The South African horse mackerel assessment for 2007 using an age-structured production model, with future biomass projections

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Summary

The conventional ASPM assessment of the South African horse mackerel resource is updated by taking account of recent trawl survey results. Projections are similar to those of previous assessments: a demersal/deepwater catch of 44 000 tons pa can be increased only provided the annual pelagic catch is kept below 5000 tons, or if the swept area survey results reflect appreciable negative bias. Acoustic survey estimates for recruit biomass are comparable with those from the ASPM, but acoustic estimates for total biomass are much less.

1. Introduction

The South African horse mackerel (*Trachurus trachurus capensis*) fishery began in 1950. It currently consists of a demersal/midwater trawl fleet (concentrated on the South coast) and a pelagic purse-seine fishery (concentrated on the West Coast). Adult horse mackerel are taken as a by-catch by the demersal trawl fleet and as a targeted catch by the mid-water trawl fleet. Juvenile horse mackerel are taken as a by-catch by the pelagic purse-seine fleet.

Previous stock assessment approaches for this fishery include a surplus production model (Punt 1989, 1992), and a Beverton-Holt yield-per-recruit approach (Butterworth and Raubenheimer 1992; Butterworth and Clarke 1996).

For convenience, the rest of this paper uses "demersal" to imply both midwater and demersal operations.

2. Methods

An age structured production model (ASPM) is used to model the South African horse mackerel resource. The model assumes one combined stock (West Coast plus South Coast). This model has been applied previously by Horsten (1999a, 1999b), OLRAC (2001) and Johnston and Butterworth (2001, 2002, 2004) for assessments of this resource. The work presented here does however incorporate updated catch and survey biomass data which previous assessments have not had available to them. The age-structured production model is described in full in the Appendix, along with the details of the likelihood function used for fitting the model to the data.

The model is deterministic and fits only two parameters, the pre-exploitation spawning biomass K^{sp}, the catchability coefficient corresponding to survey 1, q_1. Both the parameters h (the steepness parameter of the stock-recruit curve) and q_2 (the catchability coefficient corresponding to survey 2) have values which are set externally. Two values of h (0.6 and 0.9) and two values of q_2 are considered (0.5 and 1.0). These provide for four possible combinations of h and q_2.

The reason for fixing values of steepness h externally is that, as will become evident from the results below, the available data do not possess the information content to clearly distinguish even widely different values for h. The horse mackerel swept areas surveys are known to provide negatively biased estimates of abundance in absolute terms, but the extent of this bias in unknown. Results are presented for externally fixed values of q_2 (including q_2 =0.5 to reflect possible negative bias) because, again, the data do not have much power to distinguish these values.

The model assumes the population is at an unexploited equilibrium in 1950.

3. Input Data and Model assumptions

a) Historical catch

The historic catch record for both the demersal (strictly demersal + midwater) and pelagic fisheries for 1950-2006 are reported in Table 1.

b) Survey biomass estimates

The survey biomass estimates (demersal swept area surveys) and their associated CVs are reported in Table 2 (Leslie pers. commn). A further “survey 1” estimate will become available shortly for the 2006 season. Table 2 also reports whether the “old” or “new” gear has been used. From September 2003 a new net was introduced. The new gear has a higher vertical mouth opening which should increase horse mackerel catches (and estimates), but the door spread is less which should decrease herding and catches (and estimates) (Leslie pers. commn).

c) Natural Mortality

Natural mortality is assumed to constant for all ages. The base case value used here for M is 0.3 yr^{-1}.

Previous South African horse mackerel assessments (Punt and Leslie (1989), Butterworth *et al.* (1990) – for Namibian stock, Punt (1990), Butterworth and Raubenheimer (1992), Horsten 1999b, and Kinloch *et al*. (1986)) have used a value of *M* of 0.4 as a matter of convention. Kinloch *et al*. (1986) quote Pauly (1980) for the derivation of *M* = 0.4, following his relationship between natural mortality, growth rate, asymptotic length and average sea temperatures.

Horsten 1999a used three values of *M* (0.2, 0.3 and 0.4) in an age-structured production model for horse mackerel. Horsten 1997 explored the sensitivity of the Butterworth and Clarke (1996) model to different values of natural mortality, and concluded that that model output was very sensitive to the value of *M* and that it would be very valuable to obtain a more reliable value for this parameter. Horsten (1999c) goes on to report sensitivity of an ASPM for horse mackerel to values of *M*, and concludes that the ASPM model appears less sensitivity to the natural mortality assumption, and that changing the value of *M* had little relative effect on the negative log likelihood.

Here, the choice of the base case *M* = 0.3 is somewhat arbitrary, although sensitivity to alternate assumptions regarding *M* is reported.

d) Selectivity

Selectivity at age values used (from Horsten 1999a, b) are reported in Table 3. Note that there are three selectivity vectors for the pelagic fishery associated with three different periods. Essentially there is a different selectivity function for the pre-1963 period and a different selectivity function for the 1968+ period, with the average of these two selectivity functions used for the period in between (1963-1967). The reason for this change in selectivity is due to the change in fishing gear that occurred in the pelagic fishery. In 1968, anchovy gill nets were widely introduced to the purse-seine industry. These nets had 11mm wide mesh, compared to the previous 32mm nets. This led to the horse mackerel pelagic fleet targeting much smaller horse mackerel (generally ages 0-2), compared to the earlier years when juveniles were mostly avoided, and older fish aged 2-6 years were caught.

To quantify this change in pelagic selectivity, length distributions were collected spanning the history of the fishery. Van der Westhuizen (pers. commn) provided the purse-seine size-frequencies at the time. At this time, length distributions for the demersal fishery (Punt and Leslie 1989) were also examined to produce a suitable demersal selectivity function. The selectivity curves were developed, based on the catch proportions-by-age extracted from the length frequency distributions, using Kerstan's 1999 (pers. commn.) growth parameters.

e) Weight-at-age

The weight-at-age values are reported in Table 3 and are based upon a von Bertalanfy growth curve with parameters: $l_\infty = 54.56$ (cm), t_0 = -0.654 (yr), $\kappa = 0.183$ (yr^{-1}), and a weight-length relationship $w = 0.0078 l^{3.0}$ (g).

f) Age at maturity

Age-at-maturity is assumed to be the age corresponding to 100% sexual maturity, which is taken here to be described by a knife-edge function of age. For South African horse mackerel, the age-at-maturity is assumed to be 3 years (Leslie pers. commn in Butterworth and Clarke 1996).

Note: Reliable CPUE data series for this fishery are not available. The main reason is that most horse mackerel are caught as a by-catch, making "effort" spent on catching horse mackerel very difficult to quantify. The Japanese fleet (which specifically targeted horse mackerel) was able to provide a consistent CPUE series during earlier decades, but this is for the 1976-1988 period only.

4. Model variants

Four assessment model variants corresponding to four combinations of the model parameters q_2 and h are considered. They are:

- Model 1: q_2 = 1.0; h = 0.6

- Model 2: $q_2 = 1.0$; $h = 0.9$
- Model 3: $q_2 = 0.5$; $h = 0.6$
- Model 4: $q_2 = 0.5$; $h = 0.9$

These four models are selected as they seem likely to contain the most probable q_2 and h value combinations of the original nine models explored in Johnston and Butterworth (2001). Note that q_2 is the bias of the survey estimates: a value of 0.50 for example, means that the biomass is actually twice as large as the survey estimates. The h parameter is some measure of the productivity of the resource: the higher the h, the more productive the resource.

Sensitivity analyses

Sensitivity to assumptions regarding natural mortality is investigated. The base case model assumes that natural mortality is constant for all ages and is equal to 0.3. The following sensitivity analyses are reported for Model 3 ($q_2 = 0.5$; $h = 0.6$).

- $M = 0.2$
- $M = 0.4$
- M is age-dependent ($M = 0.6$ for $a = 0$; $M = 0.5$ for $a = 1$; $M = 0.4$ for $a = 2$; and $M = 0.3$ for $a = 3+$).

Sensitivity to distinguish between the old and new gear used in the surveys (see Table 2) is also investigated. Here it is assumed that

$$q_1^{new} = q_1^{old} e^{\delta} \text{ and}$$

$$q_2^{new} = q_2^{old} e^{\delta} \text{, where}$$

δ is a further estimable parameter.

5. Output statistics

The following output statistics are reported.

K^{sp}	the spawning biomass level in 1950 (the estimable parameter)
q_1 , q_2	the catchability coefficients corresponding to the two survey series

h	the steepness parameter of the stock-recruit curve
$-lnL$ total	the total $-lnL$ value which is minimised
MSY	the demeral MSY (when assuming the pelagic catch is zero, for simplicity)
B_{MSY}	the spawning biomass level that will result in MSY
B_{MSY}/K^{sp}	the ratio of B_{MSY} to K^{sp}.
$B(1950)$	the demersal exploitable biomass (mid-year) for 1950
$B(2007)$	the demersal exploitable biomass (mid-year) for 2007
$\frac{B(2007)}{B(1950)}$	the ratio of current (2007) demersal exploitable biomass relative to that at the start of the fishery

6. Projections

The model is used to project the resource biomass ahead for the period 2008-2020. A number of alternate future demersal and pelagic catch scenarios are considered as follows:

Future demersal catch scenarios

- 34000 MT for all future years (2008-2020)
- 44000 MT for all future years (2008-2020)
- 60000 MT for all future years (2008-2020)

Future pelagic catch scenarios [for 2008-2020]

- 0 MT
- 5000 MT
- 10000 MT
- 15000 MT

7. Results

Table 4a reports the various model estimates for each of the four models considered. The *MSY* estimates reported correspond to the assumption that all catch is demersal. Table 4b compares results for Model 3 (q_2 = 0.5; h = 0.6) for different assumptions regarding natural mortality.

Tables 5a-d report the spawning biomass relative to K^{sp} values for the four assessment models considered. Results are presented for all combinations of the future demersal and pelagic scenarios considered.

Figures 1a and 1b illustrate the four assessment models' estimated trends in spawning biomass relative to K^{sp} trends for 1950-2007. Figures 2a-c illustrate the projected spawning biomass relative to K^{sp} values for the different future catch scenarios.

Figure 3a illustrates the fits of each of the four models to both the survey 1 and survey 2 series.

Comparison to acoustic survey biomass estimates

Figure 4a compares the assessment model 1(h = 0.6, q_2 = 1.0) and model 3 (h = 0.6, q_2 = 0.5) estimated mid-year juvenile (ages 0) biomass with results from acoustic recruitment biomass surveys (Merkle and Coetzee 2007) for the period 1997-2006. Figure 4b is similar, except compares the model estimated total biomass estimates with the total acoustic biomass survey results also provided by Merkle and Coetzee (2007) (note that the original abundance estimates in this paper have recently been recomputed – the newer values are used here). Acoustic survey results are shown with $\pm$ 1se. The equations used to estimate the model recruitment and total biomass values are as follows:

$$\hat{B}_{0,y} = w_{0+\frac{1}{2}}[N_{0,y}e^{-M_0/2} - C_{0,y}/2] \text{ and}$$

$$\hat{B}_{total,y} = \sum_{a=0}^{m} w_{a+\frac{1}{2}}[N_{a,y}e^{-M_a/2} - C_{a,y}/2]$$

Sensitivity analyses

Sensitivity to alternate assumption for natural mortality is reported in Table 4b. Sensitivity to taking into account the change of gear type in recent years is reported in Table 4c and Figure 3b compares model 3 fits to both survey series with or without taking into account gear change.

8. Discussion

Table 4a shows that the better fits to the data are provided by Model 3 (q_2 = 0.5; h = 0.6) and Model 4 (q_2 = 0.5; h = 0.9), with Model 4 having the lowest log-likelihood value. The MSY estimate for Model 3 is some 63 000 t whilst MSY for Model 4 is higher at some 80 000t. Model 4 estimates the 2007 exploitable biomass (some 675 000 t) to be 72% of carrying capacity. The B_{msy}/K^{sp} is estimated to be 0.25. Model 4 (and the other three models) indicates that this resource is currently under-exploited. None of the four models estimate the 2007 exploitable biomass level to be below 50% K (see also Figure 1a and b). The fits to the survey series do however exhibit quite a high variance.

The model appears to be fairly robust to assumptions regarding natural mortality (Table 4b). The model also appears to be insensitive to the case where allowance is made for a difference in selectivity between the “old” and “new” gear (Table 4c and Figure 3b); the improvement in log-likelihood is not sufficient to justify the addition of the extra estimable parameter δ .

Examination of the projections (Figures 2a-d) reveal that models 1 and 2 (q_2 = 1.0) are clearly more pessimistic than models 3 and 4 (q_2 = 0.5) as would be expected. The option of increasing the demersal catch to 60 000 tons is clearly problematic for q_2 = 1.0, and also for q_2 = 0.5 for pelagic catches exceeding 5000 tons.

Comparison to acoustic survey biomass estimates

The hydroacoustic survey biomass estimates for recruits seem reasonably comparable with the model (Figure 4a). However total biomass results from these surveys are much less than the model suggests (Figure 4b), particularly for q_2 =0.5. Discussion is warranted on whether the expected negative bias in these surveys could be as large as Figure 4b suggests.

9. Future Work

During the BENEFIT/NRF/BCLME stock assessment workshop held at UCT in December 2004, the assessments of a number of horse mackerel resources of the Benguela Current region were discussed in great detail. The following are the recommendations and agreements arising from the discussions held during the workshop that have some pertinence to the South African population.. Each recommendation was ranked High, Medium or Low by the workshop participants based on the importance of the recommendation in terms of its likely impact on management decisions, and its feasibility.

Although the workshop ranked research recommendations in H, M and L categories, it did not rank them within these categories. The workshop recognised that the time required to implement some of the recommendations would be substantial, and that management advice may have to be provided prior to even some of the high priority research topics being addressed. The numbers against each recommendation refer to the sections in the main text where the recommendation arose, and where additional commentary may be found. Inspection of the lists following indicates relatively little progress over the past three years.

I. Recommendations

A. Horse mackerel – general

A.1 (H, 3.2) The BCLME proposal to analyse additional genetics data for horse mackerel should be conducted, should consider both mtDNA and microsatellite markers and be based on samples collected widely off South Africa, Namibia and Angola.

A.2 (M, 3.1) Efforts should be made to understand the influence of oceanographic changes on fish distribution and aggregation.

B. Horse mackerel – South Africa

B.1 (H, 3.3.1) A study examining how horse mackerel react to trawl nets should be conducted to provide insight as to what the demersal trawl surveys are actually surveying, and thereby insight concerning the proportion of the catch that is taken in the water column rather than off the bottom.

B.2 (H, 3.3.1) Work on developing combined acoustic and bottom trawl surveys for horse mackerel should continue.

B.3 (H, 3.4.1) Future assessments of the South African horse mackerel resource should be based on the specifications and sensitivity tests listed in Section 3.4.1. which are:

“Section 3.4.1:

a) Include the following “fleets”: the pelagic fishery prior to about 1969 when catches of large fish were recorded (the “early” pelagic fishery); the pelagic fishery after about 1969 when catches have consisted of small fish; the South African demersal fishery off the West and South Coasts separately; the foreign fleet and the recent South African midwater fishery.
b) Fit to the bottom trawl survey indices of abundance for the West and South Coasts (treated as relative indices of abundance, possibly with a constraint on the two survey catchability coefficients so that they sum to less than one) and the Japanese CPUE series.
c) Fit to the length-frequency data for each of the fleets (to determine selectivity patterns and to estimate year-class strengths). Unlike in many other assessments based on the age-structured production model approach, it may be necessary to estimate the strengths of some of the year-classes spawned during the 1950s to be able to mimic the length-frequency data for the “early” pelagic fishery.
d) Estimate the selectivity ogives rather than pre-specifying them.
e) Set the rate of natural mortality equal to 0.4 yr^{-1} instead of 0.3 yr^{-1}.

The workshop identified the following sensitivity tests and **recommended** that they be conducted:

a) Set the rate of natural mortality equal to 0.5 yr^{-1}
b) Exclude the Japanese CPUE series.

c) Increase the rate of natural mortality for age 0 fish to 1.0 or 0.9 yr^{-1} (as considered appropriate for sardine and anchovy of this age). This sensitivity test is designed primarily to examine further the trade-off between catching horse mackerel using pelagic rather than midwater gear.

d) Replace the assumption of an age-at-maturity at age 3 by the maturity-at-age vector estimated for horse mackerel off Namibia."

B.4 (H, 3.6) Industry should be fully consulted if an adaptive harvest strategy is considered for South African horse mackerel (see II.B.3.), particularly to determine desirable (and undesirable) levels of change in catch levels given the expected benefits of "adaptive management".

B.5 (M, 3.3.1) A self-consistent database containing length, weight, age and maturity information should be established and the various biological functions and relationships estimated therefrom.

B.6 (M, 3.3.1) The length-frequency data from the South African midwater and demersal fleets and the Japanese demersal fleet should be examined to determine whether it is necessary to model all three of these fleets separately.

B.7 (M, 3.1.1) A CPUE index series should be developed for the midwater trawl fishery.

II. Agreements

A. Horse mackerel – general

A.1 (3.2) The available data for *T. capensis* are consistent with the current working hypothesis that the horse mackerel off Namibia and South Africa are independent stocks and can be assessed and managed as such. There is limited sharing of a *T. capensis* stock between Namibia and Angola.

A.2 (3.3.2) If age-composition data are required, it would be better to use the LAK method of Clarke (1981) than to apply an age-length key for one year to the length-frequency data for several years (but see also Section 3.4.2). Nevertheless, it remains preferable to fit population models to catch-at-length data for years for which ageing was not conducted.

B. Horse mackerel – South Africa

B.1 (3.3.1) Although the trawl net used in the bottom trawl surveys may be catching horse mackerel off the bottom for much of the time, the catch rates could still provide a useful relative index of abundance.

B.2 (3.3.1) There are considerable benefits to collecting acoustic data from commercial midwater trawlers fishing for horse mackerel whose catches are sampled by onboard scientific observers.

B.3 (3.6) Given the relatively little information on horse mackerel off South Africa, the use of an adaptive harvest strategy is an appropriate way to substantially improve knowledge of the status and productivity of the resource in the short-to-medium term.

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Table 1: Annual landings (MT) of horse mackerel by coast and gear.

	West Coast			South Coast		Total	
Year	Pelagic	Demersal	Midwater	Demersal	Midwater	Pelagic	Demersal+ Midwater
1950	49900	316		129		49900	445
1951	98900	905		200		98900	1105
1952	102600	1109		117		102600	1226
1953	85200	1407		49		85200	1456
1954	118100	2478		72		118100	2550
1955	78800	1733		193		78800	1926
1956	45800	1006		328		45800	1334
1957	84600	769		190		84600	959
1958	56400	1836		237		56400	2073
1959	17700	1636		439		17700	2075
1960	62900	3283		429		62900	3712
1961	38900	3174		453		38900	3627
1962	67700	2525		554		67700	3079
1963	23300	880		521		23300	1401
1964	24400	1151		8371		24400	9522
1965	55000	1188		5829		55000	7017
1966	26300	1472		6124		26300	7596
1967	8800	1296		4893		8800	6189
1968	1400	309		8807		1400	9116
1969	26800	1382		10870		26800	12252
1970	7900	3600		14272		7900	17872
1971	2200	6087		27261		2200	33348
1972	1300	2323		18233		1300	20556
1973	1600	10604		24711		1600	35315
1974	2500	7070		29584		2500	36654
1975	1600	19236		50609		1600	69845
1976	400	2445		32369		400	34814
1977	1900	6593		62223		1900	68816
1978	3600	3284		32091		3600	35375
1979	4300	7956		52112		4300	60068
1980	400	2614		40013		400	42627
1981	6100	1273		32610		6100	33883
1982	1100	824		32267		1100	33091
1983	2100	1393		40114		2100	41507
1984	2800	1989		36828		2800	38817
1985	700	873		30407		700	31280
1986	500	1146		34666		500	35812
1987	2800	3551		38421		2800	41972
1988	6300	2502		31831		6300	34333
1989	25500	3216		30947		25500	34163
1990	7134	4546		39101		7134	43646
1991	548	3742		20232		548	23974
1992	1968	4140		19137		1968	23276
1993	11646	3590		14836		11646	18426
1994	8210	2019		6460		8210	8479
1995	1991	2047		4655		1991	6702
1996	18980	2633		7074		18980	9707
1997	12700	2528		8804		12700	11332

1998	26661	2791	29	6885	4177	26661	13882
1999	2050	1876	36	7372	890	2050	10174
2000	4503	1077	7	8643	14775	4503	24502
2001	916	1036	8	8764	15256	916	25064
2002	8149	791	0	5410	9472	8149	15673
2003	1012	617	3	3640	28045	1012	32305
2004	2048	1027	38	3867	27154	2048	32086
2005	5628	1714	7	8606	20758	5628	30985
2006	4824	558	0	4159	17214	4824	17772

Table 2: Swept area survey biomass estimates (MT) for the spring (Survey 1) and autumn (Survey 2) biomass series (Leslie, pers. commn).

Year	Survey 1 (Spring/Sept)	CV	Gear	Survey 2 (Autumn/April)	CV	Gear
1987	308300	0.15	Old	308816	0.15	Old
1988	-	-	-	203625	0.23	Old
1989	501100	0.23	Old	510281	0.24	Old
1990	579900	0.18	Old	431275	0.19	Old
1991	467000	0.24	Old	518211	0.19	Old
1992	320200	0.18	Old	529152	0.19	Old
1993	373500	0.23	Old	422911	0.23	Old
1994	279400	0.23	Old	241648	0.28	Old
1995	-	-	-	320342	0.71	Old
1996	-	-	-	290338	0.24	Old
1997	-	-	-	220849	0.24	Old
1998	-	-	-	-	-	-
1999	-	-	-	327409	0.25	Old
2000	-	-	-	321512	0.33	Old
2001	293221	0.20	Old	-	-	-
2002	-	-		-	-	-
2003	230957	0.20	New	141698	0.24	Old
2004	-	-	-	197096	0.32	New
2005	-	-	-	173321	0.21	New
2006	To come	-	-	387692	0.19	Old
2007	N/A	-	-	237486	0.40	New

Table 3. Selectivity and weight-at-age vectors.

a	S_a^p 1950-1962	S_a^p 1963-1967	S_a^p 1968+	S_a^d 1950+	w_a (g)*
0	0.00	0.14	0.28	0.00	1.81
1	0.00	0.50	1.00	0.33	22.57
2	0.30	0.40	0.50	0.67	72.14
3	1.00	0.50	0.00	1.00	146.88
4	0.50	0.25	0.00	1.00	238.71
5	0.50	0.25	0.00	1.00	339.40
6	0.25	0.13	0.00	1.00	442.17
7	0	0.00	0.00	1.00	542.11
8	0	0.00	0.00	1.00	636.01
9	0	0.00	0.00	1.00	722.00
10+	0	0.00	0.00	1.00	799.27

Table 4a: Base case horse mackerel stock assessment results when fitting to data in Tables 1 - 2. *B* refers to the mid-year exploitable biomass for the demersal fishery.

q_2	*h*	K^{sp}	q_1	*-lnL total*	*MSY*	*Bmsy (sp)*	*B*(1950)	*B*(2007)	$\frac{B(2007)}{B(1950)}$	B_{msy}/K^{sp}
1.0	0.6	835155	1.07	16.10	52123	290823	863554	437708	0.507	0.348
1.0	0.9	681792	1.18	17.13	60181	172742	704976	431207	0.612	0.253
0.5	0.6	1010700	0.55	1.38	63079	351951	1045060	696895	0.667	0.348
0.5	0.9	906545	0.55	0.07	80020	937371	937371	675282	0.720	0.253

Table 4b: Comparison of horse mackerel stock assessment results for different assumptions regarding natural mortality. Results are for Model 3 (q_2 = 0.5; *h* = 0.6).

M	K^{sp}	q_1	*-lnL total*	*MSY*	*Bmsy (sp)*	*B*(1950)	*B*(2007)	$\frac{B(2007)}{B(1950)}$	B_{msy}/K^{sp}
0.2	1440220	0.64	21.70	64506	509974	1480920	832612	0.562	0.354
0.3 (BC)	**1010700**	**0.55**	**1.38**	**63079**	**351951**	**1045060**	**696895**	**0.667**	**0.348**
0.4	1112190	0.48	29.52	91095	377914	116590	696002	0.820	0.340
M age dependent	1093020	0.48	8.78	69087	377943	1136980	826534	0.727	0.346

Table 4c: Comparison of horse mackerel stock assessment results for different assumptions regarding “old” and “new” gear. Results are for Model 3 (q_2 = 0.5; *h* = 0.6).

	K^{sp}	q_1	*-lnL total*	*MSY*	*Bmsy (sp)*	*B*(1950)	*B*(2007)	$\frac{B(2007)}{B(1950)}$	B_{msy}/K^{sp}
No account taken of different gear	**1010700**	**0.55**	**1.38**	**63079**	**351951**	**1045060**	**696895**	**0.667**	**0.348**
Different gear taken into account e^{δ} =0.97	1086430	0.48	1.07	67805	378324	1123380	783181	0.697	0.348

Table 5a: Values of future spawning biomass relative to K^{sp} for four different future pelagic catch scenarios (0 MT, 5000 MT, 10000 MT and 15000 MT). Future demersal catches are assumed to be either 34000 MT, 44000 MT (2006+) or 60000 MT (2006+). Results are presented for the $\boldsymbol{q_2}$ **= 1.0;** $\boldsymbol{h}$ **= 0.6** scenario. Values are shaded if they fall below 0.55 for 2010 or below 0.45 for 2020.

Future demersal catch (MT)	Year	Future pelagic catch (MT)			
		0	**5000**	**10000**	**15000**
34000	2007	0.48	0.48	0.48	0.48
	2010	0.49	0.47	0.46	0.45
	2020	0.61	0.47	0.33	0.16
44000	2007	0.48	0.48	0.48	0.48
	2010	0.46	0.45	0.44	0.42
	2020	0.51	0.37	0.21	0.04
60000	2007	0.48	0.48	0.48	0.48
	2010	0.43	0.41	0.40	0.39
	2020	0.33	0.17	0	0

Table 5b: As for Table 1a but for the $\boldsymbol{q_2}$ **= 1.0;** $\boldsymbol{h}$ **= 0.9** scenario.

Future demersal catch (MT)	Year	Future pelagic catch (MT)			
		0	**5000**	**10000**	**15000**
34000	2007	0.58	0.58	0.58	0.58
	2010	0.57	0.56	0.54	0.52
	2020	0.67	0.53	0.38	0.22
44000	2007	0.58	0.58	0.58	0.58
	2010	0.54	0.53	0.51	0.50
	2020	0.57	0.42	0.27	0.10
60000	2007	0.62	0.58	0.58	0.58
	2010	0.50	0.48	0.47	0.46
	2020	0.39	0.23	0.05	0

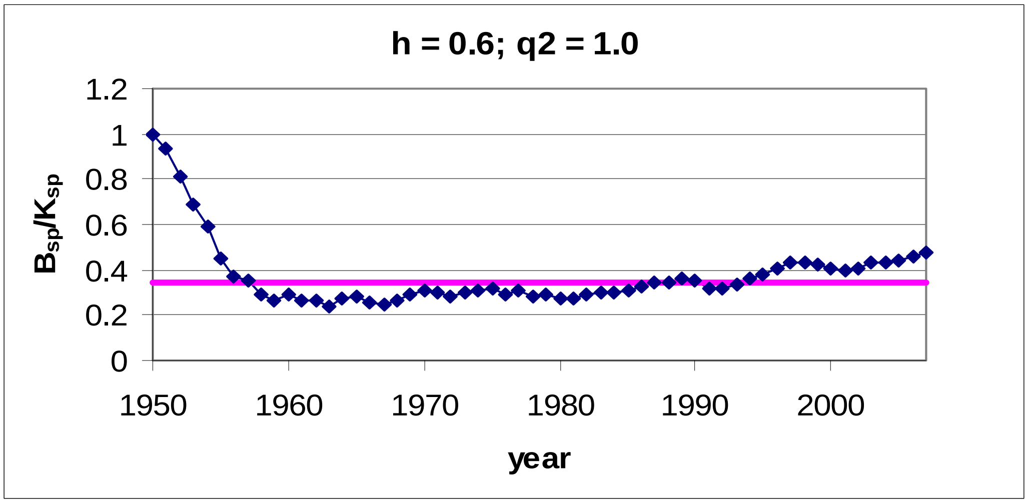
Table 5c: As for Table 1a but for the $\boldsymbol{q_2}$ **= 0.5;** ***h*** **= 0.6** scenario.

Future demersal catch (MT)	**Year**	**Future pelagic catch (MT)**			
		0	**5000**	**10000**	**15000**
34000	2007	0.65	0.65	0.65	0.65
	2010	0.64	0.63	0.62	0.61
	2020	0.72	0.62	0.51	0.39
44000	2007	0.65	0.65	0.65	0.65
	2010	0.62	0.61	0.60	0.59
	2020	0.65	0.54	0.43	0.31
60000	2007	0.65	0.65	0.65	0.65
	2010	0.60	0.58	0.57	0.56
	2020	0.53	0.42	0.30	0.18

Table 5d: As for Table 1a but for the $\boldsymbol{q_2}$ **= 0.5;** ***h*** **= 0.9** scenario.

Future demersal catch (MT)	**Year**	**Future pelagic catch (MT)**			
		0	**5000**	**10000**	**15000**
34000	2007	0.70	0.70	0.70	0.70
	2010	0.69	0.68	0.67	0.66
	2020	0.70	0.66	0.55	0.44
44000	2007	0.70	0.70	0.70	0.70
	2010	0.67	0.66	0.65	0.63
	2020	0.69	0.59	0.48	0.37
60000	2007	0.70	0.70	0.70	0.70
	2010	0.64	0.63	0.61	0.60
	2020	0.58	0.47	0.36	0.24

Figure 1a: Spawning biomass relative to K^{sp} trends. The B_{msy}/K level is shown as a solid line.



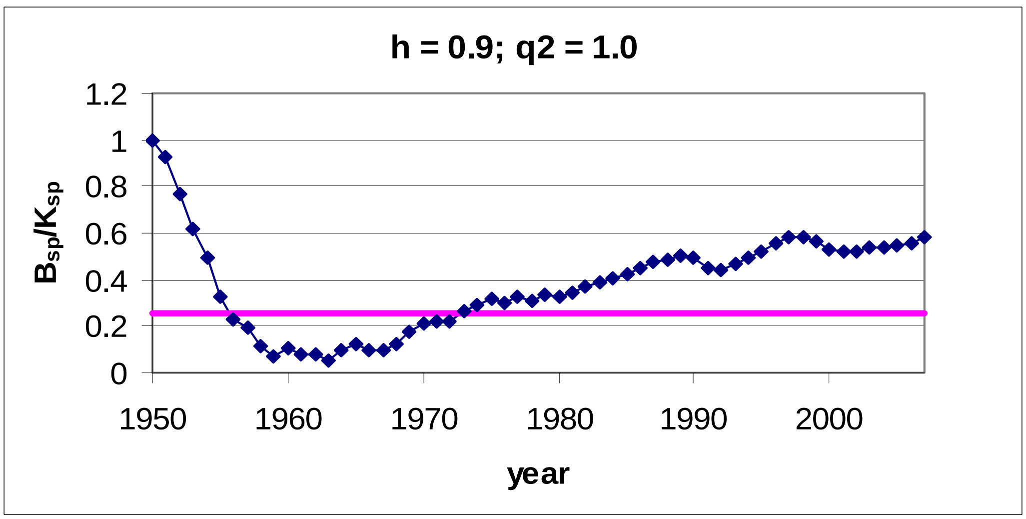
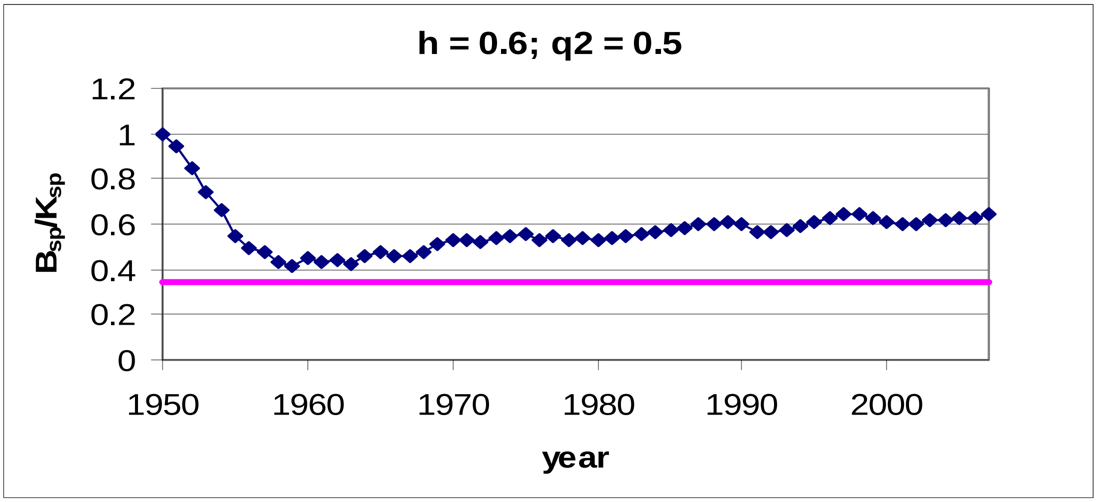


Figure 1b: Spawning biomass relative to K^{sp} trends. The B_{msy}/K level is shown as a solid line.



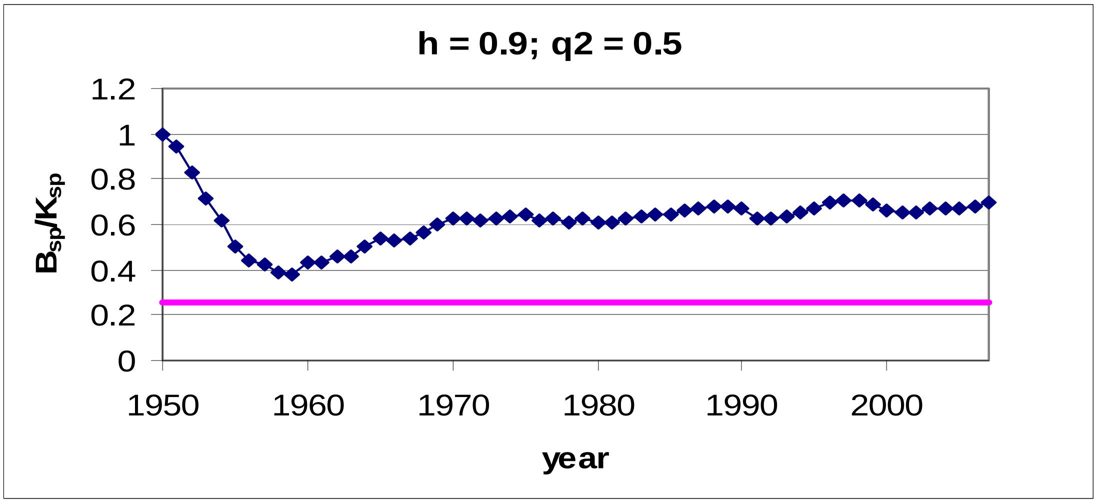


Figure 2a: Trajectories of spawning biomass relative to K^{sp}. Projections are shown for four different future pelagic catch scenarios (0 MT, 5000 MT, 10000 MT and 15000 MT), as well as for a future demersal catch of **34000** MT.

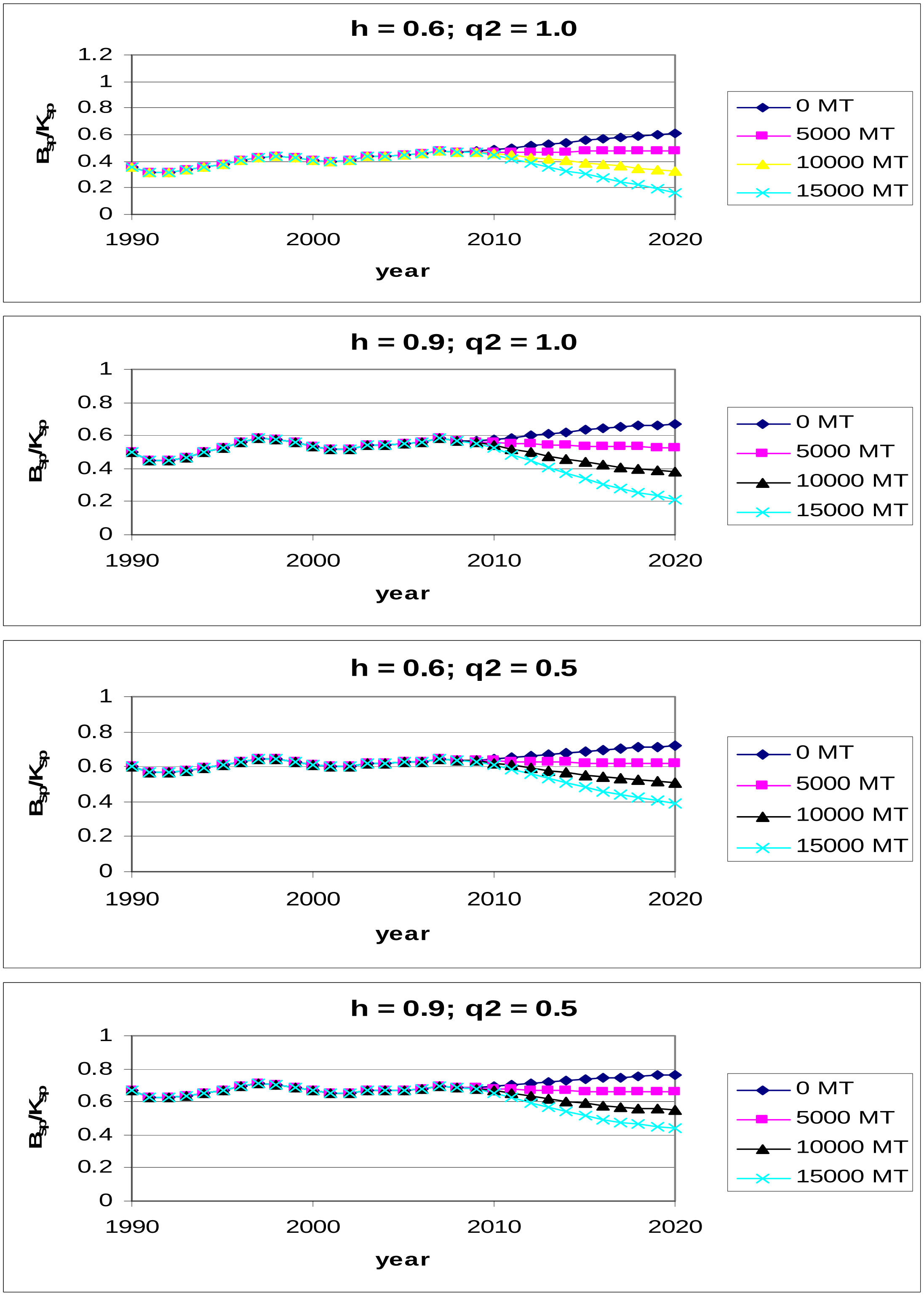


Figure 2b: As for Figure 2a, but assuming a future (2006+) demersal catch of **44000** MT.

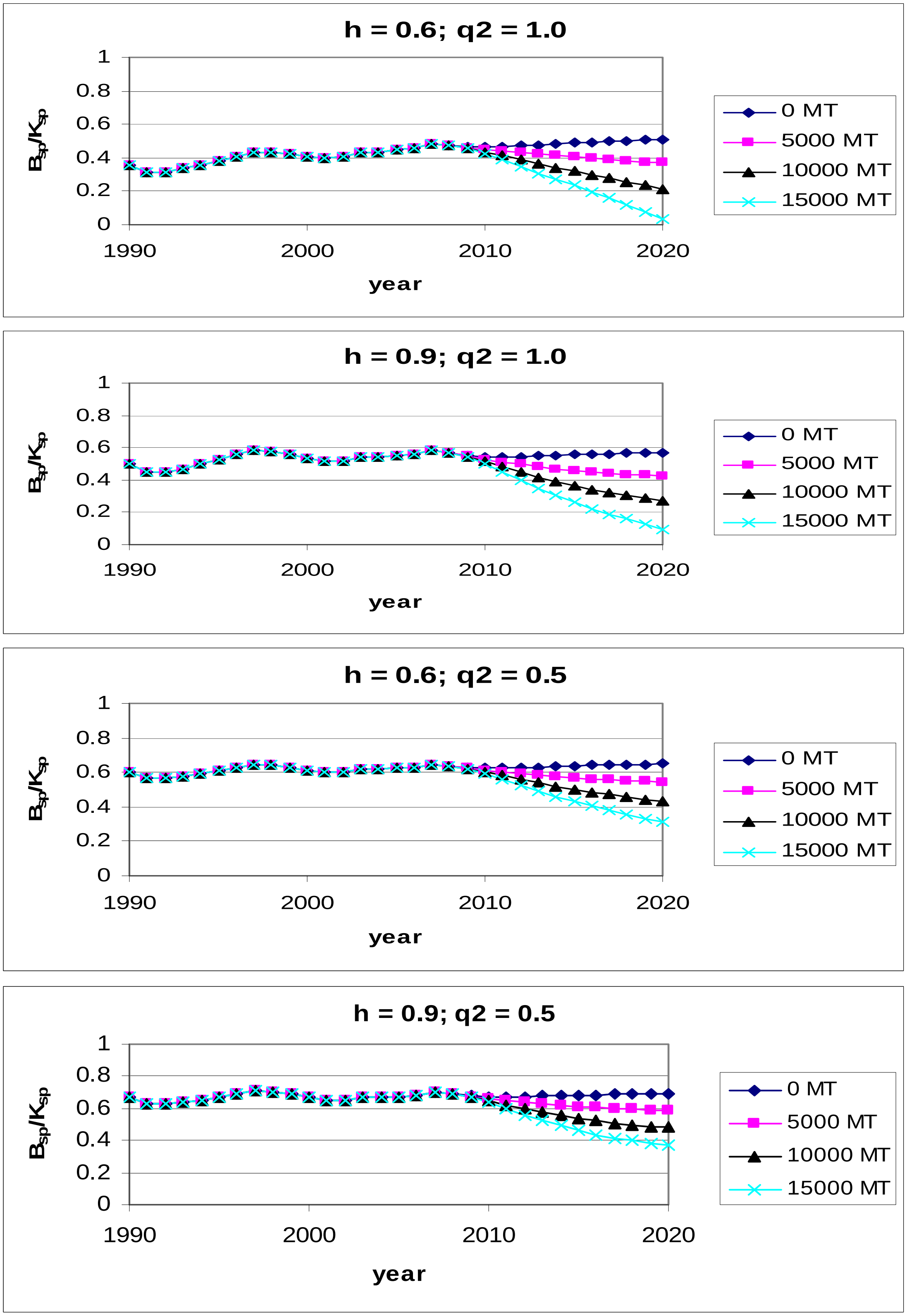


Figure 2c: As for Figure 2a, but assuming a future (2006+) demersal catch of **60000** MT.

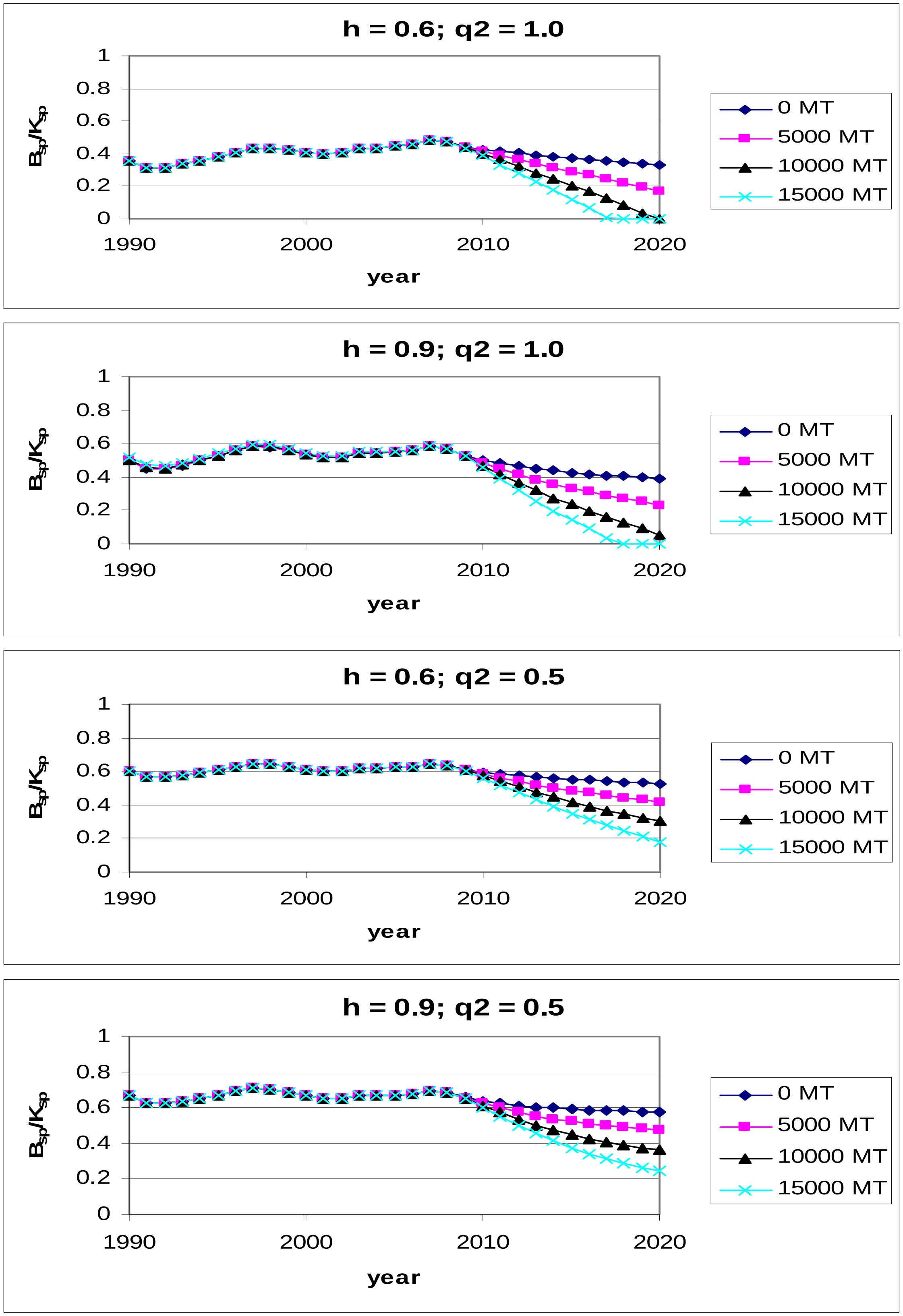


Figure 3a: Model fits to both survey series.

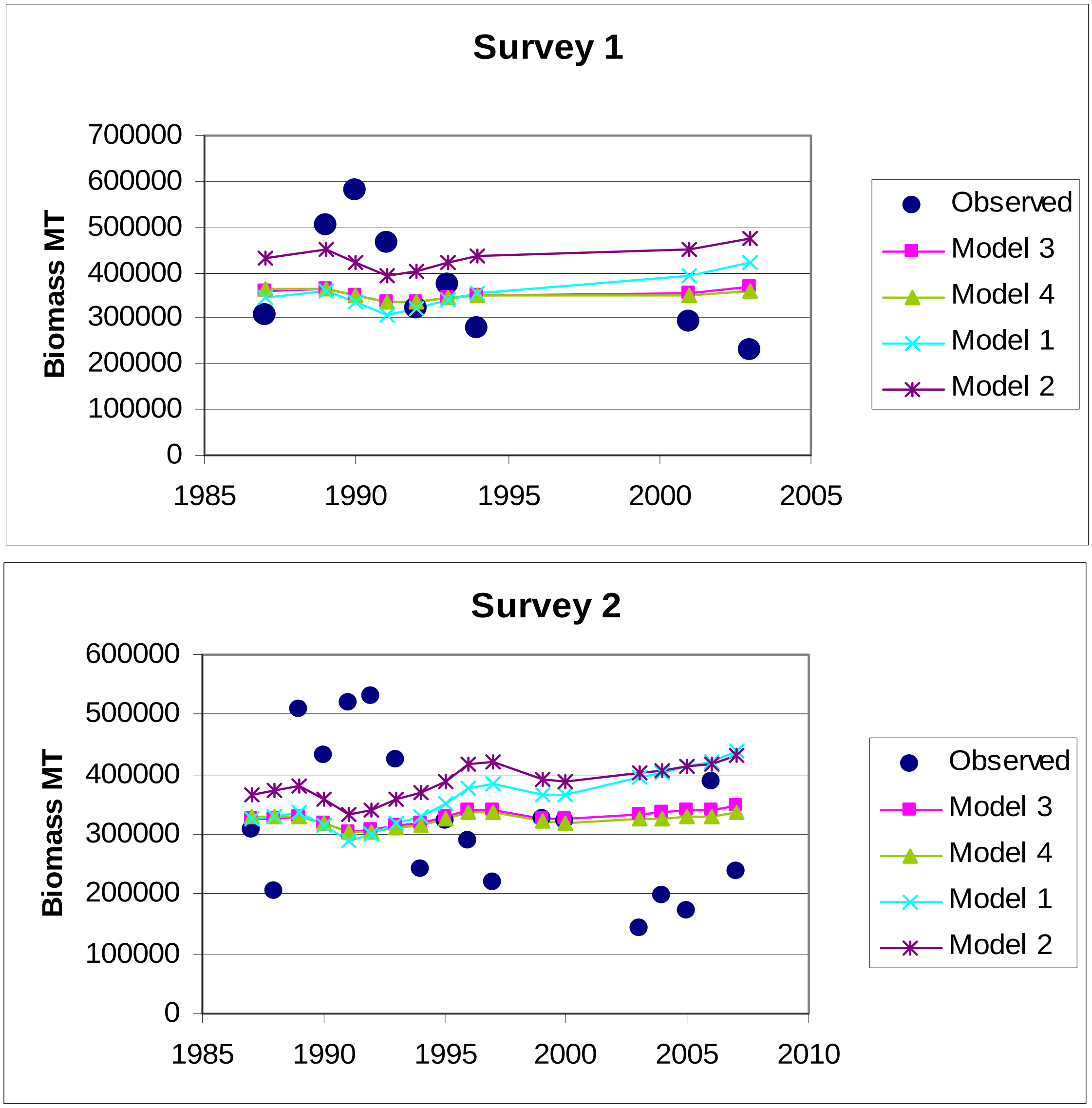
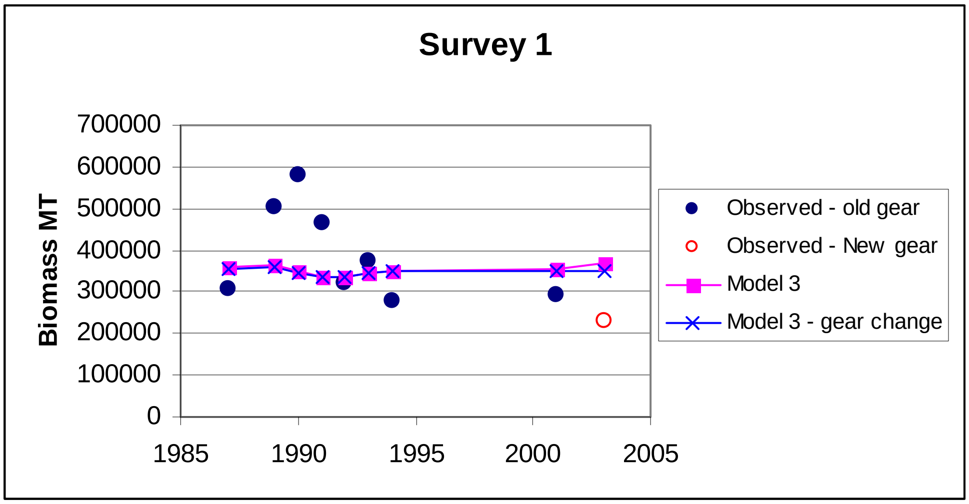


Figure 3b: Sensitivity of model 3 fits to both survey series with respect to whether or not account is taken of changing gear.



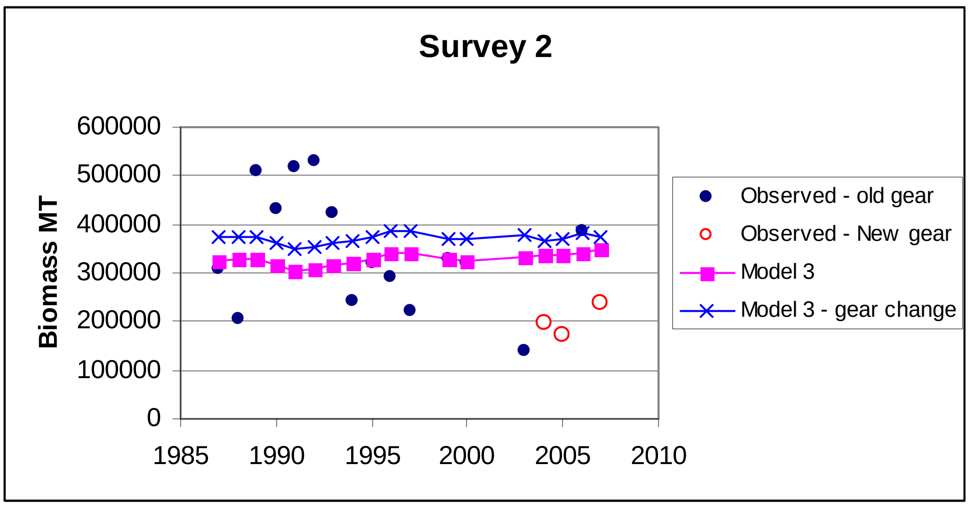


Figure 4a: Comparison between model 1 (h = 0.6, q_2 = 1.0) and model 3 (h = 0.6, q_2 = 0.5) estimated recruits (age 0) biomass with the results from acoustic biomass surveys (Merkle and Coetzee 2007 withupdated results). Acoustic survey results are shown with 1 SE.

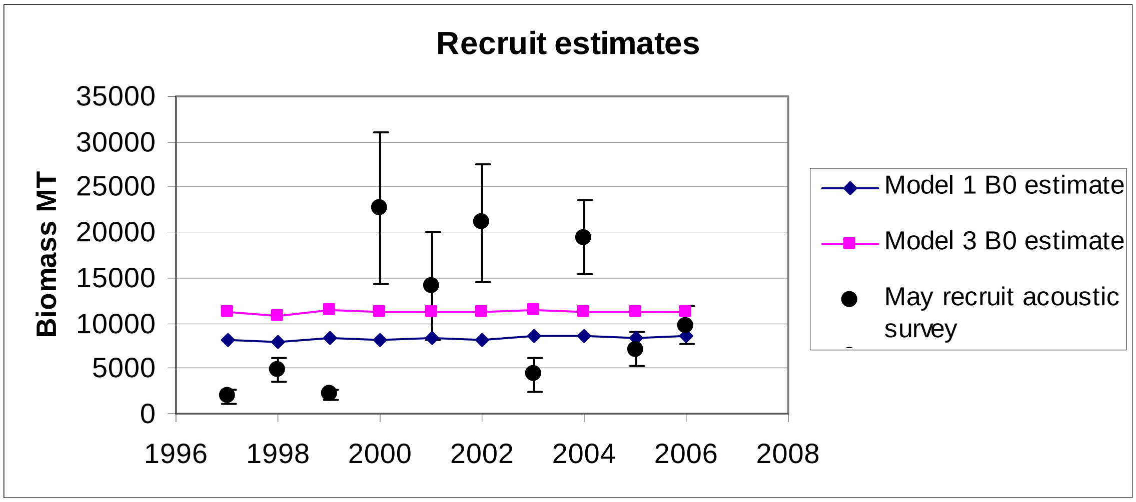
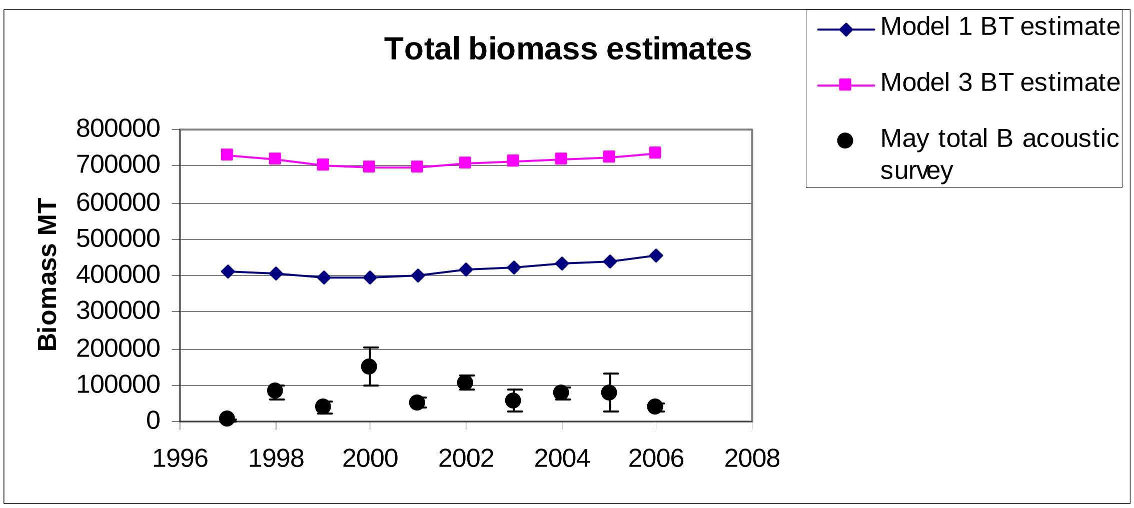


Figure 4b: Comparison between model 1 (h = 0.6, q_2 = 1.0) and model 3 (h = 0.6, q_2 = 0.5) estimated "total " biomass with the results from acoustic biomass surveys (Merkle and Coetzee 2007 with updated results). Acoustic survey results are shown with 1 SE.



Appendix

Mathematical details of the age-structured production model (ASPM) applied

Dynamics

The dynamics of the population are described using the following deterministic equations:

$$N_{y+1,0} = R(B^{sp}_{y+1}) \tag{A.1}$$

$$N_{y+1,a+1} = (N_{y,a}e^{-\frac{M_a}{2}} - C_{y,a})e^{-\frac{M_a}{2}} \qquad 0 \le a \le m\text{-}2 \tag{A.2}$$

$$N_{y+1,m} = (N_{y,m}e^{-\frac{M_m}{2}} - C_{y,m})e^{-\frac{M_m}{2}} + (N_{y,m-1}e^{-\frac{M_{m-1}}{2}} - C_{y,m-1})e^{-\frac{M_{m-1}}{2}} \tag{A.3}$$

where $N_{y,a}$ is the number of horse mackerel of age *a* at the start of year *y*,

$C_{y,a}$ is the total number of horse mackerel of age *a* taken by the fishery, i.e. by the pelagic and demersal (plus midwater) fleets combined, in year *y*,

$R(B^{sp})$ is the recruitment vs spawner biomass relationship assumed (see below),

M_a is the natural mortality rate for fish of age *a*, and

m is the largest age considered (this corresponds to a "plus group" and has a value of 10 here).

The approximation of the fishery as a pulse catch in the middle of the season is considered of sufficient accuracy for present purposes.

The total number of horse mackerel of age *a* caught each year ($C_{y,a}$) is given by:

$$C_{y,a} = \sum_f C^f_{y,a} \tag{A.4}$$

where *f* indicates the fishery/fleet concerned (pelagic or demersal).

The annual catch by mass (C^f_y) for fleet *f* is given by:

$$C^f_y = \sum_{a=0}^{m} w_{a+½} C^f_{y,a}$$

$$= \sum_{a=0}^{m} w_{a+\frac{1}{2}} S_a^f F_y^f N_{y,a} e^{-M_a/2} \qquad \text{(A.6)}$$

where S_a^f is the fishing selectivity-at-age for fleet $f = p$ (pelagic) or $f = d$ (demersal). [Note that the pelagic selectivity is assumed to change over time – see Table 3]. F_y^f is the fleet-specific fishing "mortality" (i.e. maximum of proportional catch over age classes) in year y, and $w_{a+\frac{1}{2}}$ denotes the mid-year mass of a horse mackerel of age a, assumed equal to the average of the begin-year and end-of-year mass.

The fleet-specific exploitable ("available") component of abundance is computed in terms of exploitable biomass at mid-year:

$$B_y^f = \sum_{a=0}^{m} w_{a+\frac{1}{2}} S_a^f N_{y,a} e^{-M_a/2} \qquad \text{(A.6)}$$

or numbers:

$$N_y^f = \sum_{a=0}^{m} S_a^f N_{y,a} e^{-M_a/2} \qquad \text{(A.7)}$$

The proportion of the resource harvested each year (F_y^f) by fleet f is therefore given by:

$$F_y^f = C_y^f / B_y^f \qquad \text{(A.8)}$$

and

$$C_{y,a}^f = S_a^f F_y^f N_{y,a} e^{-M_a/2} \qquad \text{(A.9)}$$

[Note: In some runs of this model for a high value of q_2, individual cohorts can become negative for early years in the fishery, even though biomass as a whole remains positive. This possibility has not been excluded, as essentially it indicates that selectivity assumptions for the early years of the fishery need some changes, but such would not affect overall results greatly.]

Spawning biomass - recruitment relationship

The spawning biomass in year y is given by:

$$B_y^{sp} = \sum_{a=a_m}^{m} w_a N_{y,a} \qquad \text{(A.10)}$$

where a_m is the age corresponding to 100% sexual maturity, which is assumed here to be described by a knife-edge function of age. For horse mackerel we assume a_m =3 years.

The number of recruits at the start of fishing year y is related to the spawner stock size by a stock-recruitment relationship. A Beverton-Holt form is assumed, i.e. :

$$R\left(B_y^{sp}\right) = \frac{\alpha\ B_y^{sp}}{\beta + B_y^{sp}} \tag{A.11}$$

In order to work with estimable parameters that are more meaningful biologically, the stock-recruit relationship is re-parameterised in terms of the pre-exploitation equilibrium spawning biomass, K^{sp}, and the "steepness" of the stock-recruit relationship, where "steepness" is the fraction of pristine recruitment (R_0) that results when spawning biomass drops to 20% of its pristine level, i.e.:

$$hR_0 = R\left(0.2K^{sp}\right) \tag{A.12}$$

from which it follows that:

$$h = 0.2\left[\beta + K^{sp}\right] / \left[\beta + 0.2K^{sp}\right] \tag{A.13}$$

and hence:

$$\alpha = \frac{4hR_0}{5h-1} \tag{A.14}$$

and:

$$\beta = \frac{K^{sp}(1-h)}{5h-1} \tag{A.15}$$

Given a value for the pre-exploitation spawning biomass K^{sp} of horse mackerel, together with the assumption of an initial equilibrium age structure, the following can be solved for R_0 :

$$K^{sp} = R_0[\sum_{a=1}^{m-1} f_a w_a e^{-\sum_{a'=0}^{a-1} M_{a'}} + f_m w_m e^{-\sum_{a'=0}^{m-1} M_{a'}} /(1-e^{-M_m})] \tag{A.16}$$

where a_m = 3 is fixed in the model, so that f_a, which is the proportion of fish of age a that are mature, is 0 for a < 3 and 1 thereafter, corresponding to the knife-edge relationship assumed.

Numbers-at-age for subsequent years are then computed by means of equations (A.1)-(A.11).

The likelihood function

In order to estimate K^{sp}, the model is fitted to two series of survey biomass data [see Table 2] by maximising an associated likelihood function.

The likelihood is calculated assuming that the observed abundance index is log-normally distributed about its expected value:

$$I_y^s = \hat{I}_y^s e^{\varepsilon_y^S} \qquad \text{or} \qquad \varepsilon_y^s = \ell n(I_y^s) - \ell n(\hat{I}_y^s) \tag{A.17}$$

where I_y^s is the survey biomass data for year *y* for survey *s* (*s* = 1 (spring) or 2 (autumn)),

$\hat{I}_y^s = q_s B_y^f$ is the corresponding model estimated value, where B_y^f is the model value for demersal exploitable resource biomass at mid-year corresponding to the demersal fleet, given by equation (A.6), and

q_s is a constant of proportionality (the demersal catchability coefficient).

The negative of the log-likelihood function (after removal of constants) is given then by:

$$-\ell\text{n}L = \sum_s \sum_y \left[\ell\text{n}\sigma_y^s + \left(\varepsilon_y^s\right)^2 / 2\left(\sigma_y^s\right)^2\right] \tag{A.18}$$

The standard deviations are calculated from the CVs reported in Table 2 by the following formula:

$$\sigma_y^s = \sqrt{\ln(1+CV_{s,y}^2)} \tag{A.19}$$

The value of q_2 is set externally, and q_1 is an estimable parameter.