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The effect of natural mortality on the estimation of stock state parameters and derived references for sustainable fisheries management

Anna Cheilari and Hans-Joachim Rätz

Abstract

The present study focuses on sensitivity analyses regarding the effects of various assumptions about the magnitude of natural mortality (M) on resulting stock assessment parameters and derived references for sustainable fisheries management. The results revealed that the estimated exploitation rate is decreasing and the stock size is increasing with increasing M. The recommended and internationally agreed fisheries management references of sustainable exploitation $F_{0.1}$ and F_{msy} are also found to sensitively react to changes in M. Both $F_{0.1}$ and F_{msy} increase with increasing M. All simulations are based on data from the Baltic sprat (Sub-divisions 22-32), which has historically undergone quite large changes in M. Nevertheless, the maximum sustainable yield (MSY) is demonstrated to be a rather robust estimator over a wide range of M, including species at a rather low trophic level. The trend to underestimate fishing mortality and to overestimate the stock size with high M might deliver, in comparison with actual catches, a positively biased perception of the state of the stock and its productivity. The elevated risk for sustainable fisheries even increases when underestimated fishing mortalities are compared with overestimated management references of exploitation, like $F_{0.1}$ and F_{msy}. It is recommended to base M assumptions in the assessment of exploited resources and the advisory process to fisheries management to the longevity of the species concerned, if no quantitative information about M is available. Furthermore, M should account for the different ontogenetic stages and for changes in fish condition if observed.

Keywords: natural mortality, fisheries management, stock assessment, Baltic sprat

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Introduction

Uncertainty regarding the magnitude of natural mortality rates in exploited marine stocks may result in different perceptions of stock productivity and thus high potential yields that can be fished sustainably over a long period. This uncertainty is especially important for stocks of a short or medium life span and on a low trophic level. Short or medium-lived species often play an important ecological role in the food chains. However, decisive for survival rates in any exploited population is the total mortality Z, as a sum of natural mortality M and fishing mortality F. In addition to the natural mortality, human induced mortality (fishing mortality), depending on its magnitude, may cause significant changes in the ecosystem. On the other hand, short or medium-lived species have proven to provide a significant amount of surplus production in biomass, which could be of a high economic value for world or national fisheries and processing industries.

The uncertainty in the appropriate level of M regarding the analytical assessments of demersal and small pelagic stocks, has led to a wide range of values of natural mortality used. In order to quantify the effect of different M assumptions on the estimation of stock parameters and derived management references, the input data and assessment of sprat (*Sprattus sprattus*) in the Baltic Sea (Sub-divisions 22-32) of ICES (2007) are adopted. Such stock parameters are then, in combination with different levels of M, applied in various assessment scenarios and their results and derived management references are compared accordingly. The stock of sprat in the Baltic was chosen because

- sprat is considered a major prey species at a low trophic level,
- it is fished intensively with recent annual yields exceeding 300,000 t,
- the stock assessment has been accepted through various reviews,
- M values vary over years of the assessment according to the state of major predator stocks, and
- M values vary over ages in order to consider effects of different life stages.

Material and methods

As a first step, the stock was re-assessed based on all input parameters and XSA (VPA) model settings (Darby and Flatman, 1994) as used by the Baltic Fisheries Assessment Working Group in 2007 (ICES, 2007). The assessment covered the period 1974 to 2006 and included age groups 1 to 8, the oldest being a plus group of all older ages. Terminal F estimations are calibrated (tuned) by three fishery independent scientific abundance surveys. The model settings and diagnostics do not deviate significantly from default settings and do not indicate any significant data problems. The re-assessed stock parameters are identical with the original ICES assessment, as can be seen in Figures 1-3.

Table 1 lists the matrix of M used by the original assessment. The M values vary over ages and years. Until the mid 1980s, the M values were relatively high and resulted from multi-species assessments reflecting the high grazing rates by the abundant cod stocks, the major predators. Such high consumptions rates were calculated from extended stomach sampling projects and incorporated into the assessment as high M values. With the following decline of the cod stock to a low level, the M values were also decreased by about 50%. Recently vary among 0.24-0.29 for ages 3-5 years. Additionally, the M values used in the assessment vary over ages, with higher M values at ages 1 and 2 and for the oldest ages. This reflects increased grazing rates of juveniles and lower catchability of older fish, partly leaving the fishing grounds.

The matrix of M values given is Table 1 is then multiplied with the factors of 0.5, 0.75, 1.25 and 1.5, and used as input to the stock assessment. All other stock parameters were kept unchanged. The resulting stock parameters, mean fishing mortality over ages 3 to 5 (F3-5), spawning stock biomass

(SSB) and recruitment at age 1 of these four assessment scenarios are compared with the original assessment (Scenario 3). They also form the basis for the calculation of the management references of fishing mortality from Yield per Recruit analyses, $F_{0.1}$, F_{max} and F_{msy} (Thompson and Bell, 1934; Beverton and Holt, 1957; Rivard, 1982; Sinclair 1999). The stock productivity parameters, maximum sustainable yield (MSY) and biomass at MSY (B_{msy}) were also calculated. The input parameters of the calculations of these sustainable management references are given in Table 2, including the parameters of the Ricker (1975) function used to estimate the relation between recruitment and stock size. The input values represent short term means of the last 3 years in the assessment (2004-2006) regarding catch weight, stock weight, maturity, natural mortality and fishing mortality at age.

Results

The results of the five stock assessment scenarios for Baltic sprat are shown in Figures 1-3 for fishing mortality F(3-5), spawning stock biomass and recruitment at age 1, respectively. All scenarios indicate a general increase in fishing mortality since the mid 1980s (Fig. 1). The estimated fishing mortality is significantly decreased with increasing M, especially during the 1970s when M values were set at a higher level due to the high abundance of the major predator cod.

The stock is estimated to have increased from a low level since the early 1980s and to remain at a higher level since the mid 1990s. Increasing M results in higher stock sizes as can be seen in Figure 2. This can be explained by the general feature of any virtual population analyses based on fish recorded as dead due to natural causes or fishing. The effect is elevated during the early years of the assessment when the M values were set to the double of the recent level. The same increasing effect of higher M values on stock size can be seen in Figure 3 illustrating the estimated trends in recruits of the five assessment scenarios. High M values result in some very high estimates of recruitment.

Variation in M has some significant effect on the magnitude of stock productivity. The yield per recruit significantly increases with decreasing M (Fig. 4). Low natural mortality implies high survival and therefore, in combination with growth, higher yield per recruit. Contrarily, high natural mortality would imply that the stock can hardly be growth overfished as the relevant functions do not reach a maximum over a reasonable range of fishing mortality. Consistently, high natural mortality does not imply strong reductions in spawning stock biomass with increasing fishing mortality (Fig. 5). Under such equilibrium conditions, high natural mortality also implies only a minor effect of fishing on the size of the stock and thus on the future recruitment. $F_{0.1}$ and F_{max} estimates derived from the slopes of the illustrated functions are increasing with increasing natural mortality (Table 3 and Fig. 7).

Figure 6 illustrates the calculations of equilibrium catches with increasing exploitation of the five scenarios of different mortality levels. Such equilibrium catch estimates consider the relationship of spawning stock and recruitment. The maximum sustainable yield (MSY) seems a quite stable parameter and ranges between 320,000 and 430,000 t/a, for four out of the five scenarios. Only the highest M factor of 1.5 results in very high recruitment estimates, which drives the MSY into unrealistic high regions. However, the F_{msy} is estimated to significantly increase with increasing natural mortality, except for the factor of 1.5 due to the elevated recruitment estimates mentioned (Table 3 and Fig. 7). B_{msy} estimates appear to decrease with increasing M from 2.3 Mill. t to 1.3 Mill. t with the exception of the factor of 1.5 resulting in an unreasonably high figure (Table 3).

Discussion

The present sensitivity analysis of different magnitudes of natural mortality M on the results of analytical and age based stock assessments using the Baltic sprat stock as an example, demonstrate that resulting exploitation rates can be considered underestimated with increasing M. Contrarily, stock sizes expressed as spawning stock biomass or recruitment can be considered overestimated with the same increasing mortality values assumed. These features can be concluded as consistent with the assessment model formulations applied in any Virtual Population Analyses (VPA) based on age structured catch figures. Thus, high M values used in assessments will result in a biased and overly optimistic perception regarding the status of the stock (overestimated) and its exploitation (underestimated). This effect clearly implies an increased risk regarding the management of sustainable fisheries.

A further increased management risk appears when the overly optimistic stock assessment results based on increased high M values are compared with reference points derived from such biased information. All reference points derived from Yield per Recruit analyses, i.e $F_{0.1}$ and F_{max}, or B_{msy} and F_{msy} with consideration of a stock-recruitment relation, react very sensitive to changes in M. High M values imply increased reference points of exploitation, $F_{0.1}$ and F_{msy}, which have recently been indicated as acceptable approximations of management targets for sustainable fisheries consistent with high yields and low risk of collapse (UN, 2002; Anon., 2007). However, the comparison of an underestimated exploitation rate with an overestimated reference point is not likely to result in sustainable and risk-averse management decisions. $F_{0.1}$ appears a reasonable (precautionary) proxy of F_{msy}, as both are found closely correlated and the former being slightly lower. In general, F_{max} should not be considered an appropriate management reference as the estimated values are very high and increase exponentially with increasing M. A decrease in B_{msy} with increasing M indicates that this biomass reference is rather uncertain as well, when high Ms are used in the assessment. In such cases, an overestimated stock would be compared with an underestimated reference level. B_{msy} has been proposed as a candidate of rebuilding or target level, but it must be recognised that stock biomass cannot be managed directly. In addition to human impacts through fisheries, stock biomass results from many other ecological effects which can hardly be controlled. The example of the Baltic sprat stock demonstrated that the estimate of the maximum sustainable yield is rather constant over a range of M values applied.

Variations of M have been related to a variety of ecological effects, i.e. environmental changes like water temperature and growth parameters (Pauly, 1980), fish condition (Dutil and Lambert, 2000) life span (Hoenig, 1983; Hewitt and Hoenig, 2005) as well as size of prey and predator stocks at all ontogenetic states. As shown above, fisheries induce additional mortality and thus also affect the magnitude of fish died due to natural causes within a certain period. However, the power of empirical relationships for predicting natural mortality can be rather limited (Vetter, 1988; Pascual and Iribarne, 1993), and the uncertainty associated with parameter estimates should be taken into account whenever possible (Patterson et *al.*, 2001). The quantification of predation through stomach sampling and estimation of consumption rates taking into account the size of predator stocks has been successfully applied in the example stock presented in this paper (Köster et *al.*, 2005; MacKenzie and Köster, 2004; Vinther, 2001). In case that no other information about M is available, the method published by Hewitt and Hoenig (2005) should be applied. Hoenig (1983) found that M is inversely correlated with the longevity across a wide variety of taxa. Hewitt and Hoenig (2005) recommend a regression estimator be used when estimation of M is based on longevity.

References

Anon. 2007. Council Conclusions Communication from the Commission (COM(2006)360 final) Implementing sustainability in EU fisheries through maximum sustainable from the 2841st Agriculture and Fisheries Council meeting, Brussels, 17 December 2007. yield. http://www.consilium.europa.eu/ueDocs/cms_Data/docs/pressData/en/agricult/97717.pdf

Beverton, R. J. H. and S. J. Holt 1957. On the dynamics of exploited fish populations. Fishery Investigations, London HMSO, Ser 2(19).

Darby, C. and S. Flatman 1994. Virtual Population Analysis: version 3.1 (Window/DOS) user guide. Ministry of Agriculture, Fisheries and Food, Directorate of Fisheries Research. Information Technology Series Number 1, UK Lowestoft 1994, 59 pp.

Dutil, J.-D. and Y. Lambert 2000. Natural mortality from poor condition in Atlantic cod (*Gadus morhua*). Can. J. Fish. Aquat. Sci., 57: 826-836.

Hewitt, D. A. and J. M. Hoenig 2005. Comparison of two approaches for estimating natural mortality based on longevity. Fish. Bull., 103: 433-437.

Hoenig, J. M. 1983. Empirical use of longevity data to estimate mortality rates. Fish. Bull., 82: 898-903.

ICES 2007. Report of the Baltic Fisheries Assessment Working Group (WGBFAS), 17 – 26 April 2007, ICES Headquarters. ICES CM 2007/ACFM:15. 727 pp.

Köster, F. W., C., Möllmann, H-H., Hinrichsen, K., Wieland, J., Tomkiewicz, G., Kraus, R., Voss, A., Makarchouk, B. R., MacKenzie, M. A., St. John, D., Schnack, N., Rohlf, T., Linkowski and J. E. Beyer 2005. Baltic cod recruitment - the impact of climate variability on key processes. ICES J. Mar. Sci., 62: 1408-1425.

MacKenzie, B. R. and F. W. Köster 2004. Fish production and climate: sprat in the Baltic Sea. Ecology, 85: 784-794.

Pascual, M. A., and O. O. Iribarne 1993. How good are empirical predictions of natural mortality? Fish. Res., 16: 17-24.

Patterson, K., R. Cook, C. Darby, S. Gavaris, L. Kell, P. Lewy, B. Mesnil, A. Punt, V. Restrepo, D. W. Skagen, and G. Stefansson 2001. Estimating uncertainty in fish stock assessment and forecasting. Fish and Fisheries, 2: 125-157.

Pauly, D. 1980. On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. J. Cons. int. Explor. Mer, 39 (2): 175-192.

Ricker, W. E. 1975. Computation and interpretation of biological statistics of fish populations. Bull. Fish. Res. Board Can., 191: 382 pp.

Rivard, D. 1982. APL programs for stock assessment (revised). Can. Tech. Rep. Fish. Aquat. Sci., 1091: 146 pp.

Sinclair, A. 1999. Biological Reference Points Relevant to a Precautionary Approach to Fisheries Management: an Example for Southern Gulf of St. Lawrence Cod. NAFO Sci. Coun. Studies, 32: 25-35.

Thompson, W. F. and F. H. Bell 1934. Biological statistics of the Pacific halibut fishery. Part 2: Effect of changes in intensity upon total yield and yield per unit of gear. Rep. Int. Fish. (Pacific Halibut) Comm., 8: 49pp.

United Nations 2002. Report of the World Summit on Sustainable Development. Johannesburg, South Africa, 26 August-4 September 2002. A/CONF.199/20*, United Nations publication, Sales No. E.03.II.A.1, ISBN 92-1-104521-5, 173 pp.

Vetter, E. F. 1988. Estimation of natural mortality in fish stocks: a review. Fish. Bull., 86: 25-43.

Vinther, M. 2001. Ad hoc multispecies VPA tuning applied for the Baltic and North Sea fish stocks. ICES J. Mar. Sci., 58: 311-320.

Table 1. Baltic sprat in Sub-divisions 22-32. Annual natural mortality values M at age and averaged over ages 3-5 as used in the original assessment by ICES (2007).

Year	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8+	Average (3-5)
1974	0.96	0.57	0.45	0.45	0.50	0.46	0.56	0.56	0.47
1975	1.39	0.76	0.57	0.55	0.63	0.59	0.73	0.73	0.58
1976	0.88	0.55	0.43	0.42	0.48	0.46	0.56	0.56	0.44
1977	0.77	0.50	0.41	0.40	0.44	0.43	0.52	0.52	0.42
1978	1.05	0.67	0.54	0.51	0.57	0.55	0.68	0.68	0.54
1979	1.17	0.80	0.65	0.59	0.67	0.68	0.86	0.86	0.64
1980	1.26	0.84	0.68	0.60	0.68	0.73	0.92	0.92	0.65
1981	1.02	0.71	0.58	0.53	0.60	0.61	0.78	0.78	0.57
1982	1.20	0.83	0.68	0.61	0.69	0.71	0.91	0.91	0.66
1983	1.06	0.78	0.63	0.59	0.69	0.69	0.88	0.88	0.64
1984	0.85	0.65	0.55	0.50	0.56	0.59	0.74	0.74	0.54
1985	0.74	0.55	0.46	0.43	0.48	0.50	0.62	0.62	0.46
1986	0.64	0.45	0.39	0.37	0.40	0.40	0.48	0.48	0.39
1987	0.53	0.40	0.35	0.34	0.36	0.36	0.42	0.42	0.35
1988	0.57	0.44	0.38	0.36	0.39	0.40	0.47	0.47	0.38
1989	0.47	0.37	0.33	0.31	0.34	0.35	0.41	0.41	0.33
1990	0.38	0.31	0.28	0.27	0.29	0.29	0.33	0.33	0.28
1991	0.32	0.27	0.25	0.24	0.25	0.25	0.28	0.28	0.25
1992	0.34	0.26	0.25	0.24	0.25	0.25	0.26	0.26	0.25
1993	0.36	0.29	0.27	0.26	0.28	0.26	0.29	0.29	0.27
1994	0.35	0.29	0.27	0.26	0.27	0.27	0.29	0.29	0.27
1995	0.33	0.28	0.26	0.26	0.27	0.27	0.30	0.30	0.26
1996	0.31	0.27	0.25	0.25	0.26	0.26	0.29	0.29	0.25
1997	0.35	0.28	0.26	0.26	0.27	0.28	0.31	0.31	0.26
1998	0.39	0.31	0.27	0.27	0.29	0.28	0.32	0.32	0.28
1999	0.41	0.32	0.28	0.28	0.29	0.29	0.33	0.33	0.28
2000	0.41	0.32	0.29	0.28	0.30	0.30	0.33	0.33	0.29
2001	0.39	0.31	0.27	0.27	0.29	0.29	0.31	0.31	0.28
2002	0.40	0.32	0.29	0.28	0.30	0.30	0.33	0.33	0.29
2003	0.30	0.26	0.24	0.24	0.25	0.25	0.26	0.26	0.24
2004	0.30	0.26	0.24	0.24	0.25	0.24	0.26	0.26	0.24
2005	0.33	0.27	0.25	0.24	0.25	0.25	0.27	0.27	0.25
2006	0.33	0.27	0.25	0.24	0.25	0.25	0.27	0.27	0.25

Table 2. Baltic sprat in Sub-divisions 22-32. Input parameters to estimate the management references points $F_{0.1}$, F_{max} and F_{msy}, B_{msy} and MSY for the five different scenarios of natural mortality (M) factors: 0.5 (Scenario 1), 0.75 (Scenario 2), 1 (Scenario 3), 1.25 (Scenario 4) and 1.5 (Scenario 5).

Scenario 1

M factor	age group	stock weight (kg)	catch weight (kg)	maturity	F	M
0.50	1	0.009	0.005	0.170	0.199	0.160
	2	0.012	0.007	0.930	0.323	0.133
Ricker a	3	0.013	0.009	1.000	0.420	0.123
74.94	4	0.014	0.010	1.000	0.491	0.120
	5	0.016	0.011	1.000	0.644	0.125
Ricker k (t)	6	0.017	0.011	1.000	0.530	0.123
2673895.14	7	0.017	0.011	1.000	0.516	0.133
	8	0.017	0.011	1.000	0.516	0.133

Scenario 2

M factor	age group	stock weight	catch weight	maturity	F	M
0.75	1	0.009	0.005	0.170	0.165	0.240
	2	0.012	0.007	0.930	0.275	0.200
Ricker a	3	0.013	0.009	1.000	0.363	0.185
98.03	4	0.014	0.010	1.000	0.430	0.180
	5	0.016	0.011	1.000	0.566	0.188
Ricker k (t)	6	0.017	0.011	1.000	0.468	0.185
1992918.73	7	0.017	0.011	1.000	0.455	0.200
	8	0.017	0.011	1.000	0.455	0.200

Scenario 3

M factor	age group	stock weight	catch weight	maturity	F	M
1.00	1	0.009	0.005	0.170	0.133	0.320
	2	0.012	0.007	0.930	0.231	0.267
Ricker a	3	0.013	0.009	1.000	0.309	0.247
137.36	4	0.014	0.010	1.000	0.370	0.240
	5	0.016	0.011	1.000	0.488	0.250
Ricker k (t)	6	0.017	0.011	1.000	0.408	0.247
1603239.46	7	0.017	0.011	1.000	0.398	0.267
	8	0.017	0.011	1.000	0.398	0.267

Scenario 4

M factor	age group	stock weight	catch weight	maturity	F	M
1.25	1	0.009	0.005	0.170	0.105	0.400
	2	0.012	0.007	0.930	0.188	0.333
Ricker a	3	0.013	0.009	1.000	0.255	0.308
199.50	4	0.014	0.010	1.000	0.310	0.300
	5	0.016	0.011	1.000	0.407	0.313
Ricker k (t)	6	0.017	0.011	1.000	0.344	0.308
1589303.37	7	0.017	0.011	1.000	0.339	0.333
	8	0.017	0.011	1.000	0.339	0.333

Scenario 5

M factor	age group	stock weight	catch weight	maturity	F	M
1.50	1	0.009	0.005	0.170	0.079	0.480
	2	0.012	0.007	0.930	0.147	0.400
Ricker a	3	0.013	0.009	1.000	0.202	0.370
135.34	4	0.014	0.010	1.000	0.250	0.360
	5	0.016	0.011	1.000	0.325	0.375
Ricker k (t)	6	0.017	0.011	1.000	0.281	0.370
8344890.18	7	0.017	0.011	1.000	0.279	0.400
	8	0.017	0.011	1.000	0.279	0.400

Table 3. Baltic sprat in Sub-divisions 22-32. Calculated reference values $F_{0.1}$, F_{max}, F_{msy}, B_{msy} and MSY under five different scenarios of natural mortality (M) factors.

M-factor	0.50	0.75	1.00	1.25	1.50
F0.1	0.21	0.29	0.39	0.50	0.62
Fmax	0.62	1.02	1.89	3.23	5.16
Fmsy	0.34	0.43	0.60	0.92	0.57
Bmsy (t)	2281017	1579209	1265938	1272823	4821964
MSY (t)	396548	320107	320027	428619	1064382

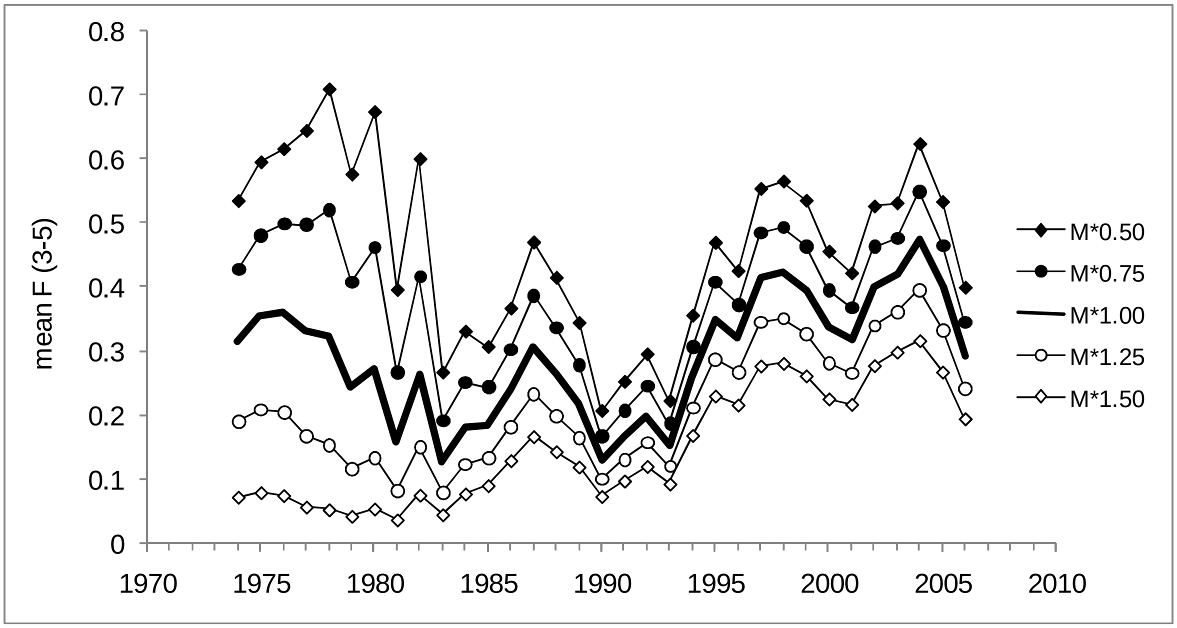

Figure 1. Baltic sprat in Sub-divisions 22-32. Trend in estimated mean fishing mortality F over ages 3-5, 1974-2006. The bold line illustrates the trend as reassessed and being identical with ICES (2007). The trends illustrated by lines below and above the bold line are estimated with varying natural mortality scaled by the factors given in the legend.

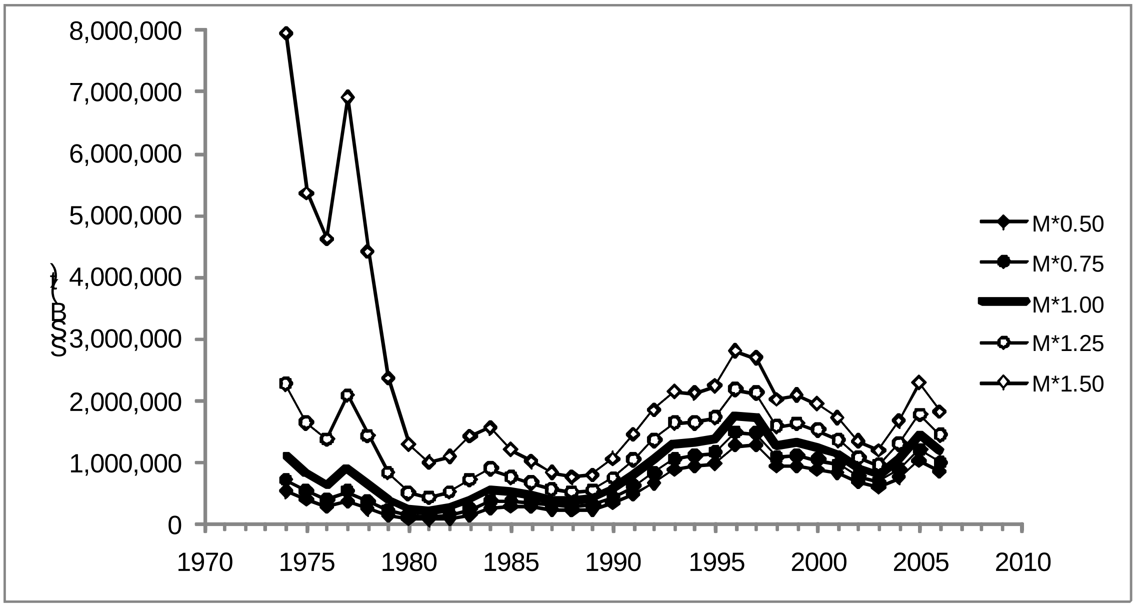

Figure 2. Baltic sprat in Sub-divisions 22-32. Trend in estimated spawning stock size, 1974-2006. The bold line illustrates the trend as reassessed and being identical with ICES (2007). The trends illustrated by lines below and above the bold line are estimated with varying natural mortality scaled by the factors given in the legend.

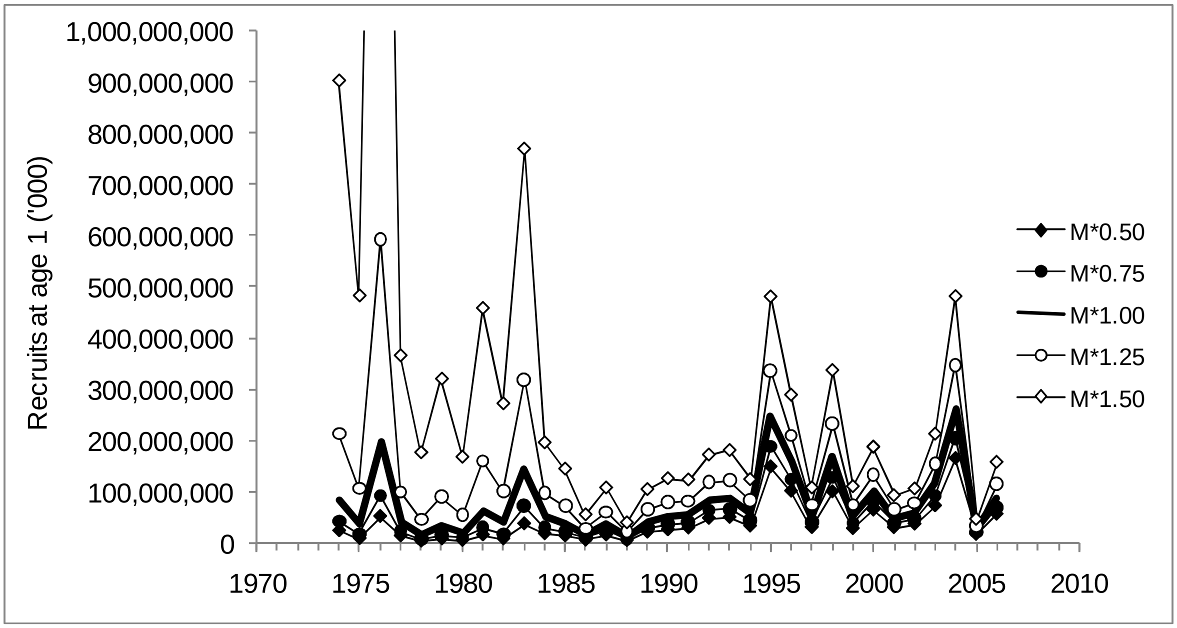

Figure 3. Baltic sprat in Sub-divisions 22-32. Trend in estimated recruitment at age 1, 1974-2006. The bold line illustrates the trend as reassessed and being identical with ICES (2007). The trends illustrated by lines below and above the bold line are estimated with varying natural mortality scaled by the factors given in the legend.

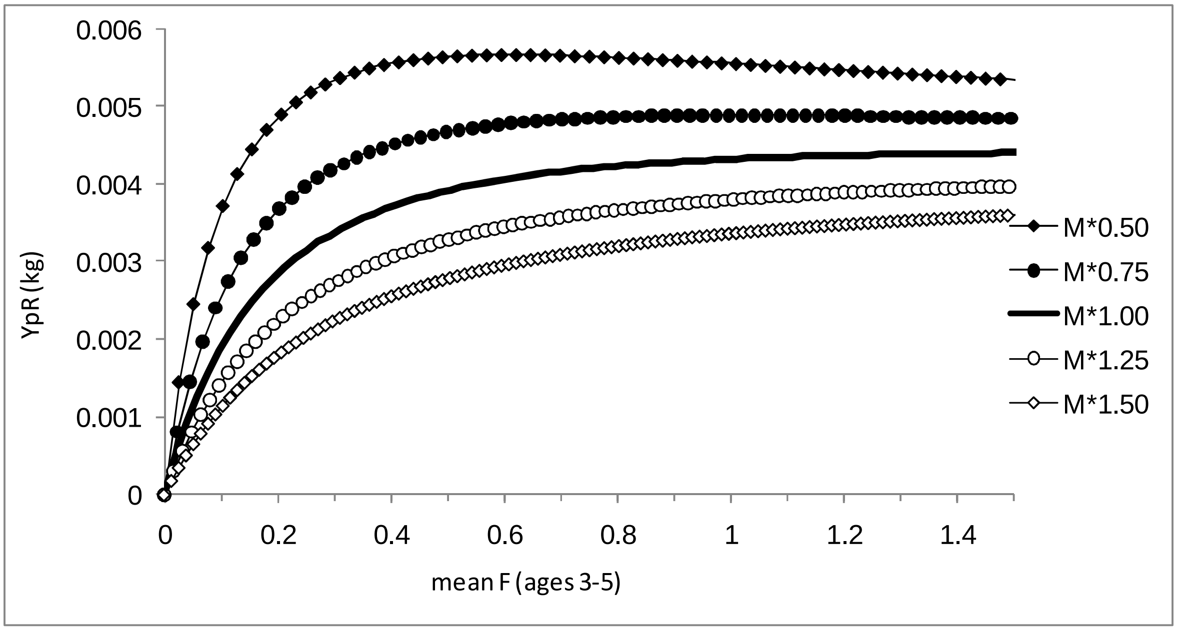

Figure 4. Baltic sprat in Sub-divisions 22-32. Yield per recruit functions over a range of annual fishing mortalities (F) for five scenarios based on different natural mortality (M) levels.

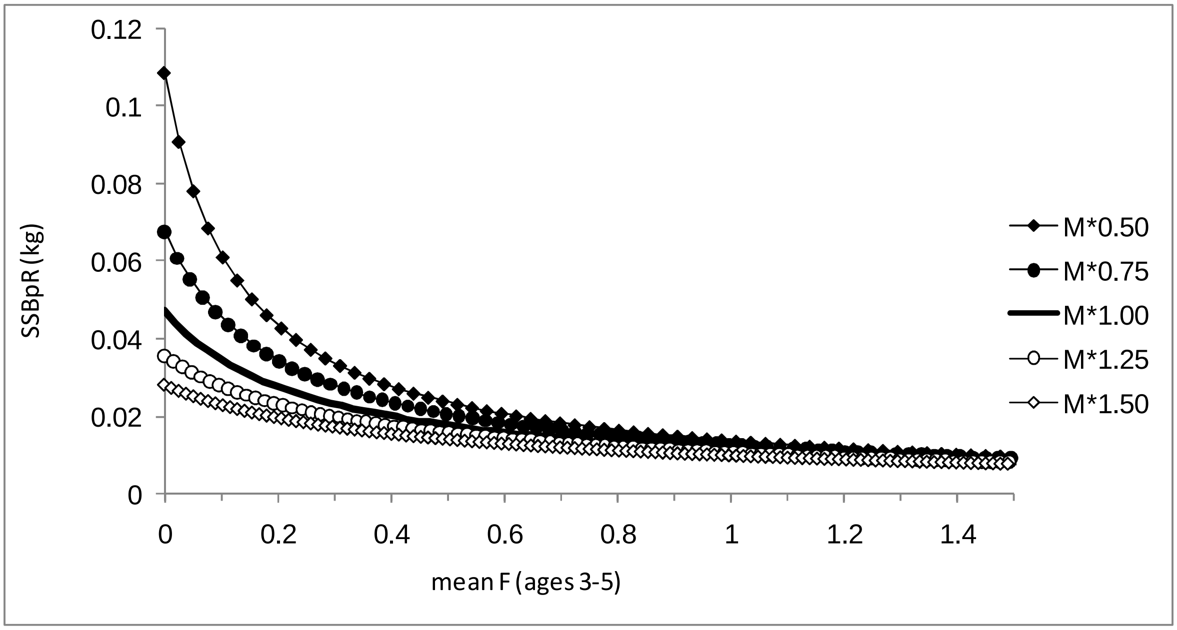

Figure 5. Baltic sprat in Sub-divisions 22-32. Spawning stock biomass per recruit functions over a range of annual fishing mortalities (F) for five scenarios based on different natural mortality (M) levels.

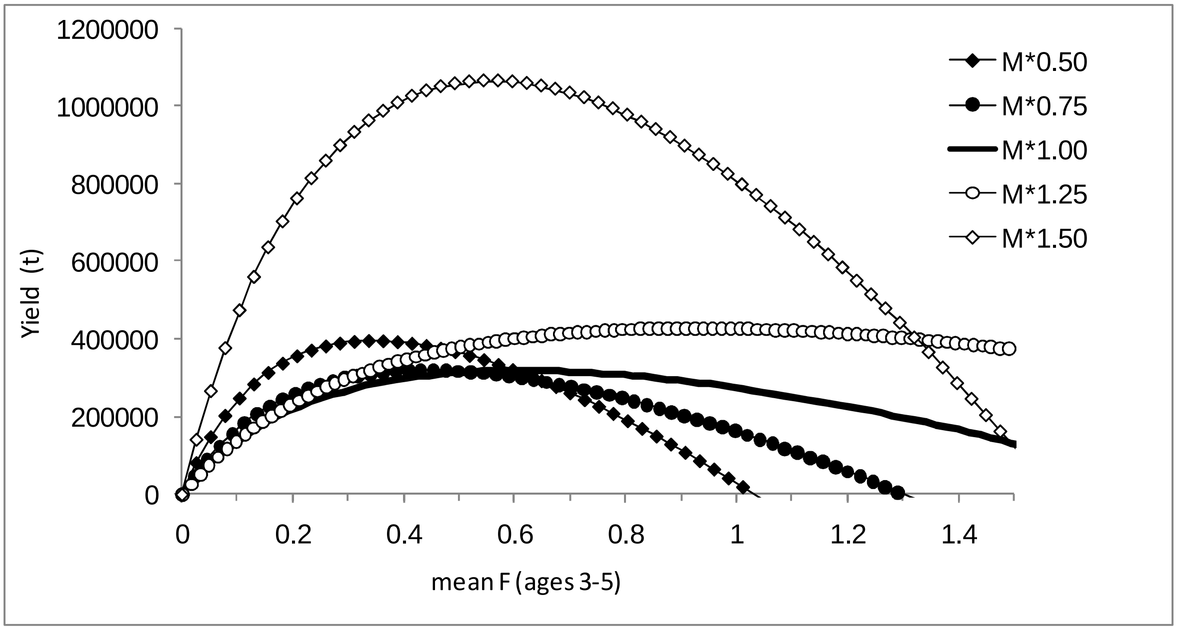

Figure 6. Baltic sprat in Sub-divisions 22-32. Equilibrium yield over a range of annual fishing mortalities (F) for five scenarios based on different natural mortality (M) levels.

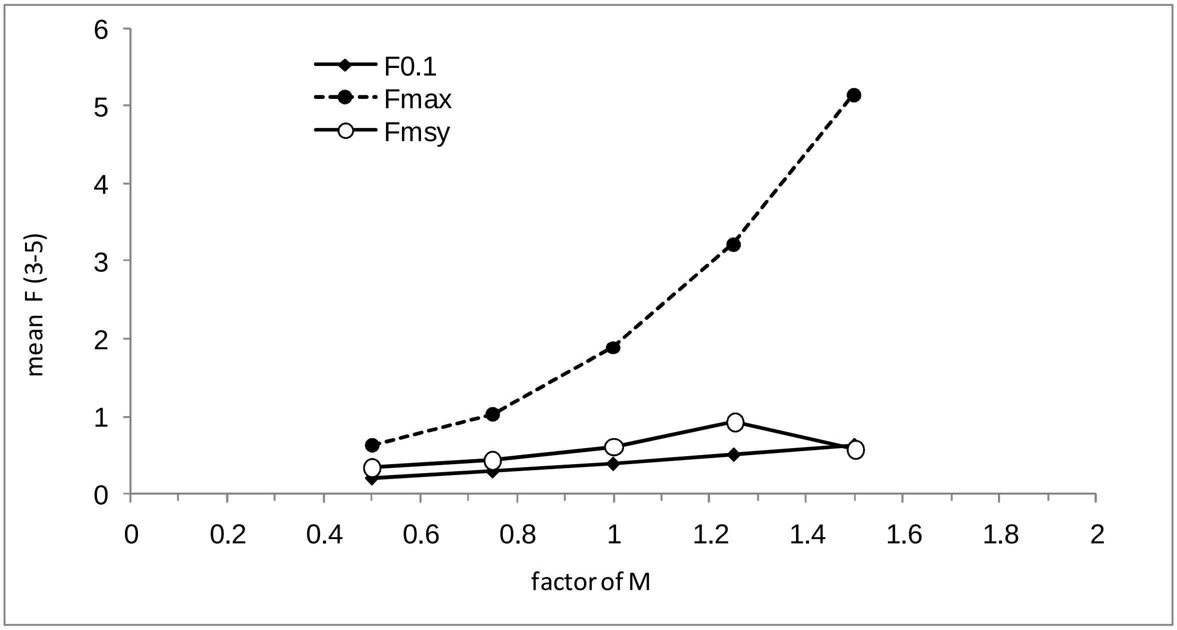

Figure 7. Baltic sprat in Sub-divisions 22-32. Estimated management reference points $F_{0.1}$, F_{max} and F_{msy} (annual) as a function of increasing mortality (M) .