Baltic herring have exhibited striking changes in growth over the past few decades (Parmanne 1992, Raid and Lankov 1995, Parmanne et al. 1997, Rönkkönen et al. 2004) when weight-at-age of adults have decreased by 30–50% from the highest values in the early 1980s (Anon. 1994, Parmanne et al. 1994, Cardinale and Arrhenius 2000). It is reasonable to hypothesize that ecosystem variability influences herring growth via both ‘bottom up’ and ‘top down’ mechanisms. The hypotheses have been linked to 1) the hydrographical changes (Anon. 1994, Flinkman et al. 1998, Vuorinen et al. 1998, Hänninen 1999, Hänninen et al. 2000, Rönkkönen et al. 2004), 2) density dependent growth (Horbowy 1997, Flinkman et al. 1998, Cardinale and Arrhenius 2000), and 3) cod predation (Sparholt and Jensen 1992, Beyer and Lassen 1994, Rudstam et al. 1994). It seems logical to assume that ecosystem dynamics have influenced herring stock and fishery: sustainability is a property of ecosystem, not only a feature of the fish stock itself (Richardson 2000, Pitcher and Pauly 2001).

The hydrographical changes hypothesis links the observed variations in herring growth to water temperature, salinity, and zooplankton community changes. Reduced salinity in recent years is suggested to have caused a reduction in large neritic copepods, the preferred food of herring (Flinkman et al. 1998, Vuorinen et al. 1998, Rönkkönen et al. 2004). These processes are affected by a single environmental factor, the Baltic salinity level, which is linked to Baltic inflow and precipitation, and ultimately to changes in the north Atlantic oscillation (Hänninen 1999, Hänninen et al. 2000).

The density dependent growth hypothesis states that an increase in the clupeid biomass reduces availability of prey per capita reducing herring growth rate (Horbowy 1997, Flinkman et al. 1998, Cardinale and Arrhenius 2000). The cod predation hypothesis suggests that variation in size-selective mortality by cod has changed size-at-age of herring (Sparholt and Jensen 1992, Beyer and Lassen 1994). Thus multispecies interactions may have a strong influence on dynamics of the herring stock in the Baltic, depending on abundance of cod as the main predator in the ecosystem (Rudstam et al. 1994, ICES 1997, ACFM 1999) and sprat as food competitor (Arrhenius 1995). None of the hypotheses are mutually exclusive. Instead, they are strongly interlinked providing cumulative evidence of the influence of large scale ecosystem variability on herring dynamics.

Utilizing increasing biological knowledge would be highly useful in stock assessments (Ulltang 1996) and in management (Stephenson and Lane 1995). For long-term stock simulations that aim to study the effects of different exploitation strategies, assumptions on possible causes of change in maturation schedule, and links between maturity, growth, and mortality are critical (Ulltang 1996). Too often, stock assessment and prediction use empirically observed parameters and the variation within, but neglects to utilize (at least in a systematic way) biological knowledge i.e. information about ecosystem status, species interactions, and pivotal causal relationships.

In addition to dramatic temporal changes, growth rates also differ among areas. The decrease in weight-at-age apparent in some parts of the Baltic Sea (ICES subdivisions 32 and 29) are less prominent in the Bothnian Sea (ICES subdivision 30) and Bothnian Bay (ICES subdivision 31) (V). This phenomenon has been related by some to asynchronous changes in hydrography in those areas compared with the rest of the Baltic (Melvasalo 1980). Whatever the exact mechanism, these large growth differences and changes within and between areas, have had a major impact on the fishery (I) and pose substantial problems for assessment and management (V). The observed contrasts in growth rate are however beneficial to learning about causalities.

2.6 Herring stock structure

Either herring stock structure is complex in the Baltic Sea or there is a single stock facing persistent isolation among groups (V). This is manifested in different growth rates, differing responses to exploitation, and other biological characteristics around the Baltic (ICES 2001b, V), in uncertainty about herring migrations (Aro 1989) and in uncertainty in stock assessment (ICES 1999). Existence of stock components and migrations leading to mixing of components complicates sampling for age distribution and allocation of landings, and subsequently to elevated uncertainty in assessment and management (V). There is no consensus about Baltic herring stock structure: early stock studies which focused on morphological characters, concluded either an existence of different populations (Rauck 1965, Ojaveer 1980; 1988) or lack of them (Parmanne 1990). Molecular genetic studies demonstrated an apparent absence of genetic divergence within the Baltic Sea (Ryman et. al 1984, Rajasilta et al. 2000). Moreover, there is no association between the variation of morphological and genetic characters (Ryman et al. 1984). According to Waldman (1999) the literature is rampant with studies in which stock structure is found with one approach but not with others, or where approaches are conflicted in their elaboration of stock structure. The lack of agreement among approaches using morphological attributes may be due to their reliance on phenotypic features (Waldman et al. 1997), all of which are to some degree plastic and environmentally induced (Waldman 1999). Genetic markers are not without limitations either: mitochondrial DNA studies are often based on a small number of genes and always on just one independently segregating locus, potentially leading to erroneous inference at the population level of resolution (Pamilo and Nei 1988). In addition, gene flow among marine fish populations is thought to be high and effective population sizes are assumed to be large, resulting in limited genetic drift and thereby low levels of genetic differentiation among spatially separated populations (Ward et al. 1994). Therefore, a weak but biologically meaningful genetic signal may easily be masked by noise due to inadequate sampling from marine populations (Jørgensen et al. 2005).

Failure to match the biological and management scales could lead to failures of assessment, or management, or both. This mismatch has plagued fisheries science and management and may have led to changes in stock structure of herring, with unknown ecological significance (Stephenson 2002). The loss of spawning components from north-west Atlantic herring and cod demonstrate unplanned, negative consequences of an aggregated management scale (Smedbol and Stephenson 2001).

2.7 The assessment problem

In an ideal world, accurate and precise estimates of the abundance of fish stocks and their dynamics would be available to set sustainable harvest levels to accommodate commercial demand. In reality, fishery management is based on imperfect estimation of the number, biomass, productivity and incomplete knowledge of population dynamics (National Research Council 1998, Hildén 1997). Accuracy (validity) of assessment outputs is unknown in reality though most existing assessment software provides some estimate of precision (repeatability) of the parameter estimates. Estimates of precision are based on the assumption that the structure of the assessment method is correct. Therefore, unless the model structure is flexible enough to allow for major sources of uncertainty about the processes and data to be incorporated, the true uncertainty in assessment tends to be underestimated (Gavaris et al. 2000, Patterson et al. 2000).

Some of the basic underlying assumptions in current fish stock assessment methodology have proven to be wrong virtually whenever it has been possible to test them (Hilborn and Walters 1992). Key assumptions include known natural mortality rate and known total catch, constant catchability, and proportionality between tuning index (e.g. commercial catch rate) and fish stock abundance. Those assumptions are often ignored in routine stock assessment procedures applied for pelagic fish stocks.

Retrospective catch-at-age analysis is a method to examine the consistency of stock estimates as new data or tuning method is applied. In a traditional retrospective analysis, successive assessments use data for different periods, all starting at same time with one year of data added to each assessment (National Research Council 1998). Model misspecification leads to pathological behavior of the estimates, which is evidenced by serious retrospective patterns but missed by standard estimates of variance derived using the same misspecified model (Parma 1993). Early recognition of stock trend is necessary for management to react in a timely fashion, and retrospective analysis is useful to determine how long it would take for assessments to recognize underlying stock trends. A strong retrospective pattern indicates marked changes in estimated quantities (biomass, fishing mortality, recruitment) in successive assessments. Consequently, high uncertainty will be involved with the short term forecasts.

Historical performance of Baltic herring assessment

Variability in spawning stock estimates for the Central Basin and the Bothnian Sea assessment units characterize the uncertainty faced by stakeholders (Fig. 5). The assessment carried out by the ICES working group during successive years show considerable changes in conception about stock abundance as well in fishing mortality rate and recruitment.

The actual historical results provide a worrisome indicator of performance of assessments and help to evaluate the effects of revisions of methodology, catch data and tuning series, and assumptions about natural mortality rate. Also, potential problems in the applied approach can possibly be tracked. The sharply increasing biomass estimate in the early 1990s (Fig. 5a) was generated by a combination of a high acoustic abundance estimate in 1991 and of the revised natural mortality rate estimates from the multispecies virtual population analysis (ICES 1992). The primary cause of the pathological outlier in the assessment of subdivision 30 herring stock remains unresolved. As the assessment working group has phrased (ICES 1998), the XSA model is very unstable and sensitive to rather small changes in tuning options and the obvious mismatch between catch-at-age matrix and the tuning fleet information may be the main reason for the conflicting results.

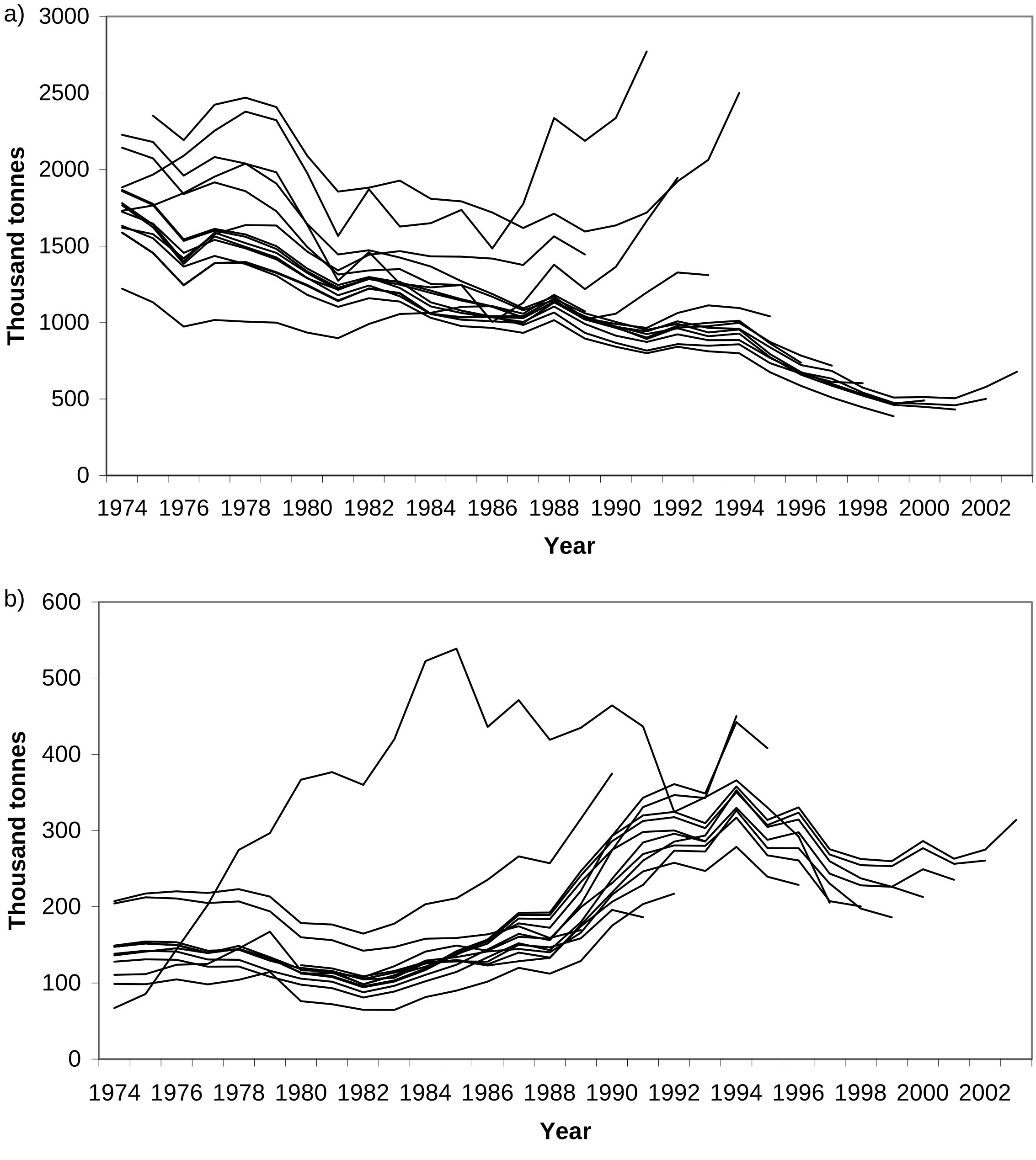

Figure 5. Herring spawning stock size in a) subdivisions 25-29, 32 (including Gulf of Riga) and b) subdivision 30 as estimated by ICES working group sessions in 1990-2004 (ICES 1990 - ICES 2004).

The historical estimates of SSB are relevant as they are used in estimating stock-recruitment function and B_{pa}. The most recent estimates are needed to correctly evaluate the state of the stock and fishery in relation to biological reference points. The basic fisheries problem is that expected management performance degrades sharply as the average error in stock size estimate increases (Walters and Parma 1996).

The Bothnian Sea is the main operating area of the Finnish herring fleet. The assumptions involved with this assessment are used as an example to describe potential errors and their consequences. Assessments have a trajectory of uncertain estimates of northern Baltic Sea herring (Fig. 5). In 1999 ACFM (1999) concluded that the state of the subdivision 30 herring stock is very difficult to judge because of low precision of the assessment. However, ACFM expected that an ongoing study focusing on improvement of tuning data (II) to improve the quality of the assessment. In the next year ACFM (2000) acknowledged that improvements both in sampling and tuning have raised the quality of the assessment significantly in recent years and there is more confidence on the results. However, some relevant uncertainties are still excluded from the assessment and from the biological advice for policy-makers.

Assumptions about the data for the Bothnian Sea herring

Non-biased catch-at-age data are a necessary condition for methods applied for evaluation of Baltic herring stocks because use of age-structured assessment models is a process where catch data are non-linearly transformed to stock estimates. In practice, correct catch data are rare due to imperfect knowledge of fisheries, sampling uncertainty, and unaccounted mortality (Table 2).

Baltic herring stocks are assessed by VPA which is tuned in Extended Survivors Analysis (XSA) (Shepherd 1999). XSA algorithms used within the tuning procedures exploit the relationship between abundance index (CPUE or acoustic estimate) and population abundance estimated by VPA, allowing the use of a reasonably complicated model for the relationship between abundance index and year class strength at the youngest ages (Darby and Flatman 1994). Difficulties with CPUE data in stock assessment could be solved in principle by investing more in fishery independent surveys but they are both extremely costly (Walters 2001) and have important limitations.

Catches-at-age for XSA are compiled by incorporating total landings with catch samples. Correct input data requires correct information about total catch and its age-structure. Catch data are flawed if they do not correspond to the true removals by the fishery from the stock. This may happen due to (intentional or unintentional) misreported landings, unreported discards, or because escaping fish do not recover and survive. Underwater discarding (III) has not received as much attention as discarding from the deck. Discarding of unmarketable, undersized or damaged fish is common practice in most fisheries worldwide (Alverson et al. 1994). Discarding is forbidden in the Baltic Sea fishery, but takes place in practice. ICES (2004) regards the discard rate as negligible but interview data from herring trawler skippers suggest that discarding can be a significant source of error (Rahikainen, unpublished data) though the magnitude of discarding in the herring fishery has not been analyzed so far. As the demand of herring for fodder has declined (I) the unreported rejection of catches (discarding) may have increased. Moreover, it would seem logical to assume that variation in the growth rate has contributed to variation in underwater discarding at age and caused varying bias (in time) in the assessment data due to considerable changes in herring weight-at-age during the last three decades (I). Both the effort expended and the area swept by trawls have increased due to a marked enlargement of trawl size (II). Therefore, unaccounted mortality has increased compared to fishing mortality. Since juvenile herring frequently form a high proportion of the total catch of trawlers fishing in the northern Baltic Sea (Suuronen et al. 1991), substantial unaccounted mortality and biased removal estimates are to be expected.

Table 2. Major uncertainties in the northern Baltic Sea herring stock assessment.

Source of uncertainty	Cause/ potential events in fishery	Direct consequences for assessment and management
Natural mortality rate	Variation in predator abundance, hydrographical variability.	Historical estimates and BRP:s are biased, influence on short predictions less severe.
Unreported discarding	Probability for discarding is higher for small sized herring (high grading).	Removals from a population underestimated, catch-at-age biased in young ages, errors in estimated partial recruitment, F, and recruitment estimates.
Underwater discarding	Low survival of escapees, codend mesh size alterations and restrictions.	-‘’-
Unreported landings	Restrictive catch quotas.	Underestimation of population biomass. If proportionate decline in abundance over time is underestimated due to underreporting, this could lead to conclusions that less strict harvesting policies are adequate to rebuild a depleted stock.
Incorrectly reported fraction of herring and sprat in the catches	Either skippers intentionally report the fraction of herring and sprat in catch in the mixed fishery to be equal to the fraction of these species in the national quota, or skippers’ are truly uncertain about catch quantity.	Biased catch statistics, direction of bias uncertain.
Incorrectly specified relationship between CPUE and abundance	Complex dynamics including change in catchability and biological processes.	Tuning biased, direction of bias uncertain.
Ageing	Lack of reliable ageing method and traditions leading to underestimated age of old herring.	Mortality overestimated, abundance underestimated.
Identification of geographic boundaries	Imperfect knowledge about stock structure and migrations.	Increased uncertainty about the resource, uncertainty of relevant assessment and management units.
Maturation schedule, fecundity	Improper sampling	Uncertainty about spawning stock biomass and effective spawning potential.

Uncertainty is also associated with the determination of the age structure of the catch, as well as with the maturation schedule and size-at-age. Sampling is subject to errors and, therefore, statistical estimators are used to quantify the random part of that error. A well designed sampling program can produce reasonably precise estimates for the age structure of catch (Schweigert and Sibert 1983, Kimura 1989). However, a danger of bias is inherent in all sampling and thus standard errors do not necessarily reflect true imperfections of knowledge. The danger of bias emphasizes the role of both the sampling design and quality control in reducing the imperfections of knowledge connected with the sampling process (Hildén 1997). From the beginning of 1998 the Finnish sampling procedure was changed from random sampling (direct ageing of samples and an extrapolation to the whole stock) into length based stratified random sampling (a two-stage sampling using the body length as an intermediate variable, Kimura 1977), which is considered to estimate the catch composition more accurately (ICES 2004).

Estimates of maturation schedule are based on small sample sizes (IV) and the resolution of the data is low. Although the average maturity-at-age has varied substantially in time

(0.04-0.81 at age 2; ICES 2004), roughly speaking only the minimum and the maximum maturity ogives are statistically different (IV). Knowledge about maturation schedule is used in the calculation of spawning stock biomass when age group abundance is multiplied with weight-at-age and maturity ogive.

The conventional age readings from whole otoliths may generate considerable errors in age distributions, especially in samples which mainly consist of older fish. Comparison of age determinations between whole otoliths and neutral red stained otolith cross sections have revealed a considerable negative bias in old fish with the whole otolith method (Peltonen et al. 2002). Revision of otolith ages is bound to influence estimates of natural mortality rate and stock assessment, and the resulting choice of fisheries management alternatives (Peltonen et al. 2002).

An understanding of ecosystem variations and of species interactions on herring stock dynamics is necessary to determine the effects of fishing and to distinguish those effects from natural changes. Assessments for the Bothnian Sea stock have not been adjusted for higher cod predation in the early 1980s and a constant natural mortality rate has been used in the XSA (ICES 2004). The adjustment for cod predation would induce an increase in the abundance estimates for that period and would most likely influence current biomass reference points (B_{lim} and B_{pa}). These biological reference points are based on the perception of spawning stock biomass where the probability of lower recruitment increases. According to assessments, a period of low SSB and recruitment prevailed before the late 1980s when the natural mortality rate may have been higher than the rate applied in the XSA. Stock abundance and recruitment may have been considerably higher and the stock-recruitment relationship may be accordingly biased.

3. Materials and methods

3.1 Fish and fishery data

Landings and effort information of the fishery was derived from fishing vessel log-book data compiled by the Finnish Game and Fisheries Research Institute. All professional fishers with vessels longer than 10 meters are obligated to submit a catch notification within 48 hours of the catch being landed. All herring trawlers have been included in this category since 1996 when the limit was set to 10 meters from 12 meters. Trap net catches and related effort have been reported monthly to the regional fishery authority as well as the catches from trawlers whose vessel length has not required maintaining log-book system.

The spatial and temporal extent of the data included in the five papers forming the basis of this thesis varied, reflecting the scope of the publications dealing with different aspects of the Baltic Sea herring resource and the Finnish fishery. Details of the data used in the constituent publications are given in Table 3.

3.2 Approaches

Linking biological and industrial aspects of Finnish herring fishery (I)

In this paper, the key biological and industrial aspects of the Finnish herring fishery in the northern Baltic Sea were synthesized using time series data about herring catch rate, weight-at-age, and price with information about market preferences and changes in the ecosystem.

Table 3. The data used by the original articles.

Type of data	Article I	 II	 III	 IV	 V
Industrial	X	X			
Biological	X		X	X	X
Natural mortality rate				X	X
Growth rate (weight-at-age)	X		X	X	X
Maturation schedule				X	X
Exploitation pattern			X	X	X
Spatial data coverage					
Subdivision 29	X			X	X
Subdivision 30	X		X		X
Subdivision 31	X				
Subdivision 32	X			X	X
Aggregated		X			
Temporal coverage					
Quarter 1			X	X	
Quarter 2			X	X	X
Quarter 3			X		
Quarter 4			X		
Aggregated	X	X			
The gear sampled for growth analysis					
Trap net					X
Bottom trawl				X	X
Pelagic trawl				X	X

Estimation of trawl size (II)

Records of basic vessel attributes (length, tonnage, engine power etc.) and gear types are accessible through vessel registers. Accurate information regarding gear characteristics is lacking. Information held by fishers and gear manufacturers was analyzed to get a measure of "average trawl size", indicated by the area of fishing circle (the area of cross-section at a trawl's mouth during towing) that can be applied to adjust effort for efficiency changes. An analogy was developed between fish and trawl populations: recruitment of fish corresponding to manufacture of new trawls and mortality corresponding to removal of trawls due to break down of construction or other reasons. These dynamics were captured with forward calculating VPA. The amount of trawls in the population is controlled by recruitment and retirement rate and the average size of gears in the fleet is controlled by amount of trawls and their sizes.

Fishing effort is defined as capacity, in fishing circle area, multiplied by activity expressed in hours trawled at sea. The nominal effort is one active trawling hour in 1980.

Calculation of underwater discarding (III)

Length-specific selection and escapee mortality functions were applied to estimate "underwater discarding" and the actual total removals from the herring stock in the Bothnian Sea. Survival experiments conducted for Baltic herring escaping from commercial trawls through codend indicated that mortality of herring was heavily dependent on fish size (Suuronen 1995, Suuronen et al. 1996b). Based on these survival experiments, it was assumed that no escaped fish under 12 cm survives. For herring over this limit 10% survival rate was applied. The influence of codend mesh size was also examined on underwater discarding and on perceived stock dynamics. Retention rate was estimated by the logistic model for selectivity (e.g. Millar and Fryer 1999) for the most commonly used codend mesh sizes (whole mesh length) by the Finnish herring trawlers: 20, 24, and 36 mm (Fig. 6). Landing statistics and mesh size information were combined on a vessel basis due to presumed systematic changes in the codend mesh sizes to estimate the fraction each mesh size has contributed to total landings.

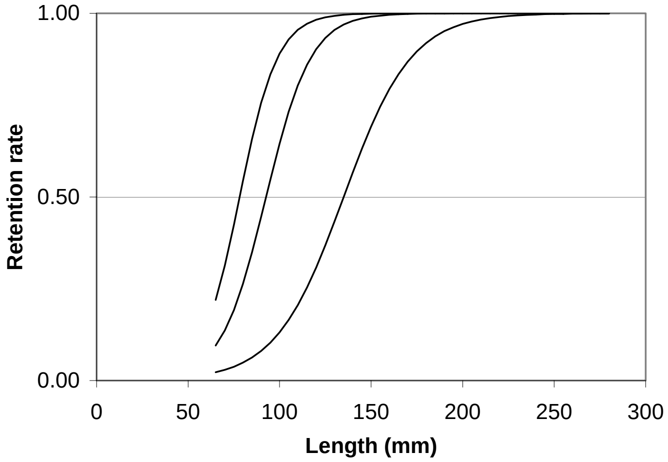

Figure 6. The applied selection functions for 20, 24, and 36 mm (from left to right) mesh size.

The applied models for contact selectivity were deterministic. Three scenarios were used to describe possible changes over time in the fleet selection pattern (III; Fig. 3):

1. Constant trawl fleet selection pattern
    - A static scenario where the fractions of total landings that were allocated to 20, 24, and 36 mm codend mesh sizes were 50%, 35%, and 15%, respectively.
2. Trawl fleet selection pattern as estimated from interview data and landing statistics
    - An empirical scenario that displayed abrupt changes in the fleet mesh size.
3. Combination of data and auxiliary information from stakeholders
    - A combination of scenario 2 and auxiliary interview information which likely served as the best guess for fleet selectivity.

A mathematical model was developed for a catch volume weighted average of length-specific retention rates assigned to particular codend mesh size (III, eq. 3).

Available selection estimates come from experimental trawling where set sizes are considerably smaller than in commercial fishing. Therefore, selectivity was accommodated to the effect of set size.

Calculation of biological reference points (IV and V)

Spawning per recruit is commonly used as a proxy for population resilience, i.e. defining a biological reference point using information about growth rate, maturation schedule, and natural mortality. The conventional input data set for SPR analysis includes a stock-recruitment scatterplot derived during many years of observations combined with an SPR curve (Fig. 4). This single SPR curve is calculated from data pooled over all or some recent years. Thus the SPR curve represents the static element and the S-R scatterplot the dynamic element of the analysis in a sense that additional S-R observations may provide new insight about stock dynamics and alter our perception of appropriate reference point definition (e.g. F_{med}). Biological reference points can be developed, by applying an SPR approach, either using actual stock size and recruitment data to define F_{med} reference points or by using knowledge of taxonomic affiliation (Mace and Sissenwine 1993, Myers et al. 1994, Myers et al. 1995) to define $F_{x\%SPR}$ reference points. Only the latter approach is relevant in this case because in the northern Baltic proper stock size or recruitment information is not available by subdivision (29 and 32). Due to the enormous changes in growth rate in time and space in northern Baltic Sea herring, the idea of using a single SPR curve seemed to be false. Instead, a set of them was generated using three different models: 1) the empirical model which is a data oriented approach based strictly on the observed values of weight-at-age, maturity ogives, and natural mortality rate estimates by MSVPA, 2) the random model which is constructed under assumption that no correlation among growth, maturity, and natural mortality exists in the herring stock and all their combinations are random, and 3) the ecological model in which biological and ecological understanding was used by assuming complete positive correlation between growth rate and maturation schedule and strong positive correlation between growth rate and natural mortality rate.

Maximum spawning per recruit, i.e. the virgin SPR, determines SPR of an unfished (F=0) population. Maximum SPR can be defined in two ways when there is variability in the input data: a) as the maximum spawning per recruit for each set of input data, and b) as the maximum of all input data sets. These values are referred to as annual maxSPR and global maxSPR, respectively. Thus annual maxSPR describes a maximum spawning per recruit of any single SPR curve, whereas global maxSPR defines a maximum from a larger set of SPR curves. Global maxSPR is, thus, a highly conservative approach. Properties of maxSPR definition on the interpretation of SPR reference points were studied in the articles IV and V.

The key question in the article IV was whether information of causal relationships between growth, maturation, and natural mortality would reduce the uncertainty of a biological reference point ($F_{30\%SPR}$). The analysis was constructed of two basic elements: i) fitting the observations of herring growth, maturation, and natural mortality to intrinsic age effects and external environmental effects, and ii) using these estimates and their possible dependencies in three models to generate a set of SPR curves using Monte Carlo simulations, when the difference among the models was in the use of biological knowledge as described above.

In article V, the impact of growth rate on two biological reference points was investigated. These BRPs are prevalent in ICES: $F_{0.1}$ (Gulland and Boerema 1973) and $F_{x\%SPR}$ (especially $F_{35\%SPR}$) (Mace and Sissenwine 1993), but imply fundamentally different considerations of stock dynamics.

4. Results and discussion

4.1 Industrial and biological aspects of the herring fishery (I)

Primarily market demand and prices, and to a lesser extent herring biology, have shaped the Finnish herring fishery. Requirements of the processing industry for herring of particular sizes have had considerable impact on the location and amount of landings. As the growth rate of herring declined in the Gulf of Finland and Archipelago Sea in the late 1980's and early 1990's (I, Fig. 6) herring of suitable size for that market (>36g) decreased (I, Fig. 11), forcing the fishery to move into the adjacent Bothnian Sea (subdivision 30) where catch rate of large herring remained at high level (I, Fig. 12). In addition to the obvious impact on total landings, there have been a number of more subtle changes to the fishery including changes in location of processing and refrigeration plants, and fishing ports.

These significant events in the fishery and changes in the industry have mostly been unforeseen. They are largely beyond a traditional catch oriented management control. However, since fisheries management, in addition to quota management, also involves decisions about assigning structural subsidies to fund fishing ports and related infrastructure, these events are very much in the center of a broader fisheries control. It is a failure of the fisheries science that these events have not been analyzed and an inadequacy of the assessment and management systems that they cannot systematically register and consider this kind of information.

The quick decrease of large herring in subdivisions 32 and 29 (I, Fig, 11) was to a large extent unpredictable, and the management system in place has no real tools to respond even if predictions were perfect. One could argue that the TAC could be used to prevent unsustainable use, but it is - at least if used alone - insufficient to control this system on the spatial and temporal scale that is required (V), and cannot be used to achieve the socio-economic objectives which appear to be relevant. The current TAC-based system is insufficient because, 1) the assessment of the present state of the population is imprecise, 2) TAC is spatially too aggregated and, therefore, unenforceable to be effective, and 3) socio-economic and biological variables change so rapidly and unpredictably that it is difficult to target an appropriate sustainable stock and catch levels.

The structure of the commercial fishery polarized in Finland in the 1980s and 1990s (Salmi and Salmi 1998). Most of the herring trawlers landed little if any herring in 1997 (Virtanen et al. 1999). Management should recognize and consider impacts of regulations on the heterogeneous fisher groups. One symptom of the polarization is probably the decreased number of purchased trawls after 1997, when only the wealthiest and most effective fishers continued to invest in their livelihood (II).

4.2 Trawl size and interpretation of CPUE (II)

A striking increase in the average size of manufactured trawls has taken place in 20 years: in 2000 the average size of recruiting trawls was 7.5 times larger than in 1980. The average trawl size in the fleet has increased by factor of 2.7 during the same period (Fig. 7). The increase of the fishing circle area was a slow but continuous process during the 1980s but the rate of change increased at the beginning of the 1990s and has been particularly rapid from 1995 onwards. From 1992 to 2000 the increase of gear size has been 100%. Stock assessment for subdivision 30 herring stock is tuned using CPUE data from 1994 onwards (ICES 2004) and clearly, the doubling in gear size is bound to bias SPA using CPUE as tuning series if this event is ignored.

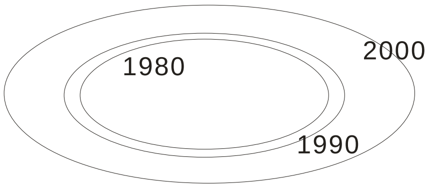

Figure 7. The average area of fishing circle of pelagic herring trawl on a relative scale in 1980, 1990, and 2000.

After the trend in the gear size was discovered, the CPUE time series was adjusted by the estimated increase in the assessments since 1999 (ICES 1999). The adjustment was made by multiplying fishing effort by the gear size index. This had a considerable impact on the abundance index which fell to around 50% of the unadjusted abundance index value in the last year in the tuning series. Although this adjustment is the simplest possible approach, it had the effect of nullifying the trend from catchability residuals in the SPA for ICES subdivision 30 herring stock (e.g. ICES 2000). VPA should be tuned with Modified Hybrid method in presence of a trend in catchability residuals (Darby and Flatman 1994) and therefore, XSA has not been an adequate method – although it was constantly applied – for tuning before CPUE data were adjusted to account for increase in fishing power.

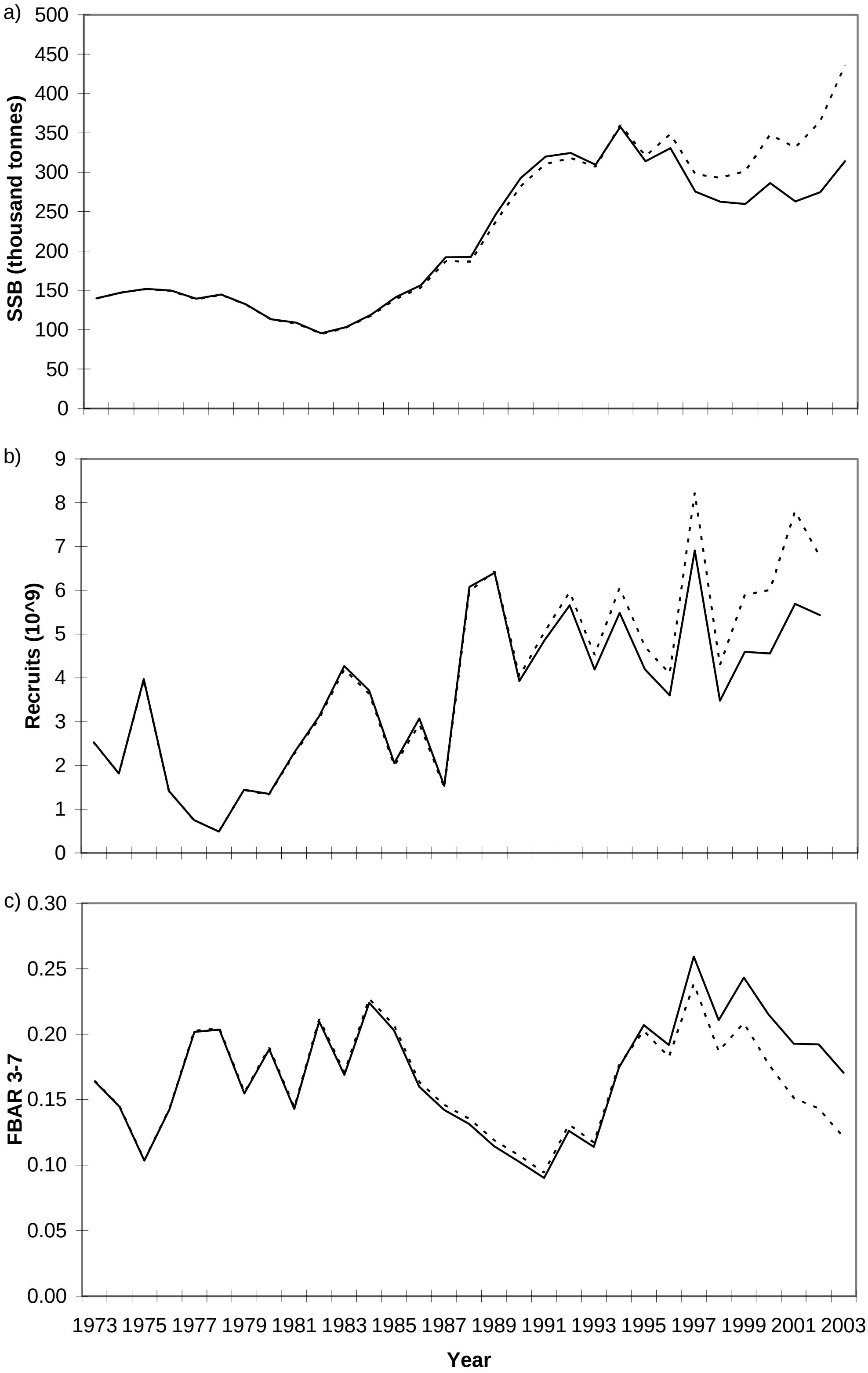

Figure 8. Estimated spawning stock biomass (a), recruitment at age 1 (b), and fishing mortality rate (FBAR 3-7) (c) by in the Bothnian Sea in 1973-2003 by two tuning series. XSA is tuned by CPUE data in accordance with trawl size information (ICES 2004, solid line) and without correcting effort data by this information (dashed line).

The bias in Finnish herring trawler CPUE data did lead to the classical flaw of an underestimate in fishing mortality and an overestimate of stock size and recruitment before the adjustment for the trawl size was made (Fig. 8). The estimated spawning stock biomass would be 120 thousand tonnes (39%) larger for the last year if CPUE data were not adjusted for fishing power creeping. Accordingly, the number of recruits would be biased by 1.3 billion fish (25%) and F by 0.05 (29%).

The decrease in the market price for herring due to withdrawal of subsidies (I) may have encouraged skippers to invest to larger trawls in a hope of a larger catch rate and profitability. According to Finnish trawl manufacturers the increase in trawl size was facilitated by modification of the sweeps. By using considerably larger mesh sizes in the sweeps and the front section, fishers have been able to tow larger trawls with their present vessels and engines. Avoiding investments into larger vessels and more powerful engines is a significant advantage. This deduction is consistent with the fact that the Finnish herring trawling fleet is one of the most profitable ones among a number of European countries despite low incomes (Virtanen et al. 1999) and despite net profits being close to zero (Anon. 2002). The key is even lower operation costs on a relative scale (Virtanen et al. 1999).

An average trawl size has thus been interpreted as an index of fishing power. However, the relationship between gear size and catchability is probably not proportional. There are several so far immeasurable variables such as skipper skill (Hilborn and Ledbetter 1985; Hilborn 1985) and the impact of other improved fishing technology including satellite positioning and seafloor imaging systems, and fish-finding equipment. Also fish behavior and on-site dynamics of vessels may bias the relationship between CPUE and abundance (Hilborn and Walters 1992, Fréon and Misund 1999). Therefore, only an element of fish capture technique is dealt with in the article II.

The catch rate – abundance relationship

Assessments have been performing poorly or incompletely globally. This has been addressed by both collapsed fisheries (Ludwig et al. 1993, Jackson et al. 2001, Pauly et al. 2002) and “blind assessments” of simulated data sets using different models (National Research Council 1998). In a simulation exercise, the majority of the estimates of exploitable biomass exceeded true values by more than 25%. It is noteworthy that the assessments that used accurate abundance indices for tuning performed roughly twice as well as those that used faulty indices (National Research Council 1998). Assessment of herring stock in subdivision 30 is tuned using a dubious abundance index, commercial catch per unit effort. Many fisheries are currently modeled assuming strict proportionality between CPUE and abundance, although it has long been recognized that CPUE may not accurately reflect changes in abundance due to non-random distribution of fish and density-dependent catchability (Gulland 1964, Paloheimo and Dickie 1964). The most common form of nonproportionality, “hyperstability” (Clark and Mangel 1979, Peterman and Steer 1981, Allen and Punsly 1984, Hilborn and Walters 1992, Swain and Sinclair 1994), involves CPUE remaining high while abundance declines. The relationship between catch per unit effort U and abundance N is usually modeled as a power curve:

$$U = qN^{\beta} \qquad (1)$$

where q is the catchability coefficient and β is the parameter describing the form of the relationship. When $\beta = 1$, there is a linear relationship between U and N. Catchability changes with abundance if $\beta \neq 1$ (Fig. 9). When $\beta > 1$, CPUE declines faster than abundance in a situation known as hyperdepletion. If $\beta < 1$, *U* declines slower than *N*, which results in hyperstability (Hilborn and Walters 1992). A meta-analysis using survey indices and commercial fisheries CPUE data provides strong evidence of hyperstability in the relationship (Harley et al. 2001) which can lead to overestimation of biomass and underestimation of fishing mortality (Crecco and Overholtz 1990). Not only does the relationship itself (parameter β) have significance but so does the level of the original population abundance and the direction of change. If proportionality does not hold and the relationship is hyperstable, then the change in *U* is smaller than in *N* for high population abundances, but is larger than the change in N for low stock sizes.

Although hyperstability and hyperdepletion may cause severe bias in perception of stock trend, there are ranges in stock abundance where proportionality is satisfactorily achieved even under hyperstability and hyperdepletion. Reasonable tolerance limits for deviation can be evaluated by having a quantitative estimate of the bias. The first order derivative of equation (1) (where q is treated as a constant) is:

$$U' = q\beta N^{\beta-1} \tag{2}$$

which specifies the slope for CPUE-abundance relationship for a given β and *N*. The violation may be subjectively regarded as acceptable – at least this should not lead to dramatic errors in assessment – when deviation is at most ± 10% from proportionality (i.e. the slope of the curve is [0.9, 1.1]). With little manipulation, equation (2) defines the range of relative stock abundances where deviation from proportionality is within these limits. We can solve (2) for N and use a given β and U' (the maximum deviation from proportionality, i.e. U' = 0.9 or U' = 1.1):

$$N = \left(\frac{U'}{q\beta}\right)^{\frac{1}{\beta-1}} \tag{3}$$

Harley et. al (2001) concluded that for a number of sedentary fish species or taxonomic groups a good ballpark figure of β would be 0.64-0.75. If such a moderate hyperstability prevails, deviation from proportionality would be acceptable when relative stock abundance is 22–39% of the virgin stock for β=0.64, and 22-48% for β=0.75 (Fig. 9). These abundance levels are realistic for many harvested stocks, and, therefore, hyperstability does not necessarily pose a dramatic problem for stock assessment, i.e. using commercial CPUE as abundance index for tuning XSA. This meta-analysis technique – combining parameters of interest across studies or populations (Cooper and Hedges 1994) - is however restricted by the problem that parameters can not be predicted for a given application, for instance for a given CPUE series and population.

Obviously, the impact of hyperstability and hyperdepletion work very differently on reliability of stock assessment. In a developing fishery, the decline of stock size and increase of fishing mortality may be masked by hyperstability. However, the commercial catch rate may reflect reasonably accurately changes in stock size in a developed fishery, where stock surplus is fully utilized and abundance has decreased to 30-50% of the virgin abundance. Hyperstability may even to some extent decrease the risk of overfishing, since CPUE starts to decline faster than abundance when stock size falls below 29-32% of virgin stock.

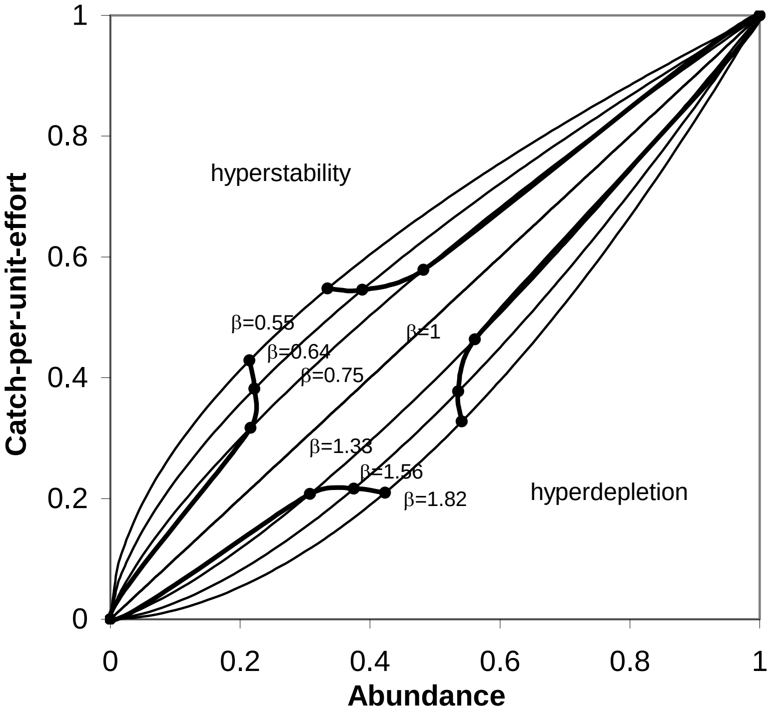

Figure 9. Regions of stock abundance where deviation from proportionality is at most ± 10% (i.e. the slope is [0.9, 1.1]) for three hyperstable and hyperdepleted situations are shown by bold curves. The diagonal represents proportionality (i.e. $\beta = 1$).

If stock collapse has actually taken place, hyperstability may lead to overly optimistic perception of population recovery from very low stock sizes. This possibility should be considered when hyperstability is to be expected, and stock assessment method relies on commercial CPUE in a recovering stock and fishery. The approach currently used by Working Group for Baltic Fisheries Assessment, XSA (Shepherd 1999), is capable of considering nonlinearity in the relationship between CPUE and abundance (Darby and Flatman 1994), but the software has some limitations. For example, it lacks the ability to incorporate information on β. In addition, Harley et al. (2001) have concluded that the power curve is an appropriate model for relating the index of abundance to population for all ages. However, with the ICES approach it was possible to apply a power fit only to the youngest ages without compromising stability of the XSA algorithm.

4.3 Unaccounted mortality (III)

Analysis of codend selection and escapee mortality revealed that the trawl fishery remove a considerably larger amount of age 0 to 1 herring from the stock than indicated by the landing statistics. The landings have been only 30% of the total actual removals at age 0, 40% at age 1, but nearly 90% at age 2 herring during 1980-1999. From age 3 onwards, underwater discarding has been less than 5% of the total removals. There is also a substantial difference in the length distribution between the observed catch and actual removal (Fig. 10). The most abundant length classes (165-174 mm) in the catch are reasonably accurately documented in the landing statistics but estimated removals of herring 70-99 mm in length are severely biased.

Variation among years in underwater discard rate is highest in age groups 0 and 1 while it is reasonably constant for older ages (Fig. 11). Scenarios about the changes in the codend mesh size did not lead to marked differences in the estimated true removals when aggregated for the whole data series. Herring weight-at-age in mature age groups (ages > 2) has experienced considerable changes during the last three decades (I, V) but has not contributed notably to variation in underwater discard rate at age because the retention rate is near 1 in these age groups.

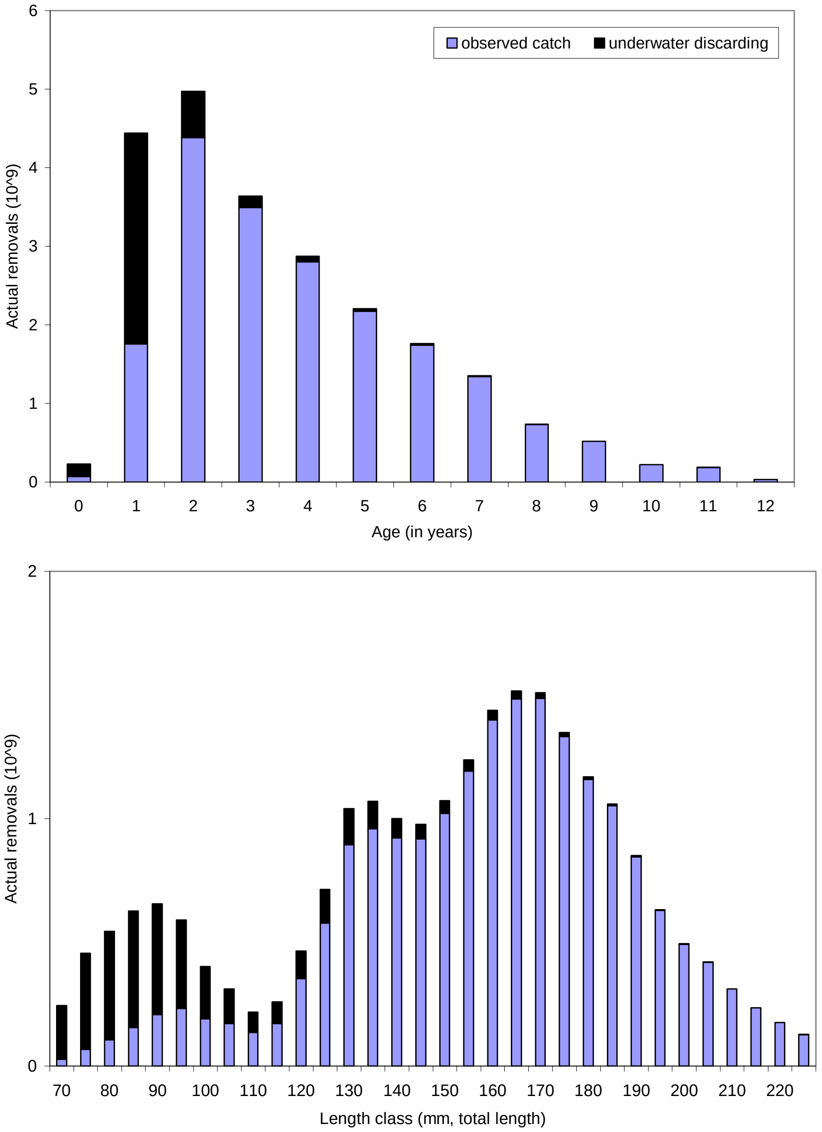

Figure 10. Reported herring trawl catch and estimated underwater discarding in the Bothnian Sea in 1980-1999. Scenario 3 was used to describe the change in codend mesh size.

Unaccounted mortality involves a marked seasonal pattern. In recent years (1997-1999) underwater discarding was highest during the two first quarters of the year (January – June) in both absolute and relative terms. In the first quarter of the year, current trawl fishery practices remove 85-94 mm herring more than any other length classes. The absolute underwater discarding is largest in the second year quarter, 70% of age 1 herring having had contact with any type of gear face unaccounted mortality. Later in the year during the third and fourth quarters, age-0 herring start being recruited into the fishery. However, their fraction in the observed catch and also in the concomitant unaccounted mortality is insignificant.

Adjusting population analysis input data for unaccounted mortality changes fishing mortality estimates considerably for age group 1 only. At age 1 the unadjusted F (FBAR97-99; arithmetic mean fishing mortality in 1997-1999) estimate is 0.06 (ICES 2000) compared to 0.15-0.17 for the three scenarios of adjusted data. Although these estimates are moderate and below F_{pa} 0.21 (a precautionary reference point defined for this stock (ICES 2001)), the relative divergence is significant. The impact of unaccounted mortality decreases rapidly with age so that at age three there is no impact at any relevant scale.

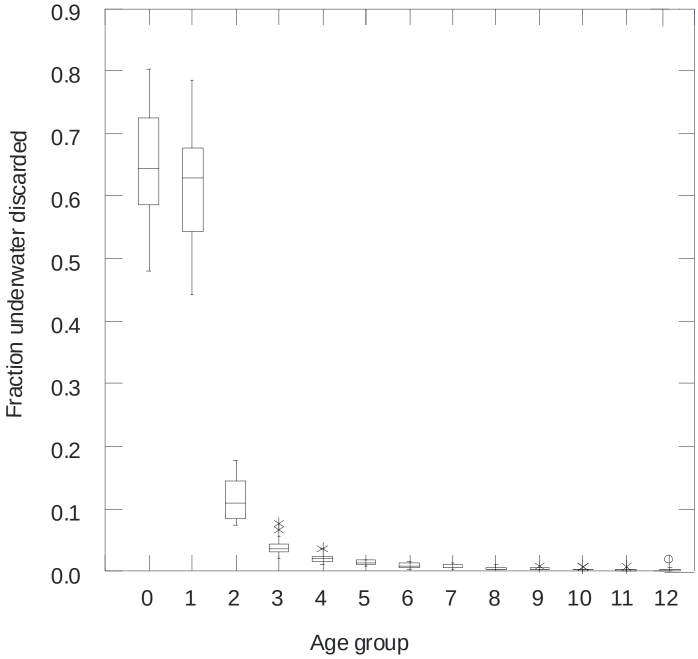

Figure 11. The fraction of total removals being discarded underwater at age according to fleet selectivity scenario 1. The center vertical line marks the median, the box edges show the first and third quartiles, the whiskers show the range of observed values that fall within the range of the corresponding quartile ± 1.5 * the interquartile range. An asterisk denotes a value between the whisker and ± 3 * the interquartile while an empty circle denotes larger deviation than this.

There was no marked difference in fleet selection between 20 and 24 mm trawl codends, but a 36 mm codend makes a difference. Consequently, the sampling program should be stratified also by codend mesh size to consider landings by vessels targeting to human consumption or animal fodder markets. Currently fishers report codend mesh size in a log book but these data are not entered in database used by assessment scientists in Finland. This loss of information should obviously be corrected.

There is no practical difference whether herring is discarded underwater or from the deck because the escapee mortality is nearly 100% (Suuronen et al. 1996a; 1996b). Underwater discarding should not be ignored in recruit-based assessments and management such as yield-per-recruit and spawning per recruit analysis. Exploring value per recruit (Neilson and Bowering 1989) will likely give relevant information because market price of herring varies with size.

As far as assessment is concerned, the major consequence of unaccounted underwater discard mortality is an underestimate of the numbers of age 1 fish in the stock. Estimates of stock-recruitment relationship are thus susceptible to changes in codend mesh sizes applied by the fleet and fishing mortality. Substantial changes in any type of unaccounted mortality are capable of blurring the relationship between spawning stock and recruitment, and masking true environmental effects or inducing spurious trends in the relationship. Ultimately, biological reference points based on stock-recruitment estimates may also be flawed. This risk is likely to be minor, given the small absolute differences between age 1 stock size estimates for the unadjusted and adjusted data and a Beverton-Holt function with lognormal error which is fit by ICES (ICES 2002) to stock-recruitment data to derive biological reference points.

Responsible fishing practices (FAO 1995) may require restrictions in temporal or spatial allocation of effort to conserve young herring because mesh size regulations would reduce the value of catch per recruit (Kuikka et al. 1996). Conventionally, a minimum mesh size is set as a form of technical regulation but in the northern Baltic herring fishery a maximum mesh size could be more appropriate because of underwater discarding. This regulation could lead to increased discarding of small herring from deck limiting usefulness of mesh size control. In fact, Beverton (1998) has emphatically warned about technical measures (gear selection) arguing that they are used by industry to escape effort control. In any case, rapid growth of herring at ages 0 and 1 address the potential of temporal fishing restrictions in the trawl fishery to mitigate the waste of young herring. Seasonal variation of escapee survivals (Suuronen et al. 1996 a) should be considered carefully before implementing these kinds of restrictions. Currently, reasonable estimates of mechanical selectivity are available but issues related to population selectivity (spatial allocation, also vertically, of effort with respect to occurrence of young fish) are far more uncertain. A combination of temporal and spatial effort control would potentially be effective to increase yield per recruit. An analysis of usefulness of this kind of regulation implies a greater demand for information about the spatial distribution of herring.

4.4 Impact of ecosystem change on $F_{x\%SPR}$ (IV and V)

The determination of risk associated with biological overfishing depends strongly on the assumptions about maximum spawning per recruit when $F_{x\%SPR}$ approach is applied (IV). “The random model” resulted 121% and “the ecological model” 43% larger maximum SPR than maxSPR in the observed data. Extremely high maxSPR has been realized in the simulations for the random model as a product of favorable but rare combinations of input parameters: low natural mortality combined with high growth rate and maturity ogive. Soaring global maxSPR scales the reference point to levels of fishing mortality rates which are unrealistically low for the random model (Fig. 12b) and very low for the ecological model (Fig. 12c). The probability distribution of $F_{30\%\,SPR}$ for the empirical model was reasonably uniform in the range of 0.09-0.45 (Fig. 12a). The potential usefulness of the reference depends on whether variation of $F_{30\%\,SPR}$ reflects a change in BRP when the environment (growth, maturity and mortality) fluctuates back and forth between low and high state, or whether it is merely stochastic variation. The sensitivity analysis (IV, Fig. 9) and result of V (V; Fig. 6c) suggest that $F_{x\%\,SPR}$ can account for changes in stock productivity when virgin spawning per recruit is defined as global maxSPR. Knowledge of compensatory processes is, however, crucial to correct interpretation of this reference point (V). The three models result in different management advice and demonstrate the structural uncertainty in addition to the parameter uncertainty shown by the wide range of the $F_{30\%\,SPR}$ distributions.

When virgin spawning per recruit was defined as annual maxSPR, the levels of the reference point were much higher as a direct consequence of lower virgin spawning per recruit estimates (Fig. 12d, e, f). According to sensitivity analysis neither year nor age effects had a notable impact on $F_{30\%\,SPR}$. The explanation for lack of any effect of variability in growth, maturation or natural mortality on the $F_{30\%\,SPR}$ in affiliation with annual maxSPR is that this biological reference point is defined as a constant fraction of SPR with no fishing. SPR curves were “internally scaled” in simulation trials in the sense that input parameters have a stronger effect on the level than on the shape of the curve. As a consequence, variance in growth, maturation and natural mortality has not had significant effect on the direction of change of the reference point. The observed instability should therefore be classified as uncertainty.

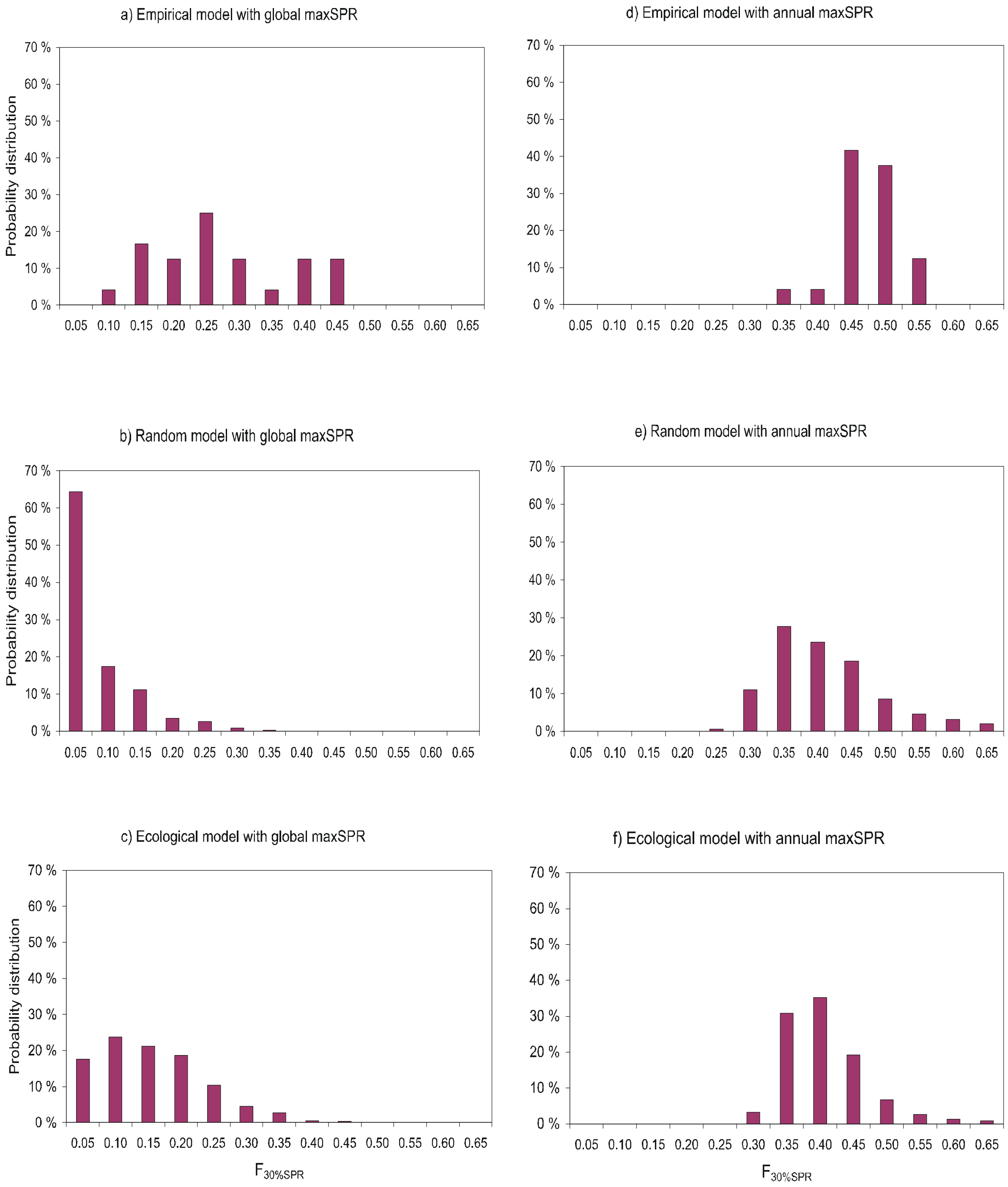

Figure 12. Simulated probability distribution of estimated $F_{30\%SPR}$ for the empirical, random, and ecological models. The values on x-axis represent the upper bound of the class.

Use of biological information in the ecological model resulted in little reduction in uncertainty and utility of this knowledge in giving management advice is minor. The cause for this is the strong positive correlation which was set between the year effects in the ecological model (IV; Table 1) canceling out their effect on the spawning per recruit and hence on reference fishing mortality rate. However, it is clear that outcomes from both random and ecological models call for more cautious management advice than would be the case if based on historical data only. This conclusion is valid with all derivations of maxSPR but it is also obvious that the $F_{30\%\ SPR}$ distributions of the random and the ecological models basically reflect the parametric distributions of input variables used for resampling in simulation trials. Therefore, simulation of scenarios about natural mortality, growth rate, and maturity and testing the outcomes against empirical data should be included in a prudent management advice.

Maximum SPR may be estimated without any confusion for a fish population having considerable stability in life history parameters. For these stocks maxSPR can be interpreted on the stock-recruitment scale assuming assessment outputs are available. When virgin spawning biomass and corresponding recruitment are obtainable they help validating whether estimated maxSPR is meaningful. Unfortunately, regarding northern Baltic herring, potential confusion in defining maximum SPR makes spawning per recruit analysis dubious. The difficulty is obtaining a reliable estimate of virgin SPR due to the large variation in growth and natural mortality, and especially due to the uncertainty about possible density dependent processes in Baltic herring. Rochet (2000) has demonstrated that density dependent mechanisms in the adult population (e.g. growth rate, maturation schedule, fecundity, and egg size) may break down the proportionality between spawning stock biomass and recruitment making spawning per recruit an ambiguous concept.

The traditional approaches for estimating biological reference points for fishery management, based on SSB as a proxy for reproductive output, may generally estimate the potential resiliency of stocks to exploitation. If the viability of eggs or larvae is positively correlated to maternal experience, age or size, the effective spawning potential of the stock will not be adequately indexed by SSB calculated from weight and maturity data (Murawski et al. 2001). This is particularly true if the age structure of the spawners has changed significantly over time. Such a mechanism could be modelled with appropriate field data, along with information on the effects of maternal demographics on survival of eggs and larvae.

The magnitude of variability inherent in the reference point and consequent management advice displayed by all used models would be hard to accept by a fisheries manager and fishing industry. Reference points should, however, depend on the true changes in environment, and would be expected to change in parallel with regime shifts in the ecosystem. Analysis based on global maxSPR meets this requirement but analysis relying on the annual maxSPR does not.

I suggest that the idea of introducing additional information to the assessment procedure by controlling the correlations between input variables was more important than the results themselves. The objective of the study was not developing the best point estimate of a biological reference point, but analyzing both the parameter and structural uncertainty of the estimate.

Another approach of looking at the influence of maxSPR definition on management conclusions was developed in article V. The reference point was relatively stable when calculated using an annual maximum SPR but spawning per recruit varied considerably as a function of $F_{35\%SPR}$ in accordance with reduced growth. The reference point was markedly variable when global maximum spawning per recruit, “maximum maxSPR”, was applied (Fig. 13). The variability is due to changes in both weight- and maturity-at-age. Applying a global maxSPR had an effect of stabilizing spawning per recruit, and also tended to stabilize SSB and recruitment. The global maxSPR option resulted in very low reference Fs for the 1990s. As a consequence, associated landings would be low when growth rate decreases.

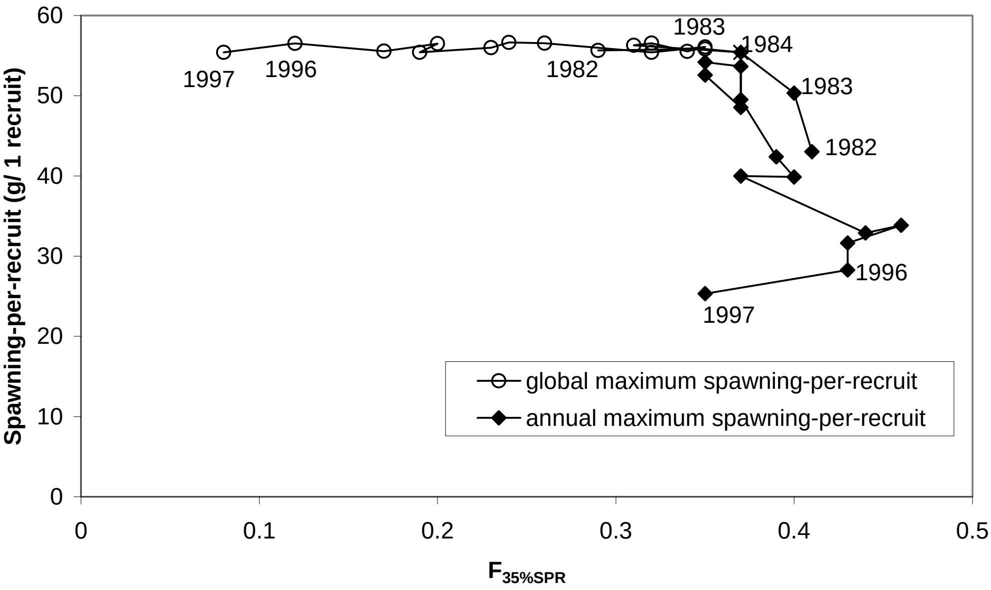

Figure 13. The relationship between $F_{35\%SPR}$ and spawning-per-recruit for SD32 herring. The first two years, the last two years and the year of the overlapping estimate are indicated. The estimate overlaps when annual and global maxSPR are the same (indicated by an asterisk).

Estimates for spawning per recruit and corresponding fishing mortality rate are based on a single data point (maxSPR) and are therefore problematic. There is also a potential risk in the global maxSPR approach which concerns the density-dependent dynamics of a population. Maintaining high abundance may cause a density-dependent decrease in growth and potential yield. Therefore, assumptions about density-dependent processes may be critical, and understanding the causal relationships of growth reduction in the northern Baltic herring stock is important. The reference points derived from annual maximum SPR, in turn, work in practice as ratio reference points, suggesting reasonably constant harvesting rates despite changes in life history parameters (V; Fig. 6). This *de facto* constant harvest rate implies that SSB would decrease and potentially affect recruitment.

Clearly care is required in defining maximum SPR. The annual and global maxSPR approaches are two sides of a coin, and must be used with knowledge of the implications in terms of risk of growth reduction vs. impaired reproduction. Global maxSPR is an unreasonably conservative approach, but a potential solution to overcome the overly conservative output resulting from its use would be to employ an appropriate maxSPR from the distribution of maxSPRs as they vary as a function of growth. This procedure would be analogous to the concept of F_{low}, i.e. using a maxSPR that is the tenth percentile.

Clark (1991) and Walters and Parma (1996) have proposed that a strategy of fixed exploitation rate performs reasonably well through large fluctuations in life history parameters and equilibrium abundance. Moreover, Walters (2001) generalizes that successful fisheries are likely to be those that are managed with conservative fixed exploitation rate policies. Accordingly, the herring stock in subdivision 32 would be an obvious candidate for that strategy. The practical problem for management advice is of course the lack of estimates of stock size and F from an analytical assessment for this stock. The link between change in weight-at-age and carrying capacity (i.e. equilibrium abundance) is unclear due to the lack of data on variation in stock size. Changes in weight-at-age do not necessarily imply corresponding changes in carrying capacity, but it would seem reasonable to assume a positive correlation between the two parameters. If carrying capacity were to change along with weight-at-age, it would clearly not be practical or rational to attempt to maintain a certain spawning biomass level. This would mean that biomass reference points would have to vary with growth rate in order to set a limit where a fishery should be restricted to allow sufficient recruitment. Moreover, ratio reference points such as $F_{0.1}$ and $F_{35\%SPR}$ (for annual maxSPR) would be attractive for this herring stock. Further, following the reasoning of Clark (1991), the herring stock in subdivision 30 would be a candidate for a biomass-based harvesting strategy. That stock has exhibited only small changes in abundance (ICES 2001) and growth rate, and consequently there is no indication that the carrying capacity has changed markedly.

Reference points are operationalized to catch quotas in Baltic herring fishery. Errors in growth and maturity schedule estimates contribute additional uncertainty to the estimated TAC values. The unpredictable growth rate has a major impact on the prediction of future spawning capacity. Growth changes have had a negative effect on the ability to assess herring and to provide advice. A usual practice is that the mean weight at age used for projections is based on the last year or some average of few last years. In the situation of a decreasing trend in the growth rate, this leads to an overly optimistic biomass prediction for a given TAC, i.e. fishing mortality will be higher than expected. In addition, if one assumes that the maturity at age is independent of weight at age (as in the Central basin stock assessment, ICES 1999), it is obvious that the biomass and catch projections are too optimistic.

4.5 Impact of ecosystem change on $F_{0.1}$ (V)

The estimated $F_{0.1}$ for herring in subdivision 30 was stable over the observed range in weight-at-age at about F = 0.3 (V; Fig. 4a). The stability of the calculation of $F_{0.1}$ for subdivision 30 was as expected, because there was no marked change in growth, and M was assumed constant. The variability in yield-per-recruit in the same subdivision was higher, ranging from 10 to 15 g per recruit, implying a larger fluctuation in potential landings than in the reference harvest rate.

Estimates of $F_{0.1}$ for subdivision 32 herring, which experienced the largest variation in growth, were also stable (V; Fig. 5a), except for two years (1982 and 1983), when a higher M (derived from MSVPA) was used in the calculations. The increase in calculated $F_{0.1}$ connected with decreasing growth implies that, under a slow growth regime (and with assumed M), the stock should be fished harder owing to the trade-off against natural mortality. The difference between the highest and the lowest yield-per-recruit was 50%, and proportional to the change in the mean weight-at-age used in the model.

$F_{0.1}$ was relatively stable over a range in growth, even for a dynamic stock such as herring in subdivision 32, implying a nearly constant exploitation rate. Consequently, if the fishery is to be managed according to an $F_{0.1}$ strategy, the quota would vary mainly as a function of stock biomass.

Consideration of the stock-recruitment relationship can result in very different conclusions about sustainable F than when yield per recruit alone is considered (Winters and Wheeler, 1987; Sinclair, 1997). This is because reference points from yield per recruit analyses ($F_{0.1}$, F_{max}) do not take into account whether sufficient spawning stock biomass is conserved to maintain recruitment in the future. F_{msy} is very dependent on the shape of the assumed stock-recruitment relationship (Ulrich and Marchal 2002). Maguire and Mace (1993) observed that a biomass reference point associated with a stock-recruitment constraint (F_{med}) resulted in a lower F than a reference point without that constraint (F_{max}) in 50% of the stocks considered by. Consequently, it is reasonable to assume that in any given application, it cannot be known whether $F_{0.1}$ will be greater or less than a sustainable or optimal long-term F. Not surprisingly, the stock-recruitment relationship is recognized as one of the central problems in the population dynamics of most exploited species (Beverton 1998, Fréon and Misund 1999).

However, Clark (1991) argued that it would be possible to calculate an exploitation rate from life history parameters that would provide a large fraction of maximum sustainable yield (MSY) for any likely stock-recruit relationship. He also found that $F_{0.1}$ gives a good approximation of that rate. There were two exceptions from this rule, linked to changes in partial recruitment and maturation schedules.

4.6 Impact of herring stock structure on assessment and management (V)

Observations from the Finnish fishery confirm and extend the unusually large temporal growth variation in Baltic herring noted by others, and demonstrate that there is also substantial spatial variation in growth. Consideration of growth over the full study period confirms that the recent change is part of a fluctuation over three decades (V).

Temporal variation in herring growth undoubtedly reflects temporal biotic and abiotic changes in the Baltic ecosystem. Spatial variation in growth suggests spatial differences in Baltic ecosystem but also spatial complexity in herring stock structure. Growth rate in the Bothnian Sea (subdivision 30) is very different from growth in the Gulf of Finland (subdivision 32). Growth in the Archipelago Sea (subdivision 29) is intermediate between the two. Very little can be concluded about stock structure by using growth as a discriminating attribute. Subdivision 29 could be a mixing area for herring from subdivision 30 and subdivision 32, a gradual cline, an individual stock component displaying intermediate growth pattern because of intermediate hydrography, or any combination of these alternatives. Under any scenario there are apparently persistent groups of herring on time and space scales that are of relevance to the assessment and management. These may be separate populations (i.e., reproductively isolated) or isolated groups of the same stock (i.e., genetic composition is same but fish are isolated in their life history) (Stephenson et al. 2001) and the isolation between groups is strong enough to cause area time interaction in growth.

Herring in general, may have a more complex stock structure than is recognized in stock assessment and management (Stephenson et al. 2001, Stephenson 2002, Smedbol and Stephenson 2001). This may well be the case in the northern Baltic, where previous authors have hypothesized that a high degree of herring home to spawning grounds widely distributed along the coast and archipelago of Finland and neighboring countries (Rajasilta et al. 1986). Complex stock structure could certainly account for the differences in growth noted here. Alternatively, herring of a single stock could demonstrate growth differences if isolation between groups was persistent, and these groups experienced different conditions.

In either case, there seems to be a compelling case to consider assessment and management on the spatial scale of sub-division. This should not only reduce the variability found in differences in growth and biological characteristics but also allow the assessment and management of stock components which are important aspect in stock structure and within-species diversity. Herring spawning groups can be lost due to fishing resulting in a reduction in spatial or temporal extent of spawning (Smedbol and Stephenson 2001). Such a reduction amounts to a reduction in within-species diversity and therefore is inconsistent with Convention on biodiversity (United Nations 1992) and the precautionary approach.

Baltic herring stocks were assessed in eight units prior to 1990 (ICES 1990). The major argument for merging the assessment units in 1990 into the present four units was that herring from different spawning areas mix during summer and autumn in the open sea. Acoustic surveys for tuning data are carried out in September-November during the period of maximal mixing of herring stocks. It was considered appropriate to enlarge the assessment unit (the present Central Baltic assessment unit) to the whole area within which these migrations take place (ICES 1990). ICES is in a process of evaluating appropriate assessment structure for the herring in the Baltic (ICES 2001b), but the assessment units have remained the same since

1990 due to a lack of sufficient information to justify an alternate assessment structure that accounts for stock complexity. ACFM (2001) has pointed out that migrations and dynamics between stock components contribute to the large variability in growth estimates increasing the uncertainty in the prognoses and making it more problematic to set TACs that meet desired objectives.

The spatial variation in growth implies an underlying stock structure as has already been discussed. However, stock complexity is not a problem if the components are fished at exploitation levels which reflect the productivity and relative abundance of components. If there are differences in the productivity of stocks mixing in the fishing grounds, then the less productive stock will decline under the same fishing pressure (National Research Council 1996). Fishing may for some reason be targeted disproportionally and the targeted sub-component may be overfished causing the overall stock to decline (Smedbol and Stephenson 2001). Respectively, applying some average exploitation rate might result in lost harvesting opportunities for the more productive component. Disaggregation of management is difficult and potentially inefficient in practice if the fishery takes place primarily on mixed stocks. Unfortunately, this distinction can not presently be made for the studied northern Baltic Sea herring stocks.

Splitting or pooling of the assessment and management units apparently has pros and cons that need to be considered. Is it better to have a small (subdivision level) units that are capable of giving only crude statements of the stock status due to lack of adequate data and techniques, but be still managing small units? Or is better to have a large unit with reduced assessment uncertainty and inevitably involved reduction of spatial resolution for management considerations, implicitly hoping that advice gets right by averaging of errors?

5. Where are we and where should we go?

5.1 Evaluation of performance of current assessment and management scheme

Legislation by European Union (Council Regulation 2002) and Finland (Fishing Act 1982) with national statutes provide the benchmark for descriptive analysis of success for the assessment and management of the Baltic Sea herring fishery. The National Fishing Act implies pursuing maximum sustainable yield (MSY) while the Union addresses long-term viability of the fisheries sector through requiring sustainable exploitation based on the precautionary approach. The influence of national legislation on management of marine fisheries in Finland is currently minor while the EU regulations possess the lead normative role.

Lack of explicit management targets hamper developing quantitative evaluation criteria but a few deductions are obtainable by qualitative analysis (Table 5) of recent assessment and management deliverables (International Baltic Sea Fishery Commission 2003, 2004). It should be noticed that ICES responds to the request by IBSFC, i.e. scientific advice will not be provided unless asked for. Clearly, aspects required by the fisheries legislation (Fishing Act 1982, Council Regulation 2002) are incompletely considered currently. Estimates of the MSY are not provided by ICES for any assessed herring stock while precautionary aspects are considered to variable extent. Biological reference points are provided by ICES, but are not computed for subdivision 32 herring stock as explained in section 2.2. An ecosystem approach is lacking, probably because herring fishery is not believed to pose a threat to the marine ecosystem, with an exception that IBSFC requests that assessments should take into account biological interactions between species. ICES does not consider economic and social aspects of the Baltic herring fishery at all. On the other hand, there has been significant divergence between the catch corresponding to the advice by ICES and the realized TACs

(Fig. 3). It seems reasonable to assume that this difference is a consequence of economic and social considerations at IBSFC induced by lobbying by fishermen' associations and by negotiations carried out among national management agencies and the EU delegation.

Table 5. An evaluation of current assessment and management considerations in three spatial units by IBSFC and ICES with respect to legislative framework for fishery. Note that the Gulf of Finland is a component of an aggregated assessment and management area (Central Basin).

	Area		
Objective	Subdivisions 22-29 (Central Basin)	Subdivision 32 (Gulf of Finland)	Subdivision 30 (Bothnian Sea)
Maximum sustainable yield	Not considered	Not considered	Not considered
Aspect of precautionary approach			
Fish biology	Considered	Not considered	Considered
Ecosystem	Exiguously considered	Not considered	Not considered
Economic	Not explicitly and transparently considered	Not explicitly and transparently considered	Not explicitly and transparently considered
Social	Not explicitly and transparently considered	Not explicitly and transparently considered	Not explicitly and transparently considered

The key tasks of an assessment include an estimate of historical stock abundance and prediction of stock trend with different harvest scenarios. Assessments have been uncertain concerning both the Central Basin and the Bothnian Sea herring stocks (Fig. 4) but the variability of the estimates is not uncommon globally. Herring stock size is nowadays estimated to be just one third in the Central Basin of what it was 30 years ago (Fig. 4) and landings have decreased by 50% compared to the maximum values (Fig. 3).

In the Gulf of Finland, an extension of the Central Basin assessment and management unit, international landings have collapsed in 2003 and 2004 (Fig. 14) and the Finnish and Estonian fleets have practically abandoned the area (T. Raid, pers. comm.). The quota was reached by the Finnish fleet in the Central Basin management area (Gulf of Finland being a part of that) in 2001 and 2002 (Ministry of Forestry and Agriculture, unpublished statistics). However, in 2003 and 2004, when landings collapsed, quotas were reached only up to 51% and 67%, respectively. CPUE of market size herring in the Gulf of Finland has been very low even without this mesh size limit (I). The combination of new mesh size regulations (Ministry of Forestry and Agriculture 2003; 2004), setting more strict restrictions to fishing with smaller than 32 mm trawl mesh size, and small size structure of herring stock caused by extremely slow growth rate may well have been damaging to fishery. The possibility of assessment and management failure cannot be excluded as an explanation for these events.

The significance that subdivisions 29 and 32 had for the Finnish herring fishery had already started to diminish in the turn of the decade 1980-90 (Fig. 2) when a fraction of the fleet moved to subdivision 30 (I). The majority of the available resource and fleet have thus concentrated to the Bothnian Sea which has gained significant importance for the Finnish commercial fishery. There has been a slight downward trend in landings in subdivision 30 during the last decade (Fig. 2). TACs have been restrictive in the management unit 3 only in the early 2000s but stock abundance in the Bothnian Sea seems to be stable (Fig. 8). Currently, the fishery is viable in MU3 but it is not clear to what extent management can be credited for this, since quotas have not been restrictive until 2001. Strong year classes in the late 1990s and after the turn of the century (ICES 2004) have been highly beneficial for the stock and fishery. Sustainability is a rough index of management success and it does not necessarily imply that resource utilization is optimal from either ecological or economic points of view (Feeny et al. 1990).

It is crucial to understand the risks that face fisheries systems and to develop a means to deal with those risks and the underlying uncertainties that produce them (Charles 2001a). Perhaps, however the risk of Baltic herring stock collapse has gained disproportionate importance in management advice.

Current reference points (limit BPR) defined by ICES are calculated to prevent stock collapse and to encourage maintenance of a stock capable of high yield. If stock collapse is defined as a fast process within less than 5 years of overexploitation, then the conclusion should be that Baltic herring stocks have not collapsed despite decades of commercial exploitation and quotas that have not been restrictive. This is true despite a 30 year period of monotonic decline of the Central Basin stocks (Fig. 5) and recent downfall of landings in the Gulf of Finland (Fig. 14). I suggest that Baltic herring stocks are not capable of collapsing in similar fashion to stocks in Atlantic and the North Sea, and decline of Baltic stocks would be better described as fading out. There are distinctions in life history parameters between Atlantic and Baltic stocks and in fishery. Spawning in northern Baltic herring is spread out along an articulated coastline and archipelago (Rajasilta et al. 1993, Kääriä et al. 1997) contrasted with Atlantic herring which aggregates to spatially very limited spawning grounds (Stephenson et al. 2001). In the northern Baltic Sea, herring spawn on relatively shallow rocky or stony bottoms along the whole coast making effective trawling on spawning grounds impossible (Parmanne 1989; 1998). Also, the recruitment of young ages into the fishery is significantly lower in the Baltic Sea (Parmanne 1998) and the age of first maturity is 2-3 in the Baltic (ICES 2001) whereas it is older (commonly 3-9) in the Atlantic (Hay et al. 2001; Table 1). Besides biological factors, the risk of stock collapse is minor due to low market price of herring which will not encourage increase of effort at very low stock sizes and concomitant low CPUEs.

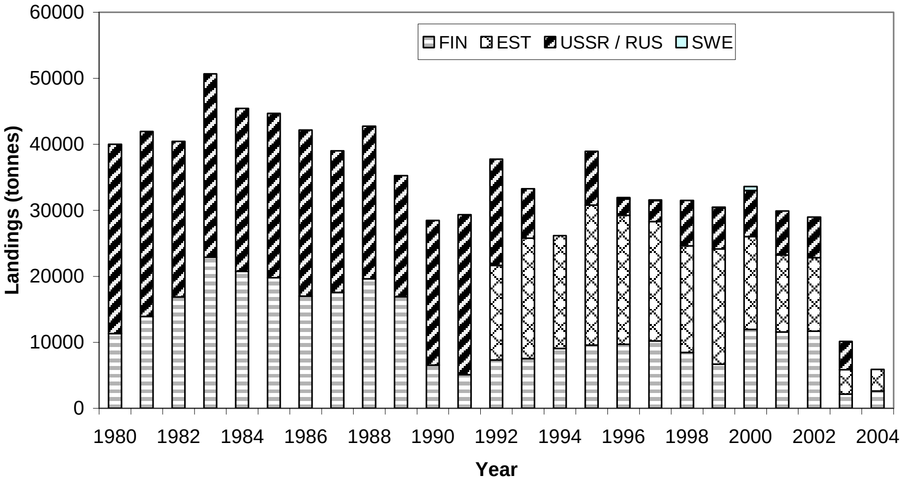

Figure 14. Landings by country in subdivision 32 in 1980-2004. Landings data in 2004 are preliminary for Finland and Estonia, and not available for Russia.

The relevance and validity of the current baseline for assessment and management strategies and biological reference points is challenged by the decline in the fishery and stock in some areas in the Baltic, limited scope of management goals, and mismatch in the geographical assessment and management units. Biological reference points, by definition, are useless unless they can be compared with stock status. $F_{0.1}$ and $F_{35\%SPR}$ are of limited use if the actual F is unknown. Moreover, biomass reference points have to be operationalized (to landing quotas, for example), which is not possible without an estimate of stock biomass for the Gulf of Finland herring stock.

Taking a prudent approach by the resource users would be compelling in the Finnish fishery. In the past, there have been three main areas for herring fisheries: Archipelago Sea, Gulf of Finland, and Bothnian Sea. Nowadays, only the last one provides a viable fishery. Therefore, if this stock should decline there would be no substitutive stock to maintain the national fishery. The importance of successful management of the Bothnian Sea herring stock is thus imperative.

5.2 Where to go?

Linking assessment and management by decision analysis

Uncertainty can lead to "paralysis by analysis" which often takes the form of increased sampling effort, inertia in biological advice, or reduced activity in improving the management strategy. Despite the problems in the Baltic herring assessment there are some recent improvements in the sampling strategy. The change from random sampling for age structure to using length based stratified random sampling and age-length keys, promoted by the International Baltic Sea Sampling Program in 1998, seems to have improved estimates of catch-at-age. This is indicated by an easier tracking of the passage of cohorts over time, although an analytical appreciation of the benefits is unavailable. Sources of uncertainty incorporated in fish stock assessment includes errors in data due to sampling variability and systematically biased fisheries statistics (discarding, unaccounted mortality, ageing difficulties), errors in model specification (changes in catchability), and variability and nonstationarity (temporal profile of M) of stock dynamics. Analyzing such influences on the estimates of stock should be a major task in the near future. Obviously, perfect estimates of stock and fishery are beyond reach but such an analysis would result in more comprehensive understanding about uncertainty.

Assessment methods and harvest strategies should be evaluated together because harvest strategies can affect stock assessments and the uncertainty inherent in stock assessments should be reflected in harvest strategies to determine their ability to attain management goals (National Research Council 1998). Clearly, defining management targets for the Baltic Sea herring fishery and combining these goals with probability of achieving them would seem to be a beneficial approach. Simulation methods provide a flexible framework for this type of exercise to overcome the influence of major uncertainty in stock assessment. Open-minded fishery scientists may be able to identify robust management measures that can at least both prevent overfishing and take into account multiple goals and find satisfactory even if not optimal strategies and solutions. An early example of robust and nearly optimal strategy relies on the conclusion that the 20% threshold of virgin biomass could be expected to protect stock against collapse (Thompson 1993; Francis 1993) and, moreover, provide yields at least 75% of the MSY (Clark 1991).

Fisheries management agencies need to design management strategies that sustain harvests and fishing communities without compromising fish stocks. Relying on the best point estimates in management advice and decision, as the current practice is regarding Baltic herring, implies ignoring uncertainty. Undoubtedly PA actions are implemented in the form of developing precautionary reference points, but the implications of uncertainties for decisions or their possible outcomes have not been considered explicitly and quantitatively. Fisheries scientist or managers should however, not arbitrarily adjust their advice or harvesting strategies to account for uncertainty, but rather should quantitatively derive the optimal uncertainty adjustment (by long term simulations beyond medium term) for each situation (Frederick and Peterman 1995). Decisions, based on comprehensive analyses that quantitatively consider uncertainties will, in the long term, produce better results than decisions made using an *ad hoc* approach (von Winterfeldt and Edwards 1986). At this point, decision analysis has marked merits for fisheries management. In decision analysis, several hypothesized values of the parameters or states of nature are used, rather than point estimates, to simulate outcomes of several management options and consider them with management objectives (Clemen 1996). To reflect risk preferences, decision makers may convert objective outcomes (e.g. yield) to their subjective equivalent (utilities), using a utility function (Clemen 1996). Utilities should be derived from management objectives but, as stated earlier, these objectives are poorly defined in Finland. However, they are vital because the optimal decision rule depends on the objective (Robb and Peterman 1998). A beneficial approach is to seek management strategy which is as robust as possible to possible errors in models, data, and implementation (Butterworth and Punt 2003). Robustness means that the anticipated performance should not change appreciably over the range of uncertainties.

Field data can be used in conjunction with Bayesian statistical analysis to calculate probabilities associated with different estimates of the uncertain parameters. These probabilities can then be used as part of a decision analysis to identify the optimal management action for each specified management objective (Peterman et al. 2001). It is worth explicitly considering uncertainties in analysis of fisheries management options because they can potentially alter the optimal decision.

Alternative model structures

Uncertainties in assessing a fishery can be divided into two fundamentally different groups: the objective uncertainty arising from variability of the underlying stochastic system, and the subjective uncertainty resulting from not having complete information of the system (Casti 1990). Variability and ignorance should be treated with separate calculation methods: probability theory should be used to propagate variability, and interval analysis should be used to propagate ignorance (Ferson and Ginzburg 1996). Recent developments in the theory of bounds on probabilities permit an analysis of variability and ignorance at the same time (Ferson and Ginzburg 1996) but their ideas have apparently not tested for fisheries applications so far. Importantly, ignorance and variability respond differently to empirical effort. Ignorance can often be reduced by additional study whereas additional effort may yield a better estimate of the magnitude of variability, but it will not tend to reduce it.

The fundamental problem in assessing uncertainty is that the true uncertainty will be underestimated when only one approach is used. Every model has its pros and cons and there is a need for an approach that transparently represents both what the modeler knows and what is unknown or uncertain. A number of structurally different models may be compared and it would require us to choose between models and sometimes data. Noncoincident but parallel trends of the estimated quantities may be acceptable for stock assessment purposes because the estimated trend is unbiased despite the error in estimation of absolute abundance. Even though actual stock parameters were unknown, it would be useful to be able to detect relative change of abundance in time. Nonparallel and noncoincident trends are a problem because neither the stock abundance nor the way it is changing over time is known.

The model-based abundance estimates are not independent from one year to the next as an underlying population model generates them. This complicates comparisons as it requires incorporation of autocorrelation in the estimation procedure but this can be carried out by e.g. general linear mixed models (Mikkonen et al., unpublished manuscript).

When using models, there are two aspects in quality management; a model interpretation and a model evaluation perspective (Brugnach et al. 2003). To be useful, a model interpretation perspective should provide researchers and managers with information about the quality and limits of model prediction by focusing on the significance of uncertainty in models. The key in any aspect of model evaluation is the identification of flaws in model logic and the determination of what type of improvements may be needed in a model. Using mathematically sophisticated models do not mitigate poor data quality (National Research Council 1998).

Some new models introducing process errors may better compensate for changes in selectivity and catchability over time. Process errors refer to variability in the population dynamics that can not be adequately described by deterministic population models, but can be modeled as random processes. Change in catchability over time is an apparent problem in the subdivision 30 herring stock assessment (II). For instance, the catch at age method known as Stock Synthesis (Methot 2000) is a statistical model which attempts to reconstruct the demographic history of a stock from observed changes in fish age or size distributions, coupled with auxiliary information such as an index of stock biomass developed from a research survey or an index of fishing mortality based on fishing effort. The stock synthesis model use all available data in one integrated assessment, simultaneously considering the issues of yield per recruit, stock-recruitment, catch-at-age data, indices of abundance, and expected consequences of alternative harvesting strategies (Methot 1989). Punt and Hilborn (1997) describe a general form of this type of integrated assessment and policy evaluation in a Bayesian context.

Artificial neural networks (Rummelhart et al. 1986) have been tested in forecasting recruitment, stock abundance, and yield. These models have proven to have strong short-term forecasting ability (Chen and Ware 1999, Laë et al. 1999, Huse and Ottersen 2003). A methodology using genetic algorithms has been proposed to evaluate the significance of threshold values uncertainty in rule-based classification models (Brugnach et al. 2003). The algorithms use uncertainties as a source of information to determine the scope of model inference, identifying those instances in which the predictions are reliable and those in which they are not. This approach might be useful in the context of setting and interpreting biological reference points.

It would be very unrealistic to seek for a ”super model” capable of embracing all sources of uncertainty and producing unbiased estimates and their standard errors. As the complexity of the models increases, the resultant output also becomes more complex and difficult to interpret. The challenge is that understanding model output is not limited to interpreting complex dynamics, but analysts must also cope with possible model error and uncertainty. At this stage, complex multi-species models are perhaps best used in exploratory research, rather than as operational tools for selecting management measures (Stefansson 2003).

In recent years, Bayesian statistical methods have been increasingly combined with conventional methods for stock assessment (McAllister and Kirkwood 1998, Meyer and Millar 1999a; 1999b, Millar and Meyer 2000) The Bayesian hierarchical meta-models (Hilborn and Liermann 1998, Michielsens and McAllister 2004) learn from data sets of stocks having similarities in taxonomic or life history trait groupings and can improve knowledge (both structural and parametric) of stock status and potential outcomes of policy options. This is likely an area where ICES methodology would gain most from Bayesian methodology without changing overall methodology. A Bayesian net methodology has been developed for decision and risk analysis to cope with the concept of structural uncertainty (Jensen 2002). Such approaches have been applied only recently in fisheries (e.g., Kuikka et al. 1999), and there is a urgent need to link this promising methodology to simulation model outcomes and to data analysis. Method allows the value-of-information analysis (Clemen, 1996), which is an estimate of how much would be gained by better scientific estimates from the point of view of management.

It has been demonstrated that both assessment outputs (Fig. 5) and biological reference points (Figs. 12 and 13) are uncertain because of imperfect knowledge about input data (II,

III) and variations in life history and ecosystem interactions (IV, V). Thus, management advisory statements derived using an approach of comparing deterministic management reference point (e.g. F_{pa}) with deterministic indicator reference point (current F) may yield erroneous conclusions about the status of fish stocks. Obviously a general approach should consider uncertainty in both indicator and management reference points (Chen and Wilson 2002). Composite risk analysis is a method of accounting for the risks resulting from various sources of uncertainty to produce an overall risk assessment for a particular decision making problem (Yen 1986) and would be worthy of further examination for the Baltic herring. By comparing the differences in biological reference points calculated under different uncertainty levels, it can be determined how a reference point responds to changes in a particular life history process (Jiao et al. 2005). This helps identify important parameters and causal relationships through which assumptions about distributional functions contribute to conclusions and aid in focusing research efforts.

Spawning per recruit analysis, and in particular $F_{x\%SPR}$ reference points rely on meta-analysis. The motivation for meta-analysis is to integrate information over several studies and fish stocks to summarize information. This involves compilation of preexisting (large) data sets to evaluate the values of the model parameters or their potential range. Meta-analysis, at its best, provides realistic estimate of uncertainty for assessment outputs by using what is known from other stocks or species. Reasoned applications consider key parameters including natural mortality, catchability, and the form of relationship between abundance indices and actual abundance, which are commonly assumed to be constant and known without error in stock assessments. Natural mortality was the subject of some of the earliest meta-analysis (Pauly 1980), a method which could highly useful for fisheries science today (Hilborn and Liermann 1998).

Considering that natural mortality is roughly estimated, different hypotheses must be tested (Caddy and Mahon 1995). The results are usually sensitive to these hypotheses on natural mortality and therefore the knowledge of this parameter may be a bottleneck in stock assessment (Fréon and Misund 1999). The most problematic cases are where fishing or natural mortality rate changes significantly (Hildén 1988) or natural mortality rate is overestimated and historical exploitation rates are low (Clark 1999). Long-term yield under F_{MSY} or $F_{x\%SPR}$ strategy is not very sensitive to error in natural mortality rate unless it is grossly underestimated (Clark 1999).

Co-management and property rights

Co-management, i.e. meaningful involvement of interested parties in management, has received some attention to overcome problems caused by lack of an appropriate holistic context for the management of commercial fisheries (Stephenson and Lane 1995). Empowerment involves bringing previously excluded user groups and stakeholders into to management decision-making process by reshuffling power and responsibility among those who form the fisheries management chain (Jentoft 2005).

In fisheries, scientists have typically had the responsibility of identifying risks and the focus has been on biological risk, e.g., the falling of stock abundance below some pre-defined threshold level (Francis and Shotton 1997). Relatively little attention has been devoted to translating biological risks into social and economic terms so that they may be understood by the fishing industry and fisheries managers (Lane and Stephenson 1998). The current approach for Baltic fisheries assessments by ICES is merely biological and does not increase the interest of stakeholders to utilize scientific risk estimates.

The product of the value of the objective function and the probability of unfavorable outcome defines risk which thereby includes subjective judgment of good and bad (Clemen

1996). In other words, an interpretation of only probability gives little guidance for management, whereas an interpretation as probability*consequence is more significant. In the fisheries context, the risk associated with stock collapse may have received unnecessary large attention at the expense of risk linked to assessments faults and market externalities, e.g. excessively conservative quotas and price fluctuations. Broad stakeholder involvement through new participatory processes in risk identification could certainly give a better description of risks (Amendola 2001) in the development and critic of fisheries management policies (Lane and Stephenson 1998). In Atlantic Canada the quantity, quality, and availability of information from the herring fishery through co-management led to improved effectiveness of management and care of the resource (Stephenson et al. 1999).

Given the uncertainty pervasive in the fisheries systems, the advantage provided by co-management, as a contribution by the resource users, is a comprehensive consideration of socioeconomic impacts of fisheries regulations, including foregone economic benefits if harvests are lower than necessary (Charles 2001a). In any case, scientific advice is a premise because decisions must be made balancing risks of resource collapse and needlessly restrictive management. The co-managed fishery will enjoy more support because co-managers will tend to feel committed to, and obligated by, the decisions made (Jentoft 2005). If fishers can be assured that co-management policies will protect their fishing opportunities, even more co-operation may be obtained from them in monitoring and enforcement than has been achieved through quota management systems (Walters 2001). The framework will also improve managers' and stakeholders' understanding of consequences of alternative policies and their influence on an array of (often conflicting) objectives and trade-offs between them. In fact, fishery management should draw upon a portfolio of approaches to provide multidimensional solutions for the multidimensional problems faced in the fishery and coastal systems (Charles 2001b). Fishers should not be treated as fixed elements, with no consideration of individual attributes based on their geographical, economic, and social operating scales.

Replacing a currently used management reference point with a more conservative value to offset the impacts of uncertainty may bias the choice of management reference points and cause fisheries stakeholders to distrust fisheries management plans and stock assessment. A better approach would be to place emphasis on risk analysis and choice of risk tolerance (Shelton and Rice 2002). Resource users should play a key role in defining socioeconomic risk tolerance while scientists pursue understanding of biological risk and managers incorporate both viewpoints. A functioning communication between stakeholders, managers and scientists is essential for successful risk management (Peterman 2004). Ludwig et al. (1993) have advised a reliance on scientists to recognize problems, but not to remedy them.

The ultimate cause for a fisheries conflict is seldom a local one, but rather outcome of mismatch in the local (resource users) and global (laws, management targets) objectives. Although moving toward decentralization, with the government and the fishing industry co-managing the fisheries, should have several advantages (Sutinen and Soboil 2003), decentralization of management of herring fishery in the Baltic Sea would be complicated due to multinational jurisdiction over management units (I) and certainly can not be accomplished without highly convincing evidence of its superiority over the current control system.

A successful management schedule usually involves a positive incentive for conservation that is created by individual property rights. As a result, the industry has a long-term perspective and is committed to the conservation objectives (Bodal 2003). There is consensus that rights-based fisheries management regimes are a pre-requisite for good fisheries governance, and contribute greatly to responsible fisheries in the marine environment by conserving fish stocks, by reducing fishing effort and by generating more resource rent than any other method of fisheries management (Sutinen and Soboil 2003). Property rights-based systems are most often operationalized in the form of individual fishing quotas. Such an approach seems reasonable for the Finnish herring fishery because co-management by itself does not safeguard against the tragedy of commons (Hardin 1968). In general, management of common property resources shares two key characteristics (problems); the exclusion (or control to access) of potential users, and subtractability which generates a problem because each user is capable of subtracting from the welfare of others (Berkes 1995). These two problems often create a divergence between individual and collective economic rationality (Berkes 1995).

Adaptive management

Modeling ecological linkages points out how they influence the outcome and the information content of the SPR analysis (IV). This addresses areas requiring further research and encourages formulation of explicit hypothesis regarding relevant biotic and abiotic ecosystem processes. In a scale of long term ecosystem variability, fisheries data for northern Baltic herring are available only for a limited temporal range to quantify the population's response to environmental factors, although the range in growth rate and natural mortality rate have been large. As a result, part of the relevant input variable combinations are likely to be absent in the data. The lack of historical perspective means that the knowledge of natural variability of fish population parameters is uncertain. In this situation, it could be worthwhile evaluating profits and costs of an adaptive management strategy applied to recognize how the partially observed complex system functions and to identify the processes controlling herring stock dynamics. The basic concept of adaptive management is to "learn about the potentials of natural populations to sustain harvesting mainly through experience with management itself, rather than through basic research or the development of general ecological theory" (Walters 1986). Importantly, adaptive management is not restricted to biological learning but the framework includes social and institutional learning from feedbacks from environment and human interventions (Berkes and Folke 1998). Adaptive management in essence includes both (1) linking science with management, and (2) implementing management itself as an experiment (Halbert 1993). In this way management designs become explicit experiments to manipulate systems into regimes of behavior that are most conducive to learning (Walters 1986).

The experimental nature of adaptive management requires that managers and politicians redefine success so that learning from error becomes an acceptable part of the learning process. Successful implementation of adaptive management requires management to take risk-prone actions while providing institutional patience and stability (Halbert 1993). It seems reasonable to assume that adaptive management will be a realistic approach in co-managed fisheries systems only because support of all stakeholders is crucial for implementation of the non-traditional management scenarios. Due to the experimental nature of adaptive management, the time frame of collecting and analyzing information exceed short term policy changes (Williams 1999). Consequently, possible attempts of implementing adaptive management in the Baltic herring case necessitates that efforts must move beyond a trial and error approach.

It is not clear whether adaptive management is consistent with a precautionary approach. PA probably does not allow aggressive harvest policy and fish stocks pushed to limits of where learning about compensatory processes would be most effective, i.e. to low abundance. The large natural fluctuations in the Baltic Sea ecosystem already provide considerable contrast in data sets, and are beneficial for establishing linkages between abiotic factors, fish stock dynamics, and resilience. Still, many of the basic biological process are not understood properly. This raises the concern that adaptive management may not have potential to provide auxiliary information. The advantage of adaptive management is experimentation, since the use of controls and replicates is fundamental to any scientific research that seeks to recognize causal relationships. Experimentation is, however, limited by certain space and time scales, and becomes impossible at some scale (Halbert 1993). Ecosystem level processes in the Baltic Sea are an example of such a case. In addition, a paradigm change in management would inevitably be difficult to achieve due to the multinational jurisdiction over regulation and management of the Baltic Sea herring fishery. At this point, modeling is a better choice as a decision analysis tool, which permits use of biological, economic, social, and administrative information in comparing large scale and long-term management options.

Contamination of the Baltic Sea and fishes with dioxins provides an example of the need for multi-dimensional objectives in management and a potential case for an adaptive management trial. While seafood in general has a good reputation as a healthy diet item, there are growing concerns about Baltic herring and salmon quality and safety due to high levels of dioxins. According to the EU regulation (Council Regulation no. 2375, 2001) the maximum permitted amount of dioxins in fish and fishing products is 4 pg/g WHO $_{\mathrm{PCDD/DF}}$ –TEQ in fresh weight. The Finnish Baltic herring exceed this level by as much as four times in some areas, with concentrations for large fish in the Gulf of Bothnia and the Archipelago Sea as high as 17.7 pg/g (http://www.elintarvikevirasto.fi/english/p2152.xls).

Marine pollutants unavoidably affect fisheries in the Baltic Sea and inevitably should be considered in management strategy. Spatial differences in dioxin levels in herring are conceivably caused by differences in the growth rate (ICES 2003). The Working Group for Baltic Sea Fisheries Assessment (ICES 2003) has suggested that eliminating old ages from the population and removing the density dependent effect on growth by decreasing the total number of population would decrease the herring dioxin content to an allowable level in ICES subdivision 30. These objectives may be incompatible with the precautionary approach and current biological reference points: reducing dioxin residue levels would require high fishing mortality rate to reshape herring stock age structure. In addition, spawning stock biomass would decline and potentially reduce recruitment and long term yields.

An alternative approach to decrease dioxin levels in consumed herring is processing and putting on the market smaller fish than presently in Finland. Dioxins accumulate in older fish and, therefore, older herring carry the greatest amounts relative to body weight. Herring that have grown to more than 17 cm are already over the limit. Smaller fish, meanwhile, remain acceptable (Kiviranta et al. 2003). The human consumption market prefers herring greater than 36 g (I) corresponding to about 18 cm in total length. Safe dioxin levels are thus exceeded in herring placed on the human market in Finland. Obviously, consumer preferences, feasibility to adjust fish cutting machinery for smaller herring, and fisheries sector attitudes would play a key role in adopting this alternative.

Besides the domestic human consumption market, there is also an equally important export market to Russia and Estonia (I). This market prefers herring smaller than 32 g as fish are canned. Also exported herring are over the limit as 32 g corresponds to 17-18 cm in length. However, EU regulations do not prohibit export of contaminated herring to outside the European Union.

The case of dioxin points out the essence of the multi-dimensional objective of Finnish herring fishery management. The objectives involve aspects linked to herring biology, environmental pollutants and food safety, economics, and ecosystem interactions. Clearly, there is need for a simulation exercise considering chances to meet multiple criteria which have been set as biological reference points, as age structure of the population and catch, dioxin residue levels in landed herring, catch rate, and investments of the processing industry.

The productivity of ecosystems is affected by environmental changes, and management measures must be responsive to these changes. Ideally, the effect on productivity caused by these environmental changes would be captured by periodic adjustments to the performance indicator reference points. Understanding of marine ecosystem structure and functioning is however, imperfect (Gavaris et al. 2005). At the international level, during 1990s there was a major change in the international obligations for the management of fisheries. The conservation objectives were to include ecosystem features in addition to protection of the target species (Sinclair et al. 2002). For instance, fishing of forage species is prohibited or restricted to protect seabirds or marine mammals (Butterworth and Punt 2003). The FAO's Code of Conduct for Responsible Fisheries calls for the use of precautionary reference points in achieving the broader conservation objectives.

The challenge is to move from the present fisheries management framework to ecosystem-based management. The key is how ecosystem considerations can be better incorporated in management of human activities. The range of problems identified by Sinclair et al. (2002) is overcapacity, overfishing, detrimental impacts of fishing on the ecosystem and the detrimental impacts of contaminants on fisheries ecosystems, which do seem to require fundamental changes in fisheries management regimes.

Socioeconomic aspects

The original articles of this thesis involve mostly biological investigations and also the considered reference points are linked to biological overfishing. However, socioeconomic aspects should have a major role in research and management because fishery is about the behavior of fish and fisherman and management is about the formulation and analysis of fisheries options under uncertainty. Insights of economic overfishing are bound to offer relevant issues for research and management considerations. The current scientific advice by ICES reflects merely biological considerations with respect to Baltic herring. It is important to note that managers have asked for no other type of information. The effective participation of managers, fishers, industry, and scientists is required to define optimality but excluding socioeconomic dimensions is the norm globally.

From previous research (Salmi and Salmi 1998) it is known that herring fishers are a highly diverse group. While resource users essentially are very heterogenous with respect to fishing strategy, effort and landings, areas of operations, scale of investment, and so on, also management decisions have a heterogenous impact. Therefore, fair and transparent management should require the identification of groups of fishers who are affected by management decisions, including identification of the impact mechanisms and expected cumulative effects. Reconciling interest conflicts among all parties is likely to gain in importance as quotas have become restrictive in the Finnish herring fishery. Understanding the views held by the stakeholders and considering them transparently in the management process increases the odds for the fair and acceptable management decisions. Ensuring quality assurance also of the scientific advice (e.g. through Regional Advisory Process as in Atlantic Canada (www.mar.dfo-mpo.gc.ca/science/rap/internet/index.htm,www.dfo-mpo.gc.ca/CSAS/) - including industry participation, involvement of external scientists and periodic framework reviews of the methodology - is pivotal.

Managers should not use researchers' explicit quantitative descriptions of ecological uncertainties as a reason to put less weight on socioeconomic concerns. This is because uncertainties also exist in economic and sociological components, and a quantitative statement of ecological uncertainties should not imply that ecological uncertainties are any greater than uncertainties in these other components of the fishery, which may simply be more difficult to quantify (Peterman et al. 2001).

The volume of landings should not probably be set as the major management target. There is a trade-off between maximizing mean catch and minimizing the standard deviation of catch

(Hilborn and Walters 1992). Variability in annual landings is generally considered undesirable compared to maintaining the average yield at a constant level because variable landings create uncertainty in fishing communities and lead to the inefficient and intermittent use of capital by fishers. Adopting precautionary approach is bound to result in suboptimal yields in the presence of uncertainty (Stefansson 2003). The framework should thus include the definition of indicators and reference points that relate to biological and socioeconomic objectives. The amount or fraction of young herring discarded underwater (III) is an indicator of biological waste and a justified performance measure of the fishery. Also, it could be used as an explicitly defined target reference point. Whatever the explicit objectives are they should be both realistic and ambitious. It is critical for the success of such an application that the overall adherence to the reference points be assessed on a routine basis (Sinclair et al. 2002).

It is advisable to predict how well different management approaches work. A tool – "harvest control law" - to conduct such evaluations has been successfully applied in many fisheries (Butterworth and Punt 2003). The key feature of this approach is the overall modelling of the bioeconomic conditions, followed by testing of the management alternatives with the help of simulations incorporating the various sources of uncertainty in order to set appropriate management measures. Difficulties in this approach are explicit characterization of uncertainty and complex ecological causal relationships. Also market externalities (I) are hard to model correctly in Finnish herring fishery.

6. Synthesis

The original articles have contributed to the assessment of the northern Baltic Sea herring stocks by identifying interaction among market factors, catch per unit effort and spatial movements of the fleet on a subdivision scale – a self-regulatory mechanism which results in a release of effort from declining stock components (I). This conservative mechanism promotes ecological sustainability and within-species diversity although the underlying stock structure of herring is unknown and management units are larger than boundaries of anticipated stock components (V). The highly variable growth rate, maturation schedule, and natural mortality rate of the northern Baltic herring profoundly confounds the $F_{x\%SPR}$ approach because the available definitions of maximum spawning per recruit are arbitrary and artificial (IV, V). This area is worthy of further research effort since current biological advice is based on reference points which do not consider the significance of changes in the life history parameters. Quantitative assessments of the Gulf of Bothnia herring stocks are impacted by changes in catchability over time driven by a significant increase in the average trawl size (II). Unaccounted mortality due to low survival of escapees had been identified as a potential assessment pitfall. The implications of unaccounted mortality have now been analyzed and judged to be of minor importance for stock assessment (III). An articulated temporal pattern was observed in the unaccounted mortality implying that the waste of the resource could be mitigated by proper temporal and spatial of fishing effort. Concluding remarks are as follows.

Herring fishery is driven by environmental and market forces

Environmental changes influencing herring growth rate, and market demand for amount and size of fish have been the major driving factors the Finnish herring fishery (I). A large fraction of the total landings have been used as fodder, and total landings have therefore been particularly sensitive to the demand for fodder herring, which is directly linked to changes in the demand of fur industry. Changing environmental conditions and ecosystem structure (which are primarily the impact of the change in salinity and resulting changes in predator and prey abundance) have apparently resulted in a change in the growth rate of herring, and the fishery has been forced to adapt to rapid changes in the proportion and CPUE of herring of suitable size for filleting.

The quick decrease of large herring in some areas was unpredictable. The fleet has basically abandoned the Gulf of Finland and desertion of the fishery infrastructure is in progress in the area. The calculation of any socio-economic valuation must be based on uncertain biological as well as economic variables. These variables change so quickly and unpredictably that it is difficult to target an appropriate sustainable stock and catch level (I, IV, V).

Ecosystem plays tricks on biological advice

Fisheries management is challenged in face of uncertainty of current and future causal relationships in the ecosystem. Clearly, assessment and management must be linked to the broader ecosystem state. If growth degradation is caused by limited access to food items (neritic zooplankton), implementation of the precautionary approach without considering density dependent processes may implicate risking population growth rate, reproduction capacity, and resilience. The essential questions that arise are: i) how much does incorporating causal biological knowledge into the assessment affect the perception of the most relevant ecological hypotheses and ii) how should the basic biological research be focused to support management conclusions.

There is evidently a need for better knowledge about the factors controlling the growth of herring and the interaction between growth, fecundity, and viability of eggs. The processes influencing growth rate are affected by the same environmental factor - the Baltic salinity level - which is linked to Baltic inflow and precipitation (Hänninen 1999). The key question is how predictable these links are in the future.

Multi-dimensional evaluation and management of complete fisheries is a requisite

Faced by major externalities, stock assessment organization should extend beyond defining the biological limits. Economic thresholds cannot be evaluated solely by the scientist - the participation of the industry and fishers is needed to define the relevant signposts. This case study emphasizes the need for development of the context and tools for evaluation and management of complete fisheries systems. Hannesson (2001) gives a review of the role of economic tools in fisheries management.

The future and the success of management of Finnish herring fishery will depend strongly on the ability to develop a comprehensive description of ecological and socioeconomic systems. Therefore, effort to establish a framework for the development of an interdisciplinary approach to environmental issues and to consider the interdependence of multiple aspects of ecological and economic systems are essential.

Vessel register data conceals increased fishing power

It is evident that assumptions about fishing efficiency drive stock assessments for the Gulf of Bothnia herring stocks. A single technical innovation, the increase of sweep mesh size (II), has ratcheted up fishing power quite rapidly, within less than ten years to a substantially higher level. The event can be classified as sudden (stepped) rather than continuous (gradual) development. Interestingly, the increase in fishing power could not be observed from data concerning vessel size or engine power (vessel register data), and auxiliary fishery information was necessary to document the phenomenon. For instance, in the North Sea bottom trawl fisheries fishing power increased with horsepower (Marchal et al. 2002).

Underwater discarding wastes the resource

The impact of unaccounted mortality with respect to other potential biases in the data and faults in the entire assessment methodology is likely to be trivial from age group two (III). Although the impact of unaccounted mortality on the standard stock assessment output is limited, it poses certain problems for the assessment procedure. These concerns are mostly related to estimated recruitment and F at age 1. Ignorance about unaccounted mortality leads to underestimated fishing mortality and overestimated recruitment. Uncertainty in short term forecasts increases as fishing mortality rate increases (III; Fig. 8). Changes in codend mesh size in the trawl fleet, induced by management actions or fishing strategies, should be recognized and their effects considered in stock assessment, in short term forecasts, and in management advice (III).

Alternatives for quota management are inadequately explored

The value of information regarding the bioeconomic effects of management as well as alternative management actions is increasing. Because efforts directed at conserving young fish by improving selectivity are based on the fundamental assumption that the majority of escaping fish recover and survive, there is little evidence supporting the usefulness and justification of minimum mesh size regulations in the Bothnian Sea herring trawl fishery. Therefore, closed seasons and/or areas may provide useful approaches, but currently there is limited knowledge about spatial and temporal distribution of age 0 and 1 herring with respect to fully recruited age groups.

$F_{x\%SPR}$ is a confusing reference point for a dynamic stock

Derivation of maximum spawning per recruit appeared to have the greatest impact on the location of reference point estimates and also the within model variation (IV, V). Estimates of $F_{x\%SPR}$ were also influenced by the model used (assumed causal connections), although results are confounded by the definition and criteria for maxSPR and biological reference point (IV). If unambiguous conceptual definition and precision of a reference point are accepted as criteria of usefulness, $F_{x\%\,SPR}$ does not seem to be a warranted biological reference point for any highly dynamic fish stock.

Unresolved stock structure issue requires precautionary approach

Baltic herring growth rate varies greatly in time and space, and the implications of this for assessment and management are marked (V). Spatial complexity is a problem if the components have differing levels of productivity (National Research Council 1996) or are subject to disproportional fishing mortality (Stephenson et al. 2001).

The assessment problem is that migrations of herring and mixing in the fishing areas could induce spurious trends and severely bias assessment outputs if the catches cannot be allocated accurately to the corresponding unit stocks – which is a basic VPA assumption. Catch at age information are obtained from landing statistics and, consequently, mixing with other stocks in the fishing grounds can violate this basic assumption. Weight-at-age is necessary for calculating catch-at-age from landings data and catch samples, but spatial differences could be overcome through proper matching of samples with catches on a spatial and temporal basis. Therefore, differences in growth need not preclude input of the data to VPA. An analytical assessment for herring in subdivision 32 has not been conducted since 1990, in part because the fish migrate out of the area in winter. Of course, this option could be explored with an assumption of constant rate of emigration, and in the assessment, this could be undertaken by altering M to account for it. A framework should be developed to evaluate conditions when VPA should be aggregated versus disaggregeted over putative stock components. Quinn at al. (1990) have reviewed techniques for estimating the abundance of migratory populations and have proposed a new age-structured model using migration rate among regions.

The management problem is that populations within a large assessment unit could have different dynamics, which are masked under a pooled assessment strategy. Management of mixed stocks requires specific attention to maintenance of population richness, through such considerations as monitoring the subunits, and to maintaining the historical spatial and temporal distribution of spawning (Smedbol and Stephenson 2001). While disaggregating management is difficult, it does seem important given the apparent differences in characteristics of northern Baltic Sea herring stocks.

Improving evaluations of stock and decisions is “the” challenge

Improving accuracy and decreasing uncertainty in stock assessment output are desired objectives. These goals seem to be difficult to achieve (II, III). There are also additional sources of uncertainty which have not been considered in the original articles but are dealt with earlier in this thesis. There is a need for screening of all potential events increasing assessment uncertainty. These events should be recognized and future research efforts should be focused on the most influential ones. Improving the assessment is not parameterizing the best models with the best data but understanding the value of team work and interaction among the experts. A holistic view is a pivotal characteristic of a successful assessment team: the process from sampling design to parameterization of the models and interpretation in the light of ecological and economic implications needs to be covered. There should be a perspective beyond the technical understanding of models, it must be understood what kind of natural phenomenon they are intended to describe and in which parts the models are successful and in which they are not. Understanding of herring stock accumulates slowly with the current research effort in Finland.

Without constant evaluation of the assessment process, quality control through mechanisms such as benchmark assessments, and without honest attempt to improve the precision and accuracy of the work, there is a significant risk of ending up with a system which produces estimates by routines which are more ritualistic than scientific. Schnute and Richards (2001) point out that an elegant mathematical model can be alluring to the analyst, and once operational, the model dictates data requirements. “After following this cycle for several years, the analyst may be increasingly convinced that the output correctly represents reality. Like the mythical sculptor Pygmalion, the creator can fall in love with his creation and become blind to other realities.”

A next step in improving assessment could be incorporating Bayesian methods to include explicit treatment of uncertainty and risk assessment. Bayesian approaches are also justified from the point of view of value of information as those methods provide an explicit way of dealing with the value of information, provided that the focus of the modeling is the management operation and not only the stock dynamics. A Bayesian decision analysis would indicate what kind of information produces the greatest improvements in the management, and more importantly, to what extent the improvement actually would "pay back" taking into account anticipated benefits for the fishery and the possibility to simplify and save on management cost, including sampling and assessment.

Methods should also account for effects of directional changes in environmental variables in the models by bringing ecological and environmental considerations and multi-species interactions into stock assessments. Decision analysis will be required if managers develop multiple objectives for the fishery. Effective policies are possible under uncertainty, but they must take uncertainty into account (Ludwig et al. 1993). The issues which should be considered obviously include variety of plausible hypothesis about ecosystem and herring dynamics, variety of possible management strategies, favor actions that are robust to uncertainties (Kuikka et al. 1999), update assessments and modify policies accordingly.

Improved data and advanced management can be shortcuts across troubled waters

Although assessments are inherently uncertain, they are the best available information and will be used as the basis of biological advice. Stock assessment conclusions are to a great extent driven by the data that are used (Hilborn and Lierman 1998) and, certainly, data collection procedures and assessment models need to be improved in terms of their ability to detect and respond to population declines. Instead of debating which is the correct approach, fishery researchers and managers should identify the critical pieces of knowledge and try to find appropriate data for those. Because there is no single method that can produce "the truth", fisheries scientists have to use clever combinations of different methods that help to limit the uncertainties, and benchmark the approaches. Because assessment models tend to perform better when measurement errors are reduced (Schnute and Richards 1995), improvements to data collection procedures should be a major goal of stock assessment research (Richards and Schnute 2001). Improved data would give better justification for some critical hypothesis, help to choose between hypotheses or assign them with probabilities.

Because stock assessment is and will be fraught with uncertainty caused by data and/or model failures, improving management regime is an interesting alternative. If a single strategy must be chosen, it should be to maintain a high level of biomass because high biomasses provide the best safeguard against overestimates of catch quotas and environmental change (Pauly et al. 2003).

By knowing the biological limits of the system, managers and the stakeholders would be in a better position to make decisions on long term strategies with regards to fleet size, number and capacity of herring processing plants and related factors. Naturally, the biological limits must be contrasted with the economic and market constraints. As there are indicators and reference points for decisions on fishing mortality and stock biomass levels, there should as well be measures for meeting the broader socioeconomic objectives. The range of possible socioeconomic objectives is large. The resultant management structures and measures could be completely different depending on emphasizes of the objectives.

Because net returns to society from fisheries management may have been negative in the past (Clark 1985), the cost-effectiveness of such trials must be considered. Creating incentives for moving to rights-based management scheme could be an option. Under this framework the significance of scientific uncertainty decreases as the burden of proof of maintaining fishery according the precautionary approach should shift to the users of marine resources (Bodal 2003). This would have an effect of shifting responsibility of socioeconomic consequences from central authorities to local level community. Consequently, users should show that their fishing practices conform to the precautionary approach as prerequisite for being allowed to use marine resources. The significance of statistical tests, models, parameters and their variances may well be overrated when conclusions are drawn in fishery science context. Therefore, information held by stakeholders must be utilized (II, III). Co-management could utilize fishers' information more effectively than the present segregated assessment and management framework.

Finnish herring fishery and management are currently in turbulence. For an academic researcher this situation offers attractive questions: will herring growth rate improve in subdivision 32 and, thereby, beckon the fleet back to the area? Can management promote this? Was the collapse of fishery due to environmental perturbations or management actions? After an extended period of low stock size, how large are adjustment costs to the industry along the shores of Gulf of Finland? Can stocks collapse in presence of habitat failures and management ineptitude, in spite of resilient life cycle of the northern Baltic herring?

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List of abbreviations

F	Instantaneous fishing mortality rate
M	Instantaneous natural mortality rate
Z	Instantaneous total mortality rate
SPR	Spawning per recruit is the total spawning biomass from a recruit over its lifespan
YPR	Yield per recruit is the total yield in weight harvested from a recruit or from a set of recruits over their lifespan
MSY	Maximum sustainable yield
MBAL	A value of spawning stock biomass below which the probability of reduced recruitment increases
B_{msy}	The biomass at which maximum sustainable yield is attained.
B_{loss}	The lowest observed spawning stock biomass.
$F_{0.1}$	The instantaneous fishing mortality rate at which the slope of a line tangential to the YPR curve is one-tenth of its slope at the origin.
F_{low}	The instantaneous fishing mortality rate corresponding to a SPR equal to the inverse of the 10th percentile of the observed recruits per spawner.
F_{med}	The instantaneous fishing mortality rate corresponding to a SPR equal to the inverse of the 50th percentile of the observed recruits per spawner.
F_{high}	The instantaneous fishing mortality rate corresponding to a SPR equal to the inverse of the 90th percentile of the observed recruits per spawner.
F_{max}	The instantaneous fishing mortality rate that maximizes yield per recruit.
F_{msy}	The instantaneous fishing mortality rate for maximum sustainable yield.
F_{ext}	The minimum instantaneous fishing mortality rate in a family of self-regenerating yield curves that lead to stock collapse.
$F_{x\%SPR}$	The instantaneous fishing mortality rate that would reduce the spawning stock biomass per recruit to x% of the level that would exist with no fishing.
F_{loss}	The instantaneous fishing mortality rate corresponding to a SPR equal to the inverse of the observed recruits per spawner at the lowest observed spawning stock.

The key concepts

Biological reference point:
Biological reference point (BRP) is an indicator level of fishing or stock size to be used as a benchmark for assessment or decision making. Biological reference points are used as long-term objectives and different types of BRP have been defined.

The Limit Reference Points, LRP are maximum values of fishing mortality or minimum values of the biomass, which must not be exceeded. Otherwise, it is considered that it might endanger the capacity of self-renewal of the stock. Several LRP have been suggested, which will generally be referred to as F_{lim} or B_{lim}.

The uncertainties associated with the estimation of F_{lim}, and $B_{lim,}$ leads to determine Precautionary Reference Points, F_{pa} or B_{pa} which will be more restrictive than the LRP's. It can be said that this is the price to pay for not having the appropriate conditions to make available reliable data and information.

The Target Reference Points, TRP are BRP defined as the level of fishing mortality or of the biomass, which permit a long-term sustainable exploitation of the stocks, with the best possible catch. For this reason, these points are also designated as *Reference Points for Management*. They can be characterized as the *fishing level* F_{target} (or by the *Biomass*, B_{target}).

For more information see e.g.:
http://www.fao.org/documents/show_cdr.asp?url_file=/DOCREP/006/X8498E/x8498e0c.htm

Growth overfishing:
Levels of F higher than F_{max} , i.e. fish are caught before reaching an optimal weight.

Recruitment overfishing:
Fishing at a high enough level to reduce the biomass of spawning stock to a level at which future recruitment is impaired.

Biological overfishing:
Biological overfishing occurs whenever sustainable yield falls below MSY.