

Consequences of growth variation in northern Baltic herring for assessment and management

Mika Rahikainen and Robert L. Stephenson

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Growth rates of herring in the northern Baltic Sea differ among areas, and have changed substantially over time in some areas in response to environmental change. Weight-at-age of adult herring in some areas of the Finnish herring fishery fluctuated by as much as 60% over the past three decades. Elsewhere, there have been similar but more subtle changes. Growth variation has implications for stock assessment and management: differences suggest a need for considering a smaller spatial structure, at least at the scale of the ICES subdivision, in the case of northern Baltic herring. Changes in growth have an impact on the calculation and use of common biological reference points, and erode the capability of yield projections beyond the short term. Investigation of the impact of growth variation on common reference points of northern Baltic herring revealed that $F_{0.1}$ was a robust reference despite the marked variability in growth, whereas $F_{x\%SPR}$ (e.g. $F_{35\%SPR}$) was less robust, depending on the definition of maximum spawning-per-recruit. 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.

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Introduction

Northern Baltic herring (*Clupea harengus membras*) have exhibited striking changes in growth over the past few decades. Previous authors have described an increase in mean weight-at-age of Baltic stocks from the early 1970s to the early 1980s, followed by a decrease to the original level or below (Parmanne, 1992; Raid and Lankov, 1995; Parmanne *et al.*, 1997). Weight-at-age of adults decreased by 30–50% from the highest values in the early 1980s (Anon., 1994; Parmanne *et al.*, 1994; Cardinale and Arrhenius, 2000). Changes in growth have been hypothesized to have been linked to “bottom-up” factors, including variation in the zooplankton community and in abundance of the clupeids grazing them (Horbowy, 1997; Flinkman *et al.*, 1998), and “top-down” factors, such as size-selective predation by cod (Sparholt and Jensen, 1992; Beyer and Lassen, 1994;

Rudstam *et al.*, 1994). In addition to dramatic temporal changes, growth also differs among areas. The decrease in weight-at-age apparent in most parts of the Baltic could not be detected in either the Bothnian Sea (ICES subdivision 30) or Bothnian Bay (ICES subdivision 31) (Anon., 1994). This phenomenon has been related by some to asynchronous changes in hydrography in those areas compared with the rest of the Baltic. Whatever the exact mechanism, these large growth differences, and changes within and between areas, have had a major impact on the fishery (Stephenson *et al.*, 2001a) and pose substantial problems for assessment and management.

Stock assessment and scientific advice for Baltic herring are provided by the ICES (International Council for the Exploration of the Sea) Advisory Committee for Fisheries Management (ACFM; e.g., ICES, 2001a, b). 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, 2001b). The scientific advice for the Baltic Sea Main Basin is for a large assessment unit (subdivisions 25–29 and 32), including also the Archipelago Sea and the Gulf of Finland (Figure 1). Biological reference points have been proposed for F, but have not been defined for SSB. For a smaller Bothnian Sea (subdivision 30) assessment unit, both SSB and F reference points have been defined. 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, 2001a).

In this paper, we describe 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, and the differences in these life history parameters among areas. We highlight the relevance of growth variation in the perception of stock structure, stock assessment indices, and the choice of appropriate biological reference points, and consider the implications for management of Baltic herring.

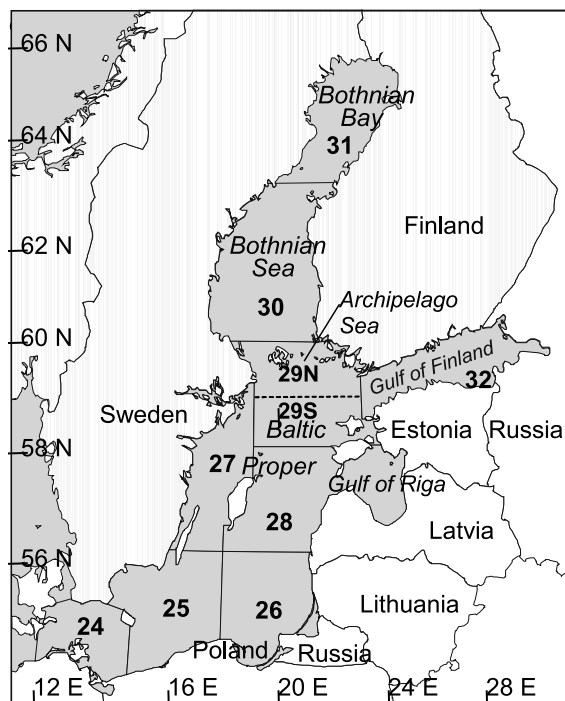


Figure 1. The Baltic Sea area, showing ICES subdivisions.

Material and methods

Size and growth information was derived from samples of the Finnish commercial herring fishery collected annually for stock assessment purposes. Samples of length, weight, and age were collected opportunistically from commercial landings at major ports from 1974 through 1997, and are considered to be representative of the fishery (Parmanne, 1990). Maturity data were also collected, beginning in 1982. The temporal sampling unit has been quarter of the year, and spatial stratification has been based on ICES subdivisions.

The two major gear types in the Finnish herring fishery are trawls and trapnets (Stephenson *et al.*, 2001a). The trapnet fishery takes place in the vicinity of, or on the migration route to, coastal spawning grounds, and catches primarily mature herring (Suuronen and Parmanne, 1984). In the northern Baltic Sea, all herring aged 1 year and about 50% of herring aged 2 years are immature. Trapnet samples are unrepresentative for those ages, because the gear selects only the fastest growing and maturing fraction of the stock. To avoid this problem, commercial trawl catch data for ages 1 and 2 and trapnet data for age 3+ have been used in growth investigations.

Analyses are based on data from the second quarter of the year. This is the time when herring are near spawning areas, to which they are presumed to “home”, so mixing among different (spawning) groups is presumed to be at a minimum. It is a period for which sampling from both trapnets and trawl fisheries has been intense and adequate for the analyses, and in which there is basically no growth in herring.

From 1974 to the mid-1980s, 20 trapnet samples on average were taken annually per subdivision during the second quarter. The number of samples increased to about 40 after the mid-1980s. The corresponding numbers of samples from trawls are 5 and 20, respectively. Each sample contained about 100 herring.

Body length was measured to the nearest millimetre, and wet body mass to the nearest gramme. Age was determined from otoliths illuminated from above against a dark background, using a stereo-microscope. The age of all fish was determined by a single reader.

The observed second quarter weights- and lengths-at-age were used to examine spatial and temporal variability in growth in the adjacent areas: the Bothnian Sea (subdivision 30), the Archipelago Sea (subdivision 29), and the Gulf of Finland (subdivision 32; Figure 1).

To study the impact of growth rate on biological reference points, we investigated two biological reference points prevalent in ICES: $F_{0.1}$ (Gulland and Boerema, 1973) and $F_{x\%SPR}$ (especially $F_{35\%SPR}$; Mace and Sissenwine, 1993). As variability in growth changes the relationship between spawning-per-recruit (SPR) and fishing mortality, the $F_{35\%SPR}$ was calculated in two different ways. The first was to apply the annual maximum SPR (at $F = 0$) to obtain

the annual estimate of F resulting in 35% of the maximum SPR. The second method was to apply the global maximum SPR to obtain the annual estimates of $F_{35\%SPR}$. Global maximum SPR is defined as the largest maximum SPR at $F = 0$ of all calculated combinations in the input data (Rahikainen *et al.*, 2003). The reference points were calculated from the observed mean weight-at-age, and maturity ogives over the whole range of observed growth rates for subdivisions 30 and 32, the areas displaying the greatest disparity in growth pattern in the northern Baltic Sea. The chosen fraction, 35% of maximum SPR, was adopted from ICES (2001b), but is essentially arbitrary.

A Thompson and Bell (1934) yield-per-recruit model was used. Reference point calculations were restricted to ages 1–9 years, because random variation in weight-at-age is large at older ages and could have had a disproportionate impact on the model output. Natural mortality rates (M) and exploitation patterns were adopted from a recent stock assessment (ICES, 2001b). For subdivision 30, we used $M = 0.2 \text{ year}^{-1}$ for all years. For subdivision 32 we used $M = 0.25 \text{ year}^{-1}$ in 1982 and 1983, and $M = 0.2 \text{ year}^{-1}$ for all other years, as done by the ICES assessment working group, to account for changes in predation. Exploitation patterns were estimated in 5–6-year periods, 1982–1987, 1988–1992, 1993–1997, to reduce the impact of random interannual variation in estimates.

Attained weight of herring was modelled as a function of additive year- and age-effects, to evaluate the impact of growth rate on the selected biological reference points for herring in subdivision 32. That area was used as the case study because the herring there exhibit the greatest contrast in weight-at-age. The parameters for intrinsic age-effects and external year-effects were estimated by means of a general linear modelling (GLM) procedure (SAS Institute Inc., 1988):

$$\ln(w) = \mu + A_a + B_b + \varepsilon, \quad (1)$$

where $\ln(w)$ is log-transformed fish mass, μ the grand mean of log-transformed weight, a and b the parameters of the linear regression for age- (A) and year- (B) effects, respectively, and ε is a normally distributed error term with mean 0. The annual variation in log-weight of herring is, therefore, an additive function of the intersection term and class variables A_a and B_b .

Results

Growth

Weight-at-age of mature herring increased during the late 1970s and early 1980s, peaked in the mid-1980s, and subsequently declined through 1997 (Figure 2). Weight-at-age of immature herring (ages 1 and 2) did not change concomitantly. Although the change in growth of herring aged 3 and older is apparent in all three areas, there are

marked differences in adjacent areas. Change in weight-at-age was greatest in subdivision 32 where, in the late 1990s, it was about 40% of its maximum level. Change was small in subdivision 30, and intermediate in subdivision 29.

The temporal pattern of length-at-age is similar to that of weight-at-age, but less pronounced as would be expected owing to the allometric growth pattern of fish (Figure 3). Herring aged 6 and 8 in subdivision 32 were approximately 55 mm shorter in the late 1990s than at the peak in growth during the early 1980s. The relative length-at-age in the late 1990s was about 66% of its maximum level.

Year-to-year variation in weight-at-age is reflected in the year effects of the linear growth model (Table 1). The main effects model is capable of explaining more than 80% of the variation in weight-at-age in spite of an apparent year \times age interaction in the data. The relationship of annual variation in weight-at-age and the reference points was best represented in the main effects model while an optimal fit to data was of secondary importance to investigation.

Reference points

The estimated $F_{0.1}$ for herring in subdivision 30 was very stable over the observed range in weight-at-age at about $F = 0.3$ (range 0.28–0.31; Figure 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 reference harvest rate.

The $F_{x\%SPR}$ reference point estimates for herring in subdivision 30 were more variable than $F_{0.1}$. Further, reference F values differed substantially, depending on the definition (method of calculation) of maximum spawning-per-recruit (Figure 4b). $F_{35\%SPR}$ was relatively stable, the range being 0.36–0.46 year^{-1} when calculated using an annual maximum SPR. Spawning-per-recruit varied considerably as a function of $F_{35\%SPR}$. However, when global maximum spawning-per-recruit, “maximum maxSPR”, was applied, this reference point was markedly variable (range 0.20–0.46 year^{-1}). The variability is due to changes in both weight- and maturity-at-age. A substantial increase in the fraction mature at age 2 contributed to the peak in 1990. Spawning-per-recruit was constant under this definition of maxSPR, and the minor variation was a result of the numerical approximation method used.

Estimates of $F_{0.1}$ for subdivision 32 herring, which experienced the largest variation in growth, were also stable in the range 0.25–0.31 year^{-1} (Figure 5a), except for 2 years (1982 and 1983), when a higher M (derived from MSVPA) was used in the calculations. Although $F_{0.1}$ increased with decreasing growth from 1984 through 1996, the change was small, especially in comparison with the overall uncertainty in the whole assessment process. The low $F_{0.1}$ for 1997 was caused by a large weight-at-age of

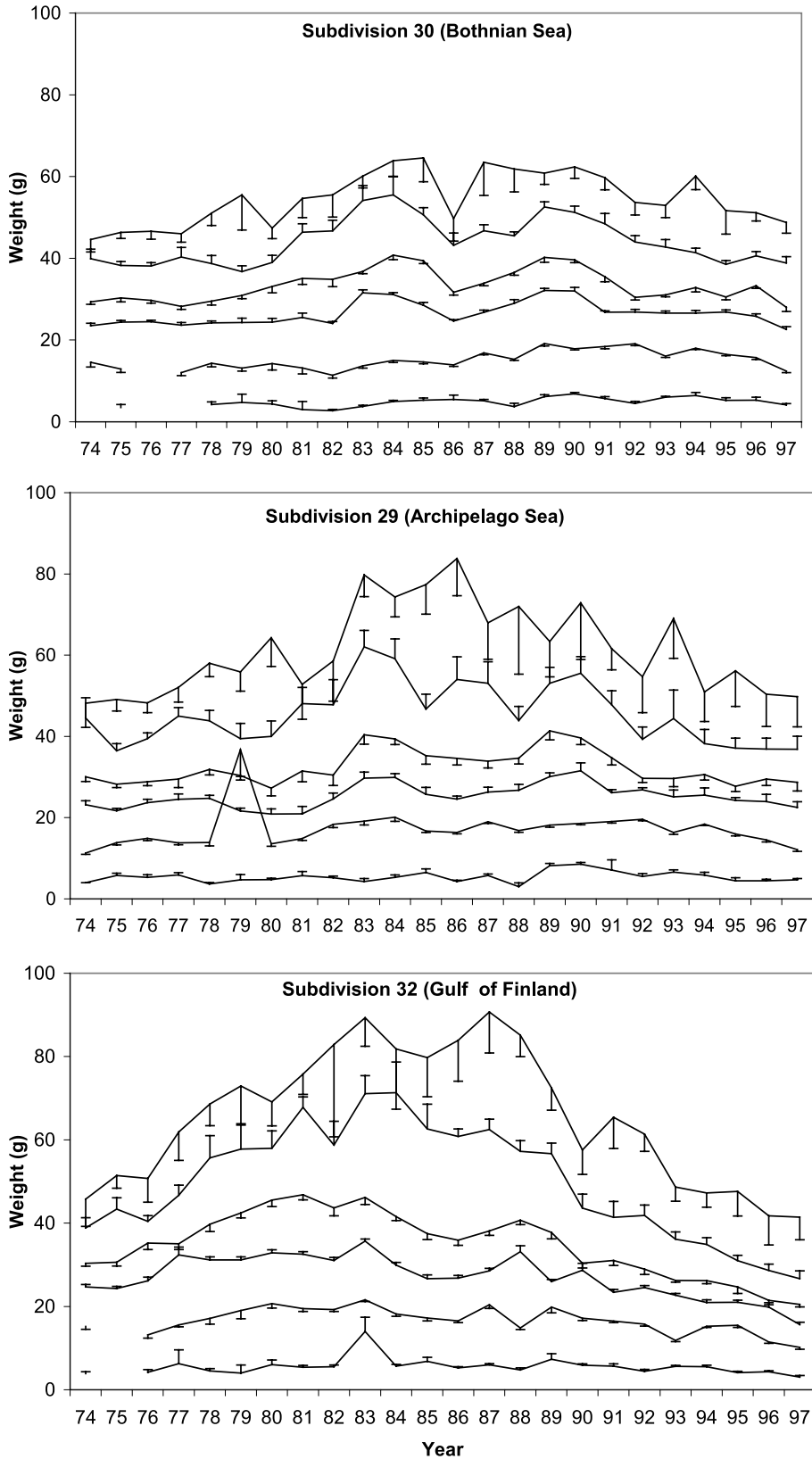


Figure 2. Mean weight-at-age of herring of age groups 1–4, 6, and 8 in ICES subdivisions 30, 29, and 32 in the years 1974–1997. Vertical bars indicate one half of the 95% confidence interval.

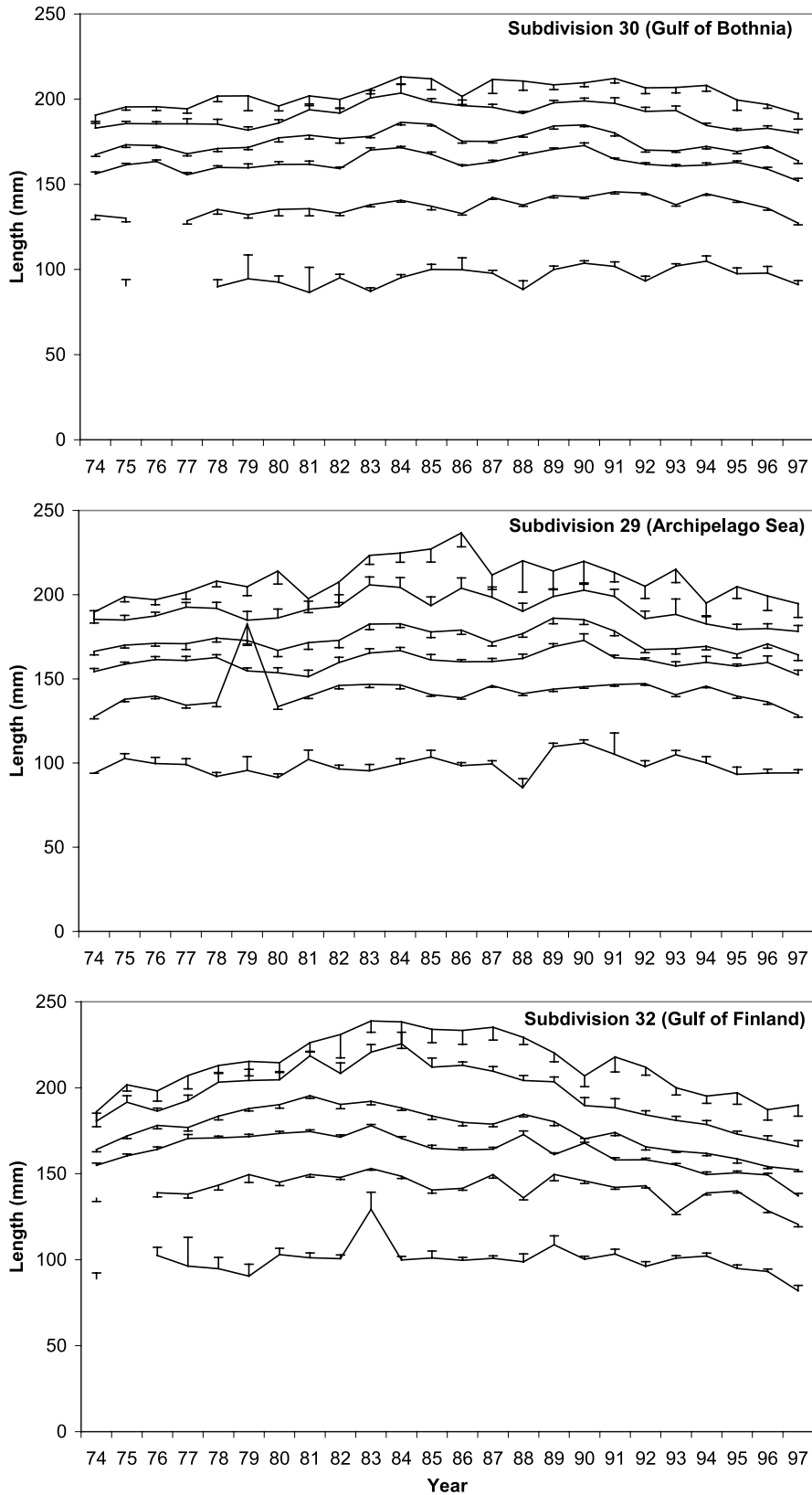


Figure 3. Mean length-at-age of herring of age groups 1–4, 6, and 8 in ICES subdivisions 30, 29, and 32 in the years 1974–1997. Vertical bars indicate one half of the 95% confidence interval.

Table 1. Analysis of variance table for \log_e -transformed weight (g) with factors of year and age. The dependent variable is attained weight in 1–9-year-old herring in subdivision 32 during the years 1982–1997. The r^2 of the model is 0.82.

Source	d.f.	Sum of squares	Mean square	F	p
Model	23	6 847.1	297.7	4 155.0	<0.0001
Year	15	1 161.2	77.4	1 080.5	<0.0001
Age	8	5 743.3	717.9	10 020.0	<0.0001
Error	20 700	1 483.1	0.071		
Corrected total	20 723	8 330.2			

herring aged 7 in that year. This demonstrates that the reliability of growth estimates in older ages is a matter of concern when mean weight-at-age is not estimated by any growth model (von Bertalanffy, for instance), which would smooth random variation in the growth estimates. The difference between the highest and the lowest yield-per-recruit was 50%, and proportional to change in mean weight-at-age used in the model.

As observed for subdivision 30, variation in $F_{35\%SPR}$ in subdivision 32 was small (range 0.35–0.46 year⁻¹), when annual estimates of maxSPR were used, but spawning-per-recruit declined by 55% (Figure 5b) in accordance with reduced growth. 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.

$F_{0.1}$ and $F_{35\%SPR}$ with annual maxSPR were robust reference points as a function of the changing weight of herring (Figure 6). The scatter plots are nearly identical, and only the level of reference Fs differs. Choice of a higher fraction of maximum spawning-per-recruit as a criterion would result in a value of $F_{35\%SPR}$ closer to $F_{0.1}$. $F_{35\%SPR}$ with global maxSPR, however, had a strongly positive correlation with growth rate, suggesting the need for a reduced harvest rate when growth is slow.

Discussion

Variation in growth

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. Growth was slow at the beginning (1970s) and end of the study period (late 1990s), but rapid in the middle. Although some other Atlantic and Pacific herring stocks have demonstrated detectable changes in growth accompanying major changes in the environment or in stock size (Hay *et al.*, 2001), and

Toresen (1990) showed considerable changes in length-at-age of Norwegian spring-spawning herring, Baltic herring stocks are unique in the magnitude of temporal and spatial variation in growth.

There appears to have been little change in weight-at-age of immature (ages 1 and 2) herring. This may be due to a difference in feeding regime between juvenile and adult fish (Ojaveer, 1981a, b; Arrhenius and Hansson, 1993; Flinkman, 1999). It may also be partly a consequence of mechanical trawl codend selectivity. We estimated the degree of gear selectivity by applying the most commonly used mathematical description of towed gear selection curves (a logistic curve, e.g. Millar and Fryer, 1999), and selectivity data for trawls deployed in the herring fishery (Suuronen and Millar, 1992; Millar and Suuronen, unpublished data). For age 1 herring (observed grand mean length 98 mm) the difference in observed and population mean length is 2–6 mm, depending on codend mesh size. The bias is estimated to be a maximum of 2 mm for age 2 herring (observed grand mean length 140 mm).

Although climate signals are highly correlated in the Baltic proper and Gulf of Finland (subdivision 32), the decrease in weight-at-age in recent years has been greatest in the northern part of the Baltic proper (Cardinale and Arrhenius, 2000). Baltic herring are selective planktivores, but they may feed periodically on energy-rich nektobenthos (Raid and Lankov, 1995). The diet of herring changes from south to north in the Baltic, as the plankton communities differ in tandem with hydrographic conditions such as salinity gradient (Flinkman, 1999). The growth of herring apparently reflects this gradient: fish are generally smaller in the northern than in the southern parts of the Baltic (Anon., 1994; ICES, 2001b). In the Bothnian Sea and Bothnian Bay, stratification of the water is weak (no halocline), in contrast to the situation in the Main Basin and Gulf of Finland, and spring and autumn turnovers keep the bottom layer well-oxygenated at all times (Melvasalo, 1980). Also, zooplankton species composition differs from that in the Baltic proper because of the lower salinity (Flinkman *et al.*, 1992).

Perceived stock structure and management units

Temporal variation in herring growth undoubtedly reflects temporal biotic and abiotic changes in the Baltic ecosystem. Spatial variation in growth, however, suggests not only spatial differences in the Baltic ecosystem, but also spatial complexity in herring stock structure. Herring growth in subdivision 30 is very different from that in subdivision 32, and growth in subdivision 29 is intermediate between the two.

Herring stock structure in the Baltic is complex, and this is manifest in different growth and other biological characteristics around the Baltic Sea (ICES, 2001c), uncertainty about herring migrations (for a review, see Aro, 1989), and uncertainty in stock assessment (ICES, 1999).

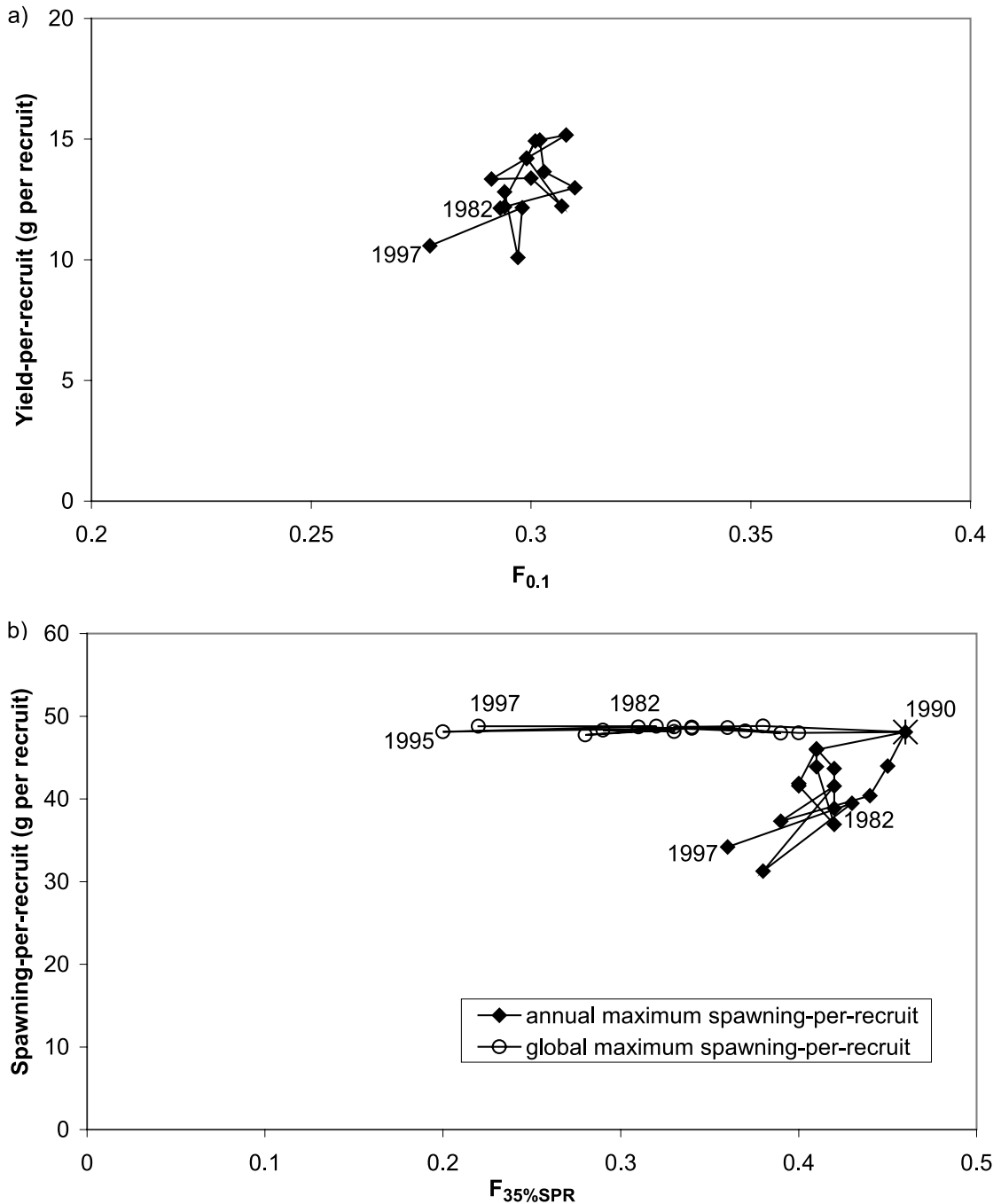


Figure 4. Relationship between (a) $F_{0.1}$ and yield-per-recruit, and (b) $F_{35\%SPR}$ and spawning-per-recruit for herring in ICES subdivision 30. The first and the last years of the series, as well as the year of overlapping estimates, are indicated. The asterisk in panel (b) indicates an overlap in annual and global maxSPR estimates.

Since the early stock studies of Baltic herring using morphological characters, some authors have argued for (Rauck, 1965; Ojaveer, 1980, 1989) and others against (Parmanne, 1990) the existence of different populations. Previous authors have suggested that there is a high degree of

“homing” of herring to specific spawning grounds widely distributed along the coast and archipelago of Finland and neighbouring countries (Rajasilta *et al.*, 1986). Notwithstanding, molecular genetic studies have failed to demonstrate genetic divergence within the Baltic Sea (Ryman

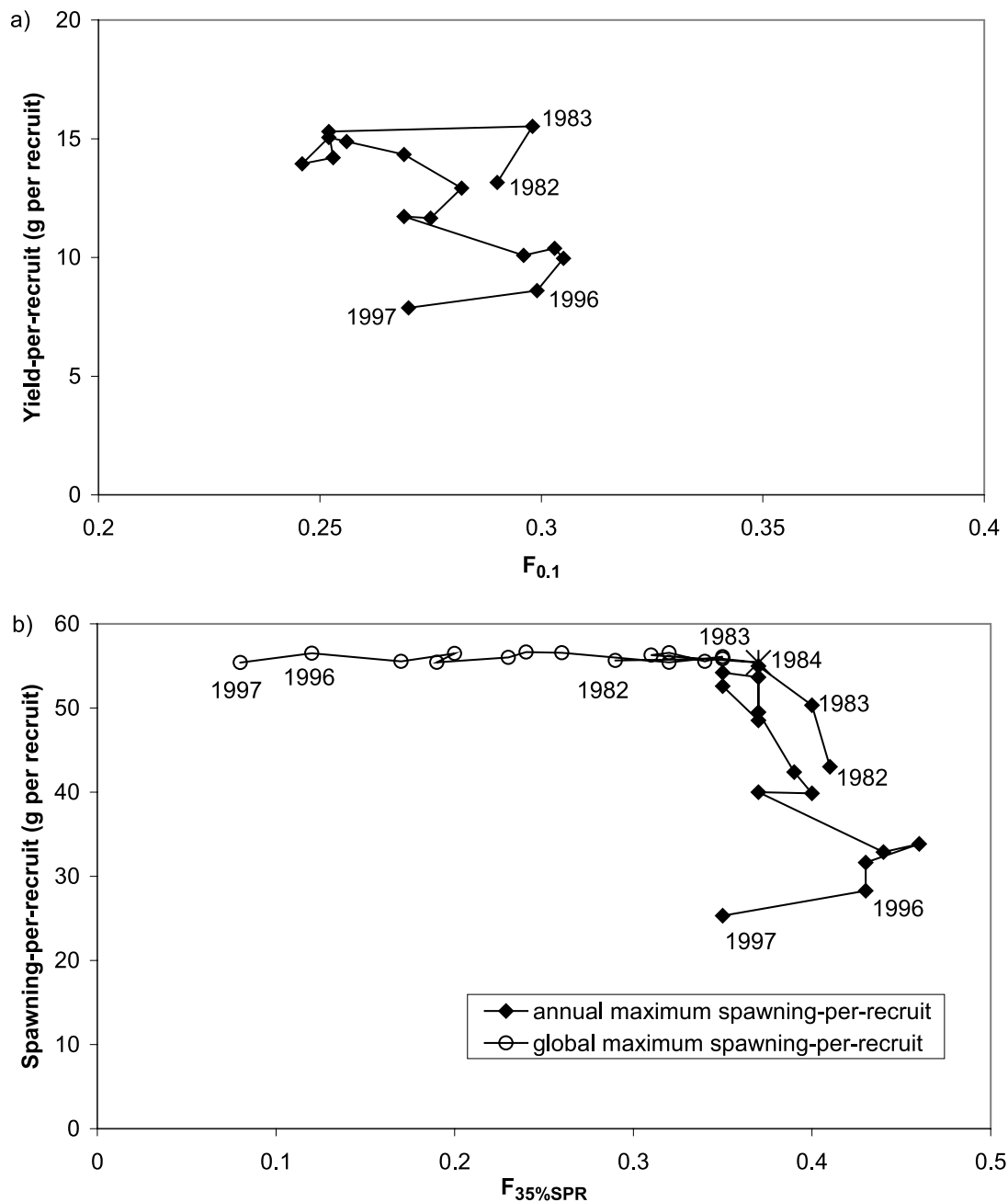


Figure 5. Relationship between (a) $F_{0.1}$ and yield-per-recruit, and (b) $F_{35\%SPR}$ and spawning-per-recruit for herring in ICES subdivision 32. The first and the last 2 years of the series, as well as the year of overlapping estimates, are indicated. The asterisk in panel (b) indicates an overlap in annual and global maxSPR estimates.

et al., 1984; Rajasilta *et al.*, 2000), or between the Baltic and Skagerrak and Kattegat (Andersson *et al.*, 1981), and there is apparently no association between the variation of morphological and genetic characters (Ryman *et al.*, 1984). While the literature on herring continues to contain studies in which stock structure is found with one approach but not

with others, or where approaches are conflicting in their conclusion regarding stock structure (Waldman, 1999), it seems that herring, in general, have a more complex stock structure than recognized in stock assessment and management (Smedbol and Stephenson, 2001; Stephenson *et al.*, 2001b; Stephenson, 2002).

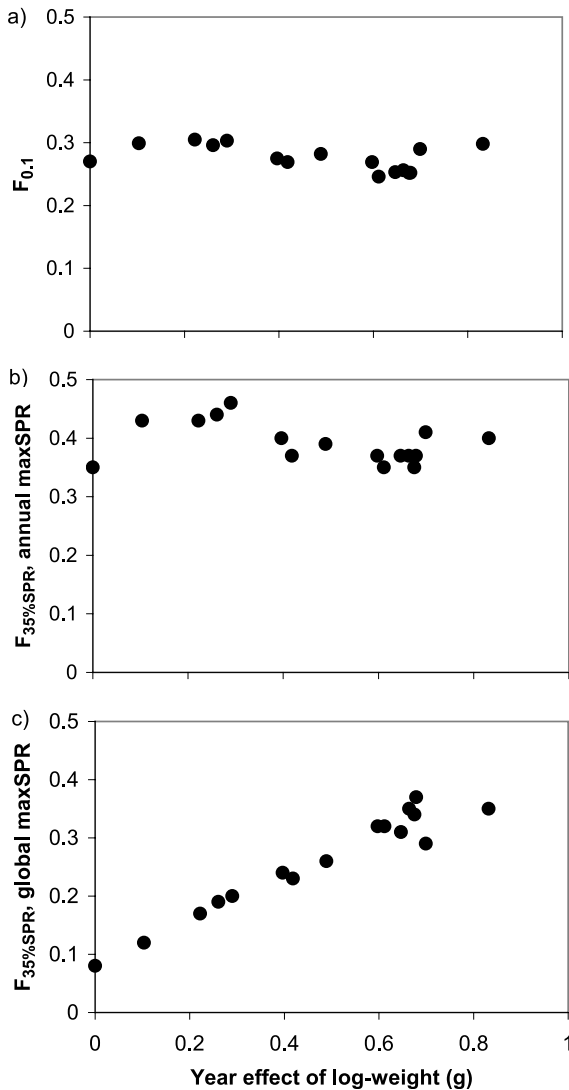


Figure 6. Biological reference points for herring in ICES subdivision 32 as a function of growth rate (a) $F_{0.1}$; (b) $F_{35\%SPR}$, using annual maxSPR; (c) $F_{35\%SPR}$, using global maxSPR.

Complex stock structure could certainly account for the differences in growth noted here. Alternatively, growth patterns of herring of a single stock could differ if isolation between groups was persistent, and those groups experienced different conditions. Such areas, then, may represent separate populations (i.e. reproductively isolated), or groups of the same population (i.e. the same genetic composition), but isolated enough in their life history to cause area/time interaction in growth. In either case, there are groups of herring with different growth rates that persist for time scales of relevance to assessment and management, and there seems to be a compelling case to reconsider the spatial scales of assessment and management. Currently,

there are no separate assessments for herring in subdivisions 29 or 32. The recent assessment for Baltic proper and northern Baltic proper herring was a pooled population analysis (VPA) for the area containing subdivisions 25–29 and 32. Although there have been recent attempts to assess smaller areas (ICES, 2001b), the latest management advice was based on a large area likely including several stock components. This large assessment unit is explicitly considered to be a compromise between assessment of biologically relevant unit stocks and practical management purposes (ICES, 1999). Separate assessments have been undertaken for Bothnian Sea (subdivision 30) and the Bothnian Bay (subdivision 31; ICES, 2001b). Further, herring are currently managed under two quotas (subdivisions 22–29S and 32, and subdivisions 29N, 30, and 31; ICES, 2001a), so there is a mismatch between assessment and management areas. The spatial differences in herring growth presented in this paper (Figures 2 and 3) and by the assessment working group (ICES, 2001b), indicate persistent differences in stock structure on a scale smaller than that of current assessment. Dividing large assessment units into smaller ones, as has been attempted in the recent assessment of Baltic herring stocks by ICES, reveals that the smaller “trial unit stocks” display different dynamics in growth, recruitment, and fishing mortality (Figure 7; ICES, 2001b). Use of the scale of subdivision should not only reduce the variability found by differences in growth and biological characteristics, but also allow assessment and management of stock components that are important aspects of stock structure and within-species diversity.

Growth variation and reference points

One obvious impact of growth variation in relation to the analytical assessment is in the calculation of biological reference points. ICES (2001d) listed some regularly used reference points. Most require weight-at-age, and therefore large changes in weight-at-age will imply that reference points will change (Sinclair, 1997). While scientists have been warning that reference points may change, managers have tended to hope for something stable. Changes in growth of Baltic herring provided an interesting context in which to examine the impact of growth on common reference points.

An assumption about M is involved in all reference point estimates. Almost all also require stock size and recruitment data, but in the northern Baltic proper, that information is not available by subdivision. The reference points that do not require stock/recruitment relationship or spawning-stock size information include $F_{0.1}$, F_{max} , $F_{x\%SPR}$, and Z_{mbp} (ICES, 2001d). The first two rely mostly on growth data, and the SPR reference point also on a more general knowledge of the resilience of other stocks having similar life history or taxonomic status to the stock under evaluation (Mace and Sissenwine, 1993; Myers *et al.*, 1995).

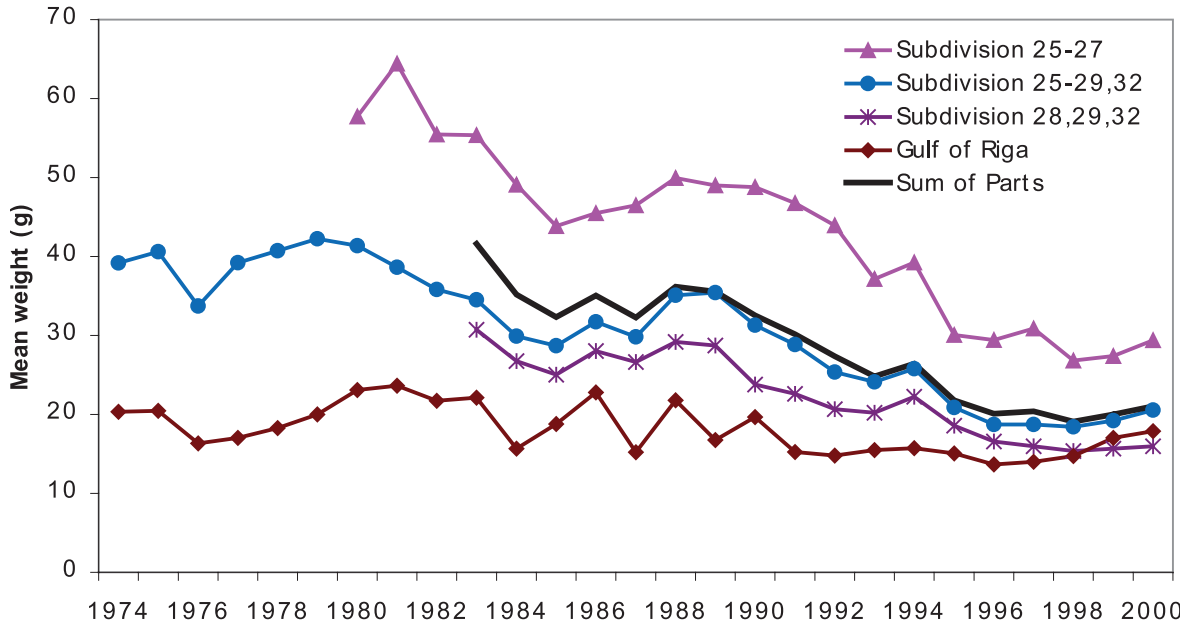


Figure 7. Mean weight (in the stock) of Baltic herring in the years 1974–2000 using trial assessment units (redrawn from Figure 11.6.1 of ICES, 2001b).

$F_{0.1}$ 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. 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.

Consideration of the stock/recruitment relationship can result in very different conclusions about sustainable F than if 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. On the other hand, 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 Maguire and Mace (1993). 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 . 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. Moreover, he 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.

Our evaluation of herring in subdivision 32 shows that the reference point calculated from an SPR analysis is dependent on the definition of maximum SPR (Figure 5). With the exception of Rochet (2000), life history parameters (growth, maturity) have been treated as fixed factors in the literature defining and developing the SPR analysis conceptually or computationally (Shepherd, 1982; Sissenwine and Shepherd, 1987; Gabriel *et al.*, 1989; Goodyear, 1993; Mace and Sissenwine, 1993). The impact of defining and deriving maximum SPR was not an issue in any of those studies. In the case of the highly dynamic Baltic herring stocks, however, it does make a difference to the result of the SPR analysis. Defining %SPR as a fraction of global maximum SPR tends to stabilize the stock biomass, resulting in lower fishing mortality reference points as growth rate decreases. There is a potential risk in this global maxSPR approach related to 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 (Figure 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 a highly 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 $F_{10\%}$, i.e. using a maxSPR that is the tenth percentile.

Clark (1991) proposed that a strategy of fixed exploitation rate performs reasonably well through large fluctuations in life history parameters and equilibrium abundance. According to his findings, the herring stock in subdivision 32 would be an obvious candidate for that strategy. The practical problem for any management is of course the lack of estimates of stock size and F from an analytical stock assessment for the stock. Lacking data on variation in stock size, the link between change in weight-at-age and carrying capacity (i.e. equilibrium abundance) is unclear. 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 with respect to carrying capacity. Therefore, 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, 2001b) and growth rate, and consequently there is no indication that the carrying capacity has changed markedly.

Stock assessment and projection

Growth assumptions are critical to projections of future yield, and clearly this is a problem in a situation beset with temporal changes in growth rate. Typical medium-term projections of 5 years or longer would seem inappropriate for Baltic herring because changes in growth are not predictable for the stock. Recent medium-term projections by ICES (2001b) for a 10-year period are essentially uncertain in the Baltic environment. The rationale for medium-term projections has been to evaluate the trade-off between long-term gain and short-term loss, but this assumes stability or predictability in parameters of growth, recruitment, etc. Unpredictable changes in growth of the magnitude seen in this population undermine the validity of projections beyond just a few years. Understanding the causal mechanisms underlying growth variation could reduce this uncertainty. For example, if growth variation was related to clupeid

abundance, then knowledge of management goals and harvest strategies would give some information about how stock abundance and hence growth rate might develop in coming years. However, if the variation was related to the hydrography, predictions would be highly uncertain, given our inability to forecast large-scale environmental processes.

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. 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. Commercial catch rate data are available for herring in subdivision 32, but these data are generally regarded as potentially biased estimators of stock abundance, especially for schooling pelagic species (Hilborn and Ledbetter, 1985; Hilborn and Walters, 1992; Gillis *et al.*, 1993; Gillis and Peterman, 1998). There would therefore be severe problems in matching estimates from the commercial fishery to reference points.

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.

Conclusions

Baltic herring growth rate varies greatly, both spatially and temporally, and the implications of this for assessment and management are marked. Our 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. Whether growth differences are the result of stock complexity or spatial variation in environmental parameters, it is clear that spatial patterns do need to be considered in management. The scale of assessment and management needs to be reviewed. The spatial variability in growth suggests that the assessment should be on a smaller spatial scale (e.g. ICES subdivision) than has been the case until now.

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.*, 2001b). 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. 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.

Most reference points cannot be calculated for separate units currently, because analytical assessment outputs regarding stock size and recruitment are not available for groups of fish in “small” spatial units. $F_{0.1}$ and $F_{35\%SPR}$ for annual maxSPR give steady estimates of reference fishing mortality over a wide range of growth rates, but the properties of these reference points have not been adequately considered. Using annual maxSPR to calculate $F_{x\%SPR}$ suggests a constant harvest rate, whereas the use of a global maxSPR results in variable harvest rate and stable stock biomass. Therefore, the actual utility of these reference points for the Baltic herring fishery is still an open question.

Different areas probably require different reference points, but the most appropriate management strategies could also be different. For subdivision 30, a biomass-based strategy would seem most appropriate, whereas a ratio-based strategy would seem more appropriate for subdivision 32. Analytical assessment is perhaps not feasible for all separate units, which then should be monitored using other biological indicators, such as age structure and extent of spawning locations. The large temporal growth variation implies that projections beyond the short term remain very uncertain.

The overall management approach should be reviewed to evaluate the validity of the goals, which are currently to maintain a biologically sustainable fishery by avoiding risky harvesting rates. Maximizing sustainable landings may require a different formulation of these goals.

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References

- Andersson, L., Ryman, N., Rosenberg, R., and Ståhl, G. 1981. Genetic variability in Atlantic herring (*Clupea harengus harengus*): description of protein loci and population data. *Hereditas*, 95: 69–78.
- Anon. 1994. Growth changes of herring in the Baltic. *Tema Nord* 1994, 532. 122 pp.
- Aro, E. 1989. A review of fish migration patterns in the Baltic. *Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer*, 190: 72–96.
- Arrhenius, F., and Hansson, S. 1993. Food consumption of larval, young and adult herring and sprat in the Baltic Sea. *Marine Ecology Progress Series*, 96: 125–137.
- Beyer, J. E., and Lassen, H. 1994. The effect of size-selective mortality on the size-at-age of Baltic herring. *Dana*, 10: 203–234.
- Cardinale, M., and Arrhenius, F. 2000. Decreasing weight-at-age of Atlantic herring (*Clupea harengus*) from the Baltic Sea between 1968 and 1996: a statistical analysis. *ICES Journal of Marine Science*, 57: 882–893.
- Clark, W. G. 1991. Groundfish exploitation rates based on life history parameters. *Canadian Journal of Fisheries and Aquatic Sciences*, 48: 734–750.
- Flinkman, J. 1999. Interactions between plankton and planktivores of the northern Baltic Sea: selective predation and predation avoidance. PhD thesis, Faculty of Science, University of Helsinki. Walter and Andree de Nottbeck Foundation Scientific Reports, 18.
- Flinkman, J., Aro, E., Vuorinen, I., and Viitasalo, M. 1998. Changes in northern Baltic zooplankton and herring nutrition from 1980s to 1990s: top-down and bottom-up processes at work. *Marine Ecology Progress Series*, 165: 127–136.
- Flinkman, J., Vuorinen, I., and Aro, E. 1992. Planktivorous Baltic herring (*Clupea harengus*) prey selectively on reproducing copepods and cladocerans. *Canadian Journal of Fisheries and Aquatic Sciences*, 49: 73–77.
- Gabriel, W. L., Sissenwine, M. P., and Overholtz, W. J. 1989. Analysis of spawning stock biomass per recruit: an example for Georges Bank haddock. *North American Journal of Fisheries Management*, 9: 383–391.
- Gillis, D. M., and Peterman, R. M. 1998. Implications of interference among fishing vessels and the ideal free distribution to the interpretation of CPUE. *Canadian Journal of Fisheries and Aquatic Sciences*, 55: 37–46.
- Gillis, D. M., Peterman, R. M., and Tyler, A. V. 1993. Movement dynamics in a fishery: application of the ideal free distribution to spatial allocation of effort. *Canadian Journal of Fisheries and Aquatic Sciences*, 50: 323–333.
- Goodyear, C. P. 1993. Spawning stock biomass per recruit in fisheries management: foundation and current use. *In Risk Evaluation and Biological Reference Points for Fisheries Management*, pp. 67–81. Ed. by S. J. Smith, J. J. Hunt, and D. Rivard. *Canadian Special Publication of Fisheries and Aquatic Sciences*, 120.
- Gulland, J. A., and Boerema, L. K. 1973. Scientific advice on catch levels. *Fishery Bulletin, US*, 71: 325–335.
- Hay, D. E. *et al.* 2001. Taking stock: an inventory and review of world herring stocks in 2000. *In Herring: Expectations for a New Millennium*, pp. 381–454. Ed. by F. Funk, J. Blackburn, D. Hay, A. J. Paul, R. Stephenson, R. Toresen, and D. Witherell. University of Alaska Sea Grant, AK-SG-01-04.
- Hilborn, R., and Ledbetter, M. 1985. Determinants of catching power in the British Columbia salmon purse seine fleet. *Canadian Journal of Fisheries and Aquatic Sciences*, 42: 51–56.
- Hilborn, R., and Walters, C. J. 1992. *Quantitative Fisheries Stock Assessment. Choice, Dynamics and Uncertainty*. Chapman & Hall, New York. 570 pp.
- Horbowy, J. 1997. Growth of the Baltic herring as a function of stock density and food resources. *Acta Ichthyologica et Piscatoria*, 27: 27–38.
- ICES 1998. Report of the Baltic Fisheries Assessment Working Group. ICES Document, CM 1998/ACFM: 16. 391 pp.
- ICES 1999. Report of the Baltic Fisheries Assessment Working Group. ICES Document, CM 1999/ACFM: 15. 560 pp.
- ICES 2000. Report of the Baltic Fisheries Assessment Working Group. ICES Document, CM 2000/ACFM: 14. 512 pp.

- ICES 2001a. Report of the ICES Advisory Committee on Fishery Management, 2001. ICES Cooperative Research Report, 246. 895 pp.
- ICES 2001b. Report of the Baltic Fisheries Assessment Working Group. ICES Document, CM 2001/ACFM: 18. 546 pp.
- ICES 2001c. Report of the Study Group on Herring Assessment units of the Baltic. ACFM/ 2001: 10.
- ICES 2001d. Report of the Study Group on the Further Development of the Precautionary Approach to Fishery Management. ICES Document, CM 2001/ACFM: 11. 48 pp.
- Mace, P. M., and Sissenwine, M. P. 1993. How much spawning per recruit is enough? *In* Risk Evaluation and Biological Reference Points for Fisheries Management, pp. 101–118. Ed. by S. J. Smith, J. J. Hunt, and D. Rivard. Canadian Special Publication of Fisheries and Aquatic Sciences, 120.
- Maguire, J.-J., and Mace, P. M. 1993. Biological reference points for Canadian Atlantic gadoid stocks. *In* Risk Evaluation and Biological Reference Points for Fisheries Management, pp. 321–331. Ed. by S. J. Smith, J. J. Hunt, and D. Rivard. Canadian Special Publication of Fisheries and Aquatic Sciences, 120.
- Melvasalo, T. (Ed.). 1980. Baltic Sea Environment Proceedings. No. 5B. Assessment of the effects of pollution on the natural resources of the Baltic Sea, pp. 114–117.
- Millar, R. B., and Fryer, F. J. 1999. Estimating size-selection curves of trawls, traps, gillnets and hooks. *Reviews in Fish Biology and Fisheries*, 9: 89–116.
- Myers, R. A., Bridson, J., and Barrowman, N. J. 1995. Summary of worldwide spawner and recruitment data. Canadian Technical Report of Fisheries and Aquatic Sciences, 2024. 327 pp.
- National Research Council 1996. *Upstream: Salmon and Society in the Pacific Northwest*. National Academy Press, Washington DC, USA. 452 pp.
- Ojaveer, E. 1980. On morphometric differences in the spring and autumn Baltic herring, *Clupea harengus membras*, in the Gulf of Riga. *Journal of Ichthyology*, 20: 86–113.
- Ojaveer, E. 1981a. Fish fauna of the Baltic Sea. *In* The Baltic Sea, pp. 275–276. Ed. by A. Voipio. Elsevier Oceanography Series, 30.
- Ojaveer, E. 1981b. Marine pelagic fishes. *In* The Baltic Sea, pp. 276–292. Ed. by A. Voipio. Elsevier Oceanography Series, 30.
- Ojaveer, E. 1989. Population structure of pelagic fishes in the Baltic. *Rapports et Procès-Verbaux des Réunions Conseil International pour l'Exploration de la Mer*, 190: 17–21.
- Parmanne, R. 1990. Growth, morphological variation and migrations of herring (*Clupea harengus* L.) in the northern Baltic Sea. *Finnish Fisheries Research*, 10: 1–48.
- Parmanne, R. 1992. Changes in the growth in the northern Baltic Sea in 1970–1991. ICES Document, CM 1992/J: 42. 19 pp.
- Parmanne, R., Popov, A., and Raid, T. 1997. Fishery and biology of herring (*Clupea harengus* L.) in the Gulf of Finland: a review. *Boreal Environment Research*, 2: 217–227.
- Parmanne, R., Rechlin, O., and Sjöstrand, B. 1994. Status and future of herring and sprat stocks in the Baltic Sea. *Dana*, 10: 29–59.
- Rahikainen, M., Kuikka, S., and Parmanne, R. 2003. Modelling the effect of ecosystem change on spawning per recruit of Baltic herring. *ICES Journal of Marine Science*, 60: 94–109.
- Raid, T., and Lankov, A. 1995. Recent changes in the growth and feeding of Baltic herring and sprat in the northeastern Baltic Sea. *Proceedings of Estonian Academy of Sciences, Ecology Series*, 5(1/2): 38–55.
- Rajasilta, M., Huusela, E., Laine, P., Rajjola, T., and Savontaus, M.-L. 2000. Mitochondrial DNA and allozyme data indicate no differentiation in the herring stock of the Baltic Sea. Poster presented at Herring 2000: an international symposium on expectations for a new millennium. Anchorage, Alaska, February 2000.
- Rajasilta, M., Kääriä, J., Eklund, J., and Ranta-aho, K. 1986. Reproduction of the Baltic herring (*Clupea harengus membras* L.) in the sea area of Turku, SW Finland. *Ophelia*, Suppl. 4: 339–343.
- Rauk, G. 1965. The structure of otoliths from the Baltic herring: a helpful means for the separation of biological groups. ICES Document, CM 1965/Herring Committee No. 39.
- Rochet, M.-J. 2000. Does the concept of spawning per recruit make sense? *ICES Journal of Marine Science*, 57: 1160–1174.
- Rudstam, L. G., Aneer, G., and Hildén, M. 1994. Top-down control in the pelagic Baltic ecosystem. *Dana*, 10: 105–129.
- Ryman, N., Lagercrantz, U., Andersson, L., Chakraborty, R., and Rosenberg, R. 1984. Lack of correspondence between genetic and morphological variability patterns in Atlantic herring (*Clupea harengus*). *Heredity*, 53: 687–704.
- SAS Institute Inc. 1988. SAS/STAT User's Guide, Release 6.03 Edition. 1028 pp.
- Shepherd, J. G. 1982. A versatile new stock-recruitment relationship for fisheries, and the construction of sustainable yield curves. *Journal du Conseil International pour l'Exploration de la Mer*, 40: 67–75.
- Sinclair, A. 1997. Biological reference points relevant to a precautionary approach to fisheries management: an example for southern Gulf of St Lawrence cod. NAFO SCR Document, 97/77. 16 pp.
- Sissenwine, M. P., and Shepherd, J. G. 1987. An alternative perspective on recruitment overfishing and biological reference points. *Canadian Journal of Fisheries and Aquatic Sciences*, 44: 913–918.
- Smedbol, R. K., and Stephenson, R. 2001. The importance of managing within-species diversity in modern fisheries, with examples from the northwestern Atlantic. *Journal of Fish Biology*, 59(Suppl. A): 109–128.
- Sparholt, H., and Jensen, I. B. 1992. The effect of cod predation on the weight-at-age of herring in the Baltic. *ICES Marine Science Symposia*, 195: 488–491.
- Stephenson, R. 2002. Stock structure and management structure: an ongoing challenge for ICES. *ICES Marine Science Symposia*, 215: 311–320.
- Stephenson, R., Peltonen, H., Kuikka, S., Pönni, J., Rahikainen, M., Aro, E., and Setälä, J. 2001a. Linking biological and industrial aspects of the Finnish commercial herring fishery in the northern Baltic Sea. *In* Herring: Expectations for a New Millennium, pp. 741–760. Ed. by F. Funk, J. Blackburn, D. Hay, A. J. Paul, R. Stephenson, R. Toresen, and D. Witherell. University of Alaska Sea Grant, AK-SG-01-04.
- Stephenson, R. L., Clark, K. J., Power, M. J., Fife, F. J., and Melvin, G. D. 2001b. Herring stock structure, stock discreteness and biodiversity. *In* Herring: Expectations for a New Millennium, pp. 559–571. Ed. by F. Funk, J. Blackburn, D. Hay, A. J. Paul, R. Stephenson, R. Toresen, and D. Witherell. University of Alaska Sea Grant, AK-SG-01-04.
- Suuronen, P., and Millar, R. 1992. Size selectivity of diamond and square mesh codends in pelagic herring trawls: only small herring will notice the difference. *Canadian Journal of Fisheries and Aquatic Sciences*, 49: 2104–2117.
- Suuronen, P., and Parmanne, R. 1984. The Baltic herring trapnet fishery off the coast of Finland. ICES Document, CM 1984/B: 35. 20 pp.
- Thompson, W. F., and Bell, F. H. 1934. Biological statistics of the Pacific halibut fishery. 2. Effect of changes in intensity upon total yield and yield per unit gear. Report of the International Pacific Halibut Fishery Commission, 8. 49 pp.
- Toresen, R. 1990. Long-term changes in growth of Norwegian spring-spawning herring. *Journal du Conseil International pour l'Exploration de la Mer*, 47: 48–56.
- Waldman, J. R. 1999. The importance of comparative studies in stock analysis. *Fisheries Research*, 43: 237–246.
- Winters, G. H., and Wheeler, J. P. 1987. Recruitment dynamics of spring-spawning herring in the northwest Atlantic. *Canadian Journal of Fisheries and Aquatic Sciences*, 44: 882–900.