Reference-case 2008 assessment model for abalone in Zones A, B, C and D

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SUMMARY

A summary is presented of the results obtained from the 2008 Reference-case model and two variants that was fit to Zones A, B, CNP, CP and D in combination (hereafter referred to as the "combined ABCD model"). The full details of the spatial- and age-structured production model (ASPM) are provided in Appendices 1 and 2. The 2008 base-case model uses an updated CPUPE index, and differs from last year's base-case in estimating one more parameter for Zone A (the historic catch multiplier).

The three model versions presented in Table 1 are as follows:

Model a) Concern was expressed by the AWG that the CPUPE trend for Zone B declines too steeply in recent years. This may be attributable to an incorrect partitioning of confiscated abalone between Zones A and B. Rather than estimating the amount poached in Zone B in recent years, this model combines the estimates of the amount poached from Zones A and B and then estimates a parameter that describes the proportion of this total that is taken from Zone A versus Zone B from 2000 onwards. The model estimated proportion poached from Zone A is 0.65 [90% Hessian-based confidence interval 0.55 – 0.75. This model version has been refined slightly from a preliminary version presented to the AWG in that parameter estimates for Zone A now result in an improved fit.

Model b) The old Reference case model is similar but estimates the Zone B poaching amount (in numbers), that is assume to apply from 2005-2008.

Model c) This model version used a single compartment per zone, rather than assuming inshore and offshore model regions. This model had the worst AIC value.

The new Reference Case Model estimates a pristine spawning biomass, B_0^{sp} (in tonnes) with 90% Hessian-based confidence intervals shown in square brackets, of 9760 [6060; 13460], 5840 [5400; 6280], 7290 [7050; 7530] and 9650 [6440; 12850] for Zones A, B, C and D respectively. The current (inshore+offshore) spawning biomasses (and associated 90% confidence intervals) of abalone in Zones A, B, C and D are estimated at ca. 33 % [26%; 39%], 25 % [19%; 30%], 4% [1%; 6%] and 12 % [8%; 16%] respectively of their pre-exploitation levels. The "nonpoached" CNP and "poached" CP areas of Zone C are estimated at ca. 6 % and 3 % respectively with the inshore region particularly depleted: the model predicts zero remaining abalone in the inshore CNP, CP and Zone D areas. Equivalent estimates for Zones A and B are 21% and 22%. Natural mortality is reasonably estimated (e.g. 0.33 yr^{-1} for age 0 and 0.14 yr^{-1} for age 15+) and in Zones C and D, the additional

mortality estimated for 0-yr old abalone (due to the ecosystem-change effect) corresponds to near zero current annual survival rates. Poaching is severely impacting the resource, with Zone A particularly impacted in recent years. The combined Zones A-D model-predicted 2008 poaching estimate is 860 MT and corresponds to the assumption that, on average, 14% of all poached abalone are confiscated.

BACKGROUND

This document provides **selected** results from fitting the abalone spatial- and age-structured production model (ASPM) to Zones/Subareas A, B, CNP, CP and D in combination (hereafter referred to as the "combined ABCD model") using the updated 2008 data. The full details of the spatial- and age-structured production model are provided in Appendix 1 and 2. A summary of model parameters is given in Table 1. This paper focuses on presenting results for the 2008 new Reference Case model only, with some selected results shown for other scenarios.

Parameters

The Reference-case ABCD model estimates the following 31 parameters:

1) B_0^{sp} for A, B, CNP, CP and D [5 parameters]
2) Inshore-offshore migration parameter ρ (CP) [1 parameter]
3) Poaching estimate for yr with assumed highest level of poaching: $CP_{\max}$ estimated for A, B, C (combined), and D. [4 parameters]
4) $\boldsymbol{p}_{\mathbf{poach}}$ [1 parameter] – equates roughly to old assumption that 10% of the Zone C poaching take is from CNP;
5) ***Cmult*** – historic catch multiplier for Zone A.
6) $M_a:\mu$ $(\lambda=0.2)$ where the formulation to model age-dependent mortality rates is $M_a=\mu+\dfrac{\lambda}{a+1}$. Natural mortality parameter assumed common to all Zones [1 parameter]
7) Two "recruitment failure" effect parameters common to CNP, CP and D: a steepness of recruitment failure parameter ν and a maximum increase in mortality parameter M_{max}. [2 parameters]
8) Three parameters for each of five selectivity functions (assumed common to all Zones) [15 parameters]
9) One parameter that determines the proportion of the combined Zones A and B poaching that is taken from Zone A.

RESULTS

Model parameter estimates as well as log-likelihood contributions for the Reference case combined ABCD model and some sensitivities are given in Table A.1, with a summary of results provided in Tables 1 and 2. The model selectivity functions and fits to the abundance indices are presented in Figs. 1 to 12. A number of additional diagnostics results are presented for purposes of indepth analysis of model results.

Parameter estimates

Model results estimates a pristine spawning biomass, B_0^{sp} (in tonnes), of of 9760 [6060;13460], 5840 [5400;6280], 7290 [7050;7530] and 9650 [6440;12850] for Zones A, B, C and D respectively. The current (inshore+offshore) spawning biomasses (and associated 90% confidence intervals) of abalone in Zones A, B, C and D are estimated at ca. 33 % [26%;39%], 25 % [19%; 30%], 4% [1%; 6%] and 12 % [8%; 16%] respectively of their pre-exploitation levels. The "nonpoached" CNP and "poached" CP areas of Zone C are estimated at ca. 6 % and 3 % respectively with the inshore region particularly depleted: the model predicts zero remaining abalone in the inshore CNP, CP and Zone D areas.

Natural mortality is reasonably estimated (e.g. 0.33 [0.31; 0.34] yr^{-1} for age 0 and 0.14 [0.09; 0.13] yr^{-1} for age 15+) and in Zones C and D, the additional mortality estimated for 0-yr old abalone (due to the ecosystem-change effect) corresponds to near zero current annual survival rates (Table A.1). The estimated additional variance parameter σ_{Add} is 0.15 with 90% confidence interval (normal approximation) of [0.06; 0.24].

The Reference-case selectivity estimates are illustrated in Fig. 1a. The estimated commercial and recreational selectivity functions reflect the fact that the minimum legal size corresponds to an age of approximately 9 years, whereas the estimated poaching selectivity function reflects the fact that sub-legal-size animals are caught. The minimum size of animals caught has been set at 3. The estimated FIAS selectivity function reflects the fact that the FIAS transects are situated inshore where smaller animals occur (Fig. 1a).

Fig. 1b shows the estimated selectivity trends when using the combined inshore/offshore model version (Model c). The model tries to distinguish between the commercial and poaching selectivities by estimating a steep near-linear decline in selectivity with age for the poaching sector (Fig. 1b).

Fits to data

The Reference Case model fits to the CPUE and FIAS data are shown in Figs. 2-6. In particular, there is an improvement in the fit to the Zone B FIAS data.

The inshore/offshore combined model version also fits the FIAS data reasonably (Fig. 7), but the overall model fit is significantly and substantially worse.

Biomass trajectories and projections

Fig. 8. shows the combined Zones A-D commercially exploitable biomass trajectory compared to historic data. Overall, the resource is estimated to be at 18% of the pre-exploitation spawning biomass level.

Fig. 9 shows the new Reference-case total (inshore + offshore) spawning biomass trajectories for Zones A to D. Note that the 20-yr projections shown (indicated by vertical bar) represent scenarios under which future poaching levels are assumed to remain at the current estimated level (average of 2007 and 2008) and future commercial catches are set to zero.

Fig. 10 shows the inshore and offshore spawning biomass components separately. Fig. 11 shows the model estimates of the numbers of abalone available to the FIAS sector in each Zone. Fig. 12 includes confidence intervals associated with the model estimates of spawning biomass.

Poaching estimates

Poaching is severely impacting the resource, with Zone A particularly impacted in recent years. The combined Zones A-D model-predicted 2008 poaching estimate from the new reference case model is 840 MT and corresponds to the assumption that, on average, 14% of all poached abalone are confiscated. Figs. 13 to 15 show the model estimates of the numbers and corresponding biomass of abalone that is assumed poached.

Density estimates

Reference-case model estimated abalone density per Zones A-D is shown in Fig. 16. Density is computed as the total number of abalone (inshore and offshore combined) divided by the habitat area, which is measured either as a) kelp area multiplied by a scaling factor of 1.5 or b) kelp area. Given difficulties in accurately computing abalone habitat area, it is difficult to compare model density estimates with observed estimates. Maharaj *et al.* (2008) note that the abalone density in Betty's Bay (a relatively pristine region) measured by FIAS during 1995-1999 was 2.7 (range: 0.9-5.5) abalone per square metre. Depending on the habitat area estimate as described above, the model-estimated pristine density estimates for Zones A and B are 1.8-2.7 and 1.4-2.1 per square metre. As these represent the average density throughout the model area, the inshore densities are likely to be higher than the offshore densities (but it is not possible to split the inshore/offshore habitat estimates). The model is thus not inconsistent with the possibility that pristine densities were much higher than the current values.

CONCLUSIONS

Model results suggest that the abalone resource has been heavily impacted by poaching and is currently declining in all Zones.

Appendix 1. The base-case inshore/offshore population model used for estimating resource dynamics parameters and projecting biomass trends

The description which follows is for Zone C but the same equations apply to the other Zones.

1 Dynamics

For each subarea, the dynamics of the **inshore** component are given by:

(A1) $$N^I_{y+1,0} = r_I \cdot R(B^{sp}_{y+1})$$

(A2) $$N^I_{y+1,a+1} = \left(N^I_{y,a} e^{-\frac{M_a}{4}} - C^I_{y,a}\right) e^{-\frac{3M_a}{4}} \qquad 0 \le a \le 4$$

(A3) $$N^I_{y+1,a+1} = \left((1-\rho) \cdot N^I_{y,a} e^{-\frac{M_a}{4}} - C^I_{y,a}\right) e^{-\frac{3M_a}{4}} \qquad 5 \le a \le z\text{-}2$$

(A4) $$N^I_{y+1,z} = ((1-\rho) \cdot N^I_{y,z} e^{-\frac{M_z}{4}} - C^I_{y,z}) e^{-\frac{3M_z}{4}} + ((1-\rho) \cdot N^I_{y,z-1} e^{-\frac{M_{z-1}}{4}} - C^I_{y,z-1}) e^{-\frac{3M_{z-1}}{4}}$$

where $N^I_{y,a}$ is the *inshore* number of abalone of age *a* at the start of Model year *y*,

ρ is the proportion of inshore animals of age *a* ($5 \le a \le z$) that move offshore at the start of Model year *y*,

$C^I_{y,a}$ is the total number of abalone of age *a* taken by recreationals and by poachers in Model year *y*, as well as the *inshore* number of abalone taken by the commercial fishery,

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

r_I is the proportion of the recruits which settle inshore,

M_a is the (time-invariant) natural mortality rate on abalone of age *a*, and

z is the largest age considered (i.e. corresponding to a “plus group”).

Similarly, for each subarea, the dynamics of the **offshore** component are given by:

(A5) $$N^O_{y+1,0} = r_O \cdot R(B^{sp}_{y+1})$$

(A6) $$N^O_{y+1,a+1} = \left(N^O_{y,a} e^{-\frac{M_a}{4}} - C^O_{y,a}\right) e^{-\frac{3M_a}{4}} \qquad 0 \le a \le 4$$

(A7) $$N^O_{y+1,a+1} = \left((N^O_{y,a} + \rho \cdot N^I_{y,a}) e^{-\frac{M_a}{4}} - C^O_{y,a}\right) e^{-\frac{3M_a}{4}} \qquad 5 \le a \le z\text{-}2$$

(A8) $$N^O_{y+1,z} = ((N^O_{y,z} + \rho \cdot N^I_{y,z}) e^{-\frac{M_z}{4}} - C^O_{y,z}) e^{-\frac{3M_z}{4}} + ((N^O_{y,z-1} + \rho \cdot N^I_{y,z-1}) e^{-\frac{M_{z-1}}{4}} - C^O_{y,z-1}) e^{-\frac{3M_{z-1}}{4}}$$

where $N^O_{y,a}$ is the *offshore* number of abalone of age *a* at the start of Model year *y*,

r_O is the proportion of the recruits which settle offshore (= 1-r_I), and

$C^O_{y,a}$ is the *offshore* number of abalone of age *a* taken by the commercial fishery.

The commercial abalone fishery season currently extends from October to June but several historic changes in the commencement and closure dates for the commercial fishing season are on record. For reasons of internal consistency in the assessment process, a standard Model or fishing year y is thus taken to run from October of year y-1 to September of year y. The population model used here assumes pulse fishing (Pope's approximation – Pope 1984), rather than the more customary Baranov catch equations which assume continuous fishing through the year (Baranov 1918). Pope's approximation has been used in order to simplify computations. As long as mortality rates are not too high, the differences between the Baranov and Pope formulations will be minimal. The approximation of the fishery as a pulse catch at the start of each calendar year is here considered to be of sufficient accuracy given that most of the catch is made over the October-March period, and because the annual catches from this long lived resource are not that large a fraction of the overall biomass. This last reason also constitutes the justification for treating inshore-to-offshore movement as a pulse at the start of the Model year. The equations reflect the fact that catches are subtracted at the end of the first quarter of the Model year (i.e. in the middle of the October-March period of high catches). As the fishery-independent surveys (FIAS) are conducted only towards the end of the second quarter of the Model year, comparisons with the abundance indices obtained from FIAS are made at time $y+\frac{1}{2}$ in terms of the model whereas comparisons with the CPUE data are made at time $y+\frac{1}{4}$ in the model.

Because different sectors of the fishery exhibit different selectivity patterns with age, the following five sectors are explicitly differentiated in the model: the commercial fishery sector (mostly offshore); the recreational sector (mostly inshore); the poaching/illegal sector (mostly inshore), the fishery-independent survey (inshore and offshore) and the "old survey" (inshore and offshore).

The equations given below are applied separately to each of the inshore and offshore components of the two subareas CNP and CP.

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

(A9)
$$C_{y,a} = \sum_s C^s_{y,a}$$

where s indicates the sector of the fishery (e.g. commercial, recreational, poaching).

The annual catch by mass (C^s_y) for sector s is given by:

(A10)
$$C^s_y = \sum_{a=3}^{z} w_{y,a+1/4} C^s_{y,a}$$

where $w_{y,a+1/4}$ is the mass of an abalone of age a at the end of the first quarter of Model year y (note however that only the plus group mass $w_{y,z}$ is year-dependent in the model formulation pursued and that the plus group mass is modelled separately for the inshore and offshore components). The summation is taken from age a = 3 as no abalone of a size corresponding to ages below 3 are taken by any of the fishing sectors.

A von Bertalanffy growth equation is used to relate shell length ℓ (mm) to age in years (t), and is based on tagging data from Betty's Bay (Tarr 1995):

(A11)
$$\ell(t) = \ell_\infty [1 - e^{-\kappa(t-t_0)}]$$

The relationship between *shell length* (mm) and abalone whole wet mass (g) is based on data from the Betty's Bay and Danger Point areas and is determined using the following power relationship:

(A12) $$w_{y,a} = w(y,t=a) = c\cdot(\ell)^d$$

Note that mass-at-age is year-independent for abalone of age $a < z$ and that $w_{y,a+\frac{1}{4}} = w(y, t = a + \frac{1}{4})$ is computed for use in calculating the sector-specific exploitable biomasses after the first quarter of each year (see below). However, the mass-at-age for the plus group varies over time, depending on the average age of the inshore and offshore plus group components in year *y*, $\bar{z}_y^I$ and $\bar{z}_y^O$ respectively, which are calculated as:

(A13) $$\bar{z}_y^I = \frac{\left(\bar{z}_{y-1}^I+1\right)\left((1-\rho)N_{y,z}^I - C_{y,z}^I\right)e^{-M_z} + z\cdot\left((1-\rho)N_{y,z-1}^I - C_{y,z-1}^I\right)e^{-M_{z-1}}}{N_{y,z}^I}$$

(A14) $$\bar{z}_y^O = \frac{\left(\left(\bar{z}_{y-1}^O+1\right)\left(N_{y,z}^O - C^O{}_{y,z}\right) + \left(\bar{z}_{y-1}^I+1\right)\rho\, N_{y,z}^I\right)e^{-M_z} + z\cdot\left(N_{y,z-1}^O + \rho\, N_{y,z-1}^I - C_{y,z-1}^O\right)e^{-M_{z-1}}}{N_{y,z}^O}$$

The above is an approximation only (as it ignores, e.g., the fact that catches are subtracted not at the start of the year but at the end of the first quarter of each year) but is considered sufficiently accurate for present purposes.

The recreational catch by mass in year *y* is given by:

(A15) $$C_y^s = \sum_{a=8}^{z-1} w_{a+\frac{1}{4}} N_{y,a}^I (1-\rho)e^{-M_a/4} S_a^s F_y^s + w_{y,\bar{z}_y+\frac{1}{4}}^I N_{y,z}^I (1-\rho) e^{-M_z/4} S_z^s F_y^s$$

and the poaching catch by mass in year *y* by:

(A16) $$\begin{aligned} C_y^s &= w_{4+\frac{1}{4}} N_{y,4}^I\, e^{-M/4} S_4^s F_y^s + \sum_{a=5}^{z-1} w_{a+\frac{1}{4}}\, N_{y,a}^I (1-\rho) e^{-M/4} S_a^s F_y^s \\ &\quad + w_{y,\bar{z}_y+\frac{1}{4}}^I (1-\rho) N_{y,z}^I\, e^{-M/4} S_z^s F_y^s \end{aligned}$$

where S_a^s is the fishing selectivity-at-age for sector *s* (this pattern is assumed not to change over time), $w_{y,\bar{z}_y+\frac{1}{4}}^I$ is the mean mass of the inshore plus group with average age $\bar{z}_y + \frac{1}{4}$ after the first quarter of Model year *y*, and F_y^s is the fishing "mortality" (strictly here that proportion of the numbers present after the first quarter of the Model year which are caught) at a reference age, set for these computations to be a = 11 for all sectors. Based on an analysis of confiscated abalone samples, the minimum age of animals assumed caught by the poaching sector is 4 years, so that for this sector $S_a^s = 0$ for $a < 4$. Note also (cf. Eqn. A16) that there is no inshore-offshore movement of animals aged four and younger. The commercial and recreational sectors are both assumed not to catch animals below the legal size limit, so that for these sectors $S_a^s = 0$ for $a < 8$.

In the case of the recreational sector (which reports in terms of numbers rather than mass), estimates of the annual catch by mass are computed using equation (A15) but it is necessary to first compute the fishing "mortality" F_y^s, using the following relation for the numbers caught in year *y*:

(A17) $$N_y^s = \sum_{a=8}^{z} N_{y,a}^I (1-\rho) e^{-M_a/4} S_a^s F_y^s$$

The relative proportions of the Zone C recreational catch (i.t.o. numbers) taken from the two subareas CP and CNP is assumed to be proportional to the relative lengths of the coastline (CP:CNP = 1:2).

The amount of poached abalone is estimated in terms of numbers and hence the following relation is used to compute the fishing "mortality" F_y^s for the poaching sector in year y:

(A18) $$N_y^s = \sum_{a=5}^{z} N_{y,a}^I (1-\rho) e^{-M_a/4} S_a^s F_y^s + N_{y,4}^I e^{-M_a/4} S_4^s F_y^s$$

Equations (A15) to (A18) assume that poaching and recreational activities occur exclusively in the inshore region. In the case of the commercial sector, the 0-2 m depth range is thought to be the only habitat that is almost never fished by commercial divers encroaching inshore because the shallow depth prevents boats from operating easily in these waters. Inshore encroachment by commercial divers is seen as being particularly common in areas that do not have residential houses along the beachfront. Thus, whereas this is thought to be a relatively minor problem in subarea CNP, inshore encroachment by commercial fishers is considered to have been a problem throughout the history of the fishery in subarea CP (and in all the other zones).

Thus, whereas the commercial catch by mass in year y in subarea CP is given by:

(A19) $$C_y^s = \sum_{a=8}^{z-1} w_{a+1/4} \left(N_{y,a}^I + N_{y,a}^O\right) e^{-M_a/4} S_a^s F_y^s + \left(w_{y,\bar{z}_y+1/4}^I N_{y,z}^I + w_{y,\bar{z}_y+1/4}^O N_{y,z}^O\right) e^{-M_z/4} S_z^s F_y^s$$

in subarea CNP, the commercial catch by mass in year y is given by equation (A19) above for years prior to 1967, and by equation (20) for years 1967 onwards:

(A20) $$C_y^s = \sum_{a=8}^{z-1} w_{a+1/4} \left(N_{y,a}^O + \rho\, N_{y,a}^I\right) e^{-M_a/4} S_a^s F_y^s + \left(w_{y,\bar{z}_y+1/4}^O N_{y,z}^O + \rho\, w_{y,\bar{z}_y+1/4}^I N_{y,z}^I\right) e^{-M_z/4} S_z^s F_y^s$$

where $w_{y,\bar{z}_y+1/4}^O$ is the mean mass of the offshore plus group with average age $\bar{z}_y + 1/4$ after the first quarter of Model year y.

The exploitable ("available") components of abundance for the recreational and poaching sectors are both expressed in terms of population numbers and are computed using Eqn. (A21) below for the recreational sector and Eqn. (A22) for the poaching sector:

(A21) $$B_y^{exp,s} = \sum_{a=8}^{z} S_a^s (1-\rho) N_{y,a}^I e^{-M_a/4}$$

(A22) $$B_y^{exp,s} = \sum_{a=5}^{z} S_a^s (1-\rho) N_{y,a}^I e^{-M_a/4} + S_4^s N_{y,4}^I e^{-M_4/4}$$

On the other hand, the exploitable components of abundance for the commercial sector operating in subareas CP (all years) and CNP (years prior to 1967) are computed as:

(A23) $$B_y^{exp,s} = \sum_{a=8}^{z-1} S_a^s w_{a+1/4}\left(N_{y,a}^I + N_{y,a}^O\right)e^{-M/4} + S_z^s\left(w_{y,\bar{z}_y+1/4}^I N_{y,z}^I + w_{y,\bar{z}_y+1/4}^O N_{y,z}^O\right)e^{-M/4}$$

and in the case of subarea CNP, exploitable biomass for years from 1967 onwards is computed as:

(A24) $$B_y^{exp,s} = \sum_{a=8}^{z-1} S_a^s w_{a+1/4}\left(N_{y,a}^O + \rho N_{y,a}^I\right)e^{-M_a/4} + S_z^s\left(w_{y,\bar{z}_y+1/4}^O N_{y,z}^O + \rho\, w_{y,\bar{z}_y+1/4}^I N_{y,z}^I\right)e^{-M_z/4}$$

In the case of FIAS, which for these purposes can be considered as another fishery sector *s*, "available" population numbers are given by:

(A25) $$N_y^{exp,s} = \sum_{a=5}^{z} S_a^s\left((1-\rho)N_{y.a}^I e^{-M_a/4} - C_{y,a}^I\right)e^{-M_a/4}$$

The summation is from age $a = 5$ as only animals larger than 100mm shell length are recorded so as to reduce uncertainty in the estimates due to the non-emergent/cryptic behaviour of juveniles. This corresponds to a minimum sampling age of approximately 5 years, so that for this sector $S_a^s = 0$ for $a < 5$.

The proportion of the resource harvested each year (F_y^s) by sector *s* is given by:

(A26) $$F_y^s = C_y^s \;/\; B_y^{exp,s}$$

so that numbers-at-age removed each year by the poaching and recreational sectors can be computed from:

(A27) $$C_{y,a}^s = S_a^s F_y^s (1-\rho) N_{y,a}^I e^{-\frac{M_a}{4}}$$ for $a \geq 5$ and

(A28) $$C_{y,a}^s = S_a^s F_y^s N_{y,a}^I e^{-\frac{M_a}{4}}$$ for $a = 4$ (poaching catches)

In the case of the commercial sector, the numbers-at-age removed each year from subarea CP is given by:

(A29) $$C_{y,a}^s = S_a^s F_y^s\left(N_{y,a}^I + N_{y,a}^O\right)e^{-M_a/4}$$

The commercial numbers-at-age removed from subarea CNP for each of the years prior to 1967 is given by equation (A29) above, and then by equation (A30) below as from 1967:

(A30) $$C_{y,a}^s = S_a^s F_y^s\left(N_{y,a}^O + \rho \cdot N_{y,a}^I\right)e^{-M_a/4}$$

2 Spawning biomass - recruitment relationship

The spawning biomass for each subarea in year *y* is given by:

(A31) $$B_y^{sp} = \sum_{a=1}^{z-1} f_a w_a\left(N_{y,a}^I + N_{y,a}^O\right) + f_z\left(w_{y,\bar{z}_y}^I N_{y,z}^I + w_{y,\bar{z}_y}^O N_{y,z}^O\right)$$

where f_a is the proportion of abalone of age *a* that are mature. Note that this formulation assumes independence of subareas in terms of recruitment, *viz*. the recruitment in one subarea depends only on the spawning biomass in that subarea and not on the biomass in adjoining subareas.

The number of recruits in each of the two subareas at the start of Model year *y* is related to the spawner stock size by a stock-recruitment relationship. A Beverton-Holt form (Beverton and Holt, 1957) is assumed, i.e. :

(A32) $$R\left(B_y^{sp}\right) = \frac{\alpha\, B_y^{sp}}{\beta + B_y^{sp}}$$

Note from equations (A1) and (A5) that the relative proportion of recruits settling inshore versus offshore in each subarea is determined by parameter r_I.

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, B_0^{sp}, and the "steepness" of the stock-recruit relationship, where "steepness" is the fraction of pristine recruitment that results when spawning biomass drops to 20% of its pristine level, i.e.

(A33) $$hR_0 = R\left(0.2 B_0^{sp}\right)$$

from which it follows that:

(A34) $$h = 0.2\left[\beta + B_0^{sp}\right] / \left[\beta + 0.2 B_0^{sp}\right]$$

and hence:

(A35) $$\alpha = \frac{4hR_0}{5h-1}$$ and:

(A36) $$\beta = \frac{B_0^{sp}(1-h)}{5h-1}$$

3 Starting values for biomass trajectories

The resource is assumed to be at the deterministic equilibrium (corresponding to an absence of harvesting) at the start of 1951, the initial year considered here. Given a value for the pre-exploitation spawning biomass B_0^{sp} of abalone, together with the assumption of an initial equilibrium age structure, it follows that on a subarea basis:

(A37) $$B_0^{sp} = R_0 \cdot \left[\sum_{a=1}^{z-1} f_a w_a \exp\left(-\sum_{a'=0}^{a-1} M_{a'}\right) + f_z w_{0,\bar{z}_0} \frac{\exp\left(-\sum_{a'=0}^{z-1} M_{a'}\right)}{1-\exp\left(-M_z\right)}\right]$$

which can be solved for R_0. Note that here $w_{0,\bar{z}_0}$ means the equilibrium value of this quantity prior to exploitation, computed using the equilibrium plus group mean age $\bar{z}_0$, where:

(A38)
$$\bar{z}_0 = z + \frac{e^{-M_{z-1}}}{1-e^{-M_z}}$$

The initial **inshore** numbers at age for the projections, corresponding to the deterministic equilibrium, are:

(A39)
$$\begin{aligned}
&N^I_{0,0} = r_I R_0 \\
&N^I_{0,a+1} = N^I_{0,a} e^{-M_a} && 0 \le a \le 4 \\
&N^I_{0,a+1} = N^I_{0,a}(1-\rho)e^{-M_a} && 5 \le a \le z-2 \\
&N^I_{0,z} = \frac{N^I_{z-1}(1-\rho)e^{-M_{z-1}}}{1-(1-\rho)e^{-M_z}}
\end{aligned}$$

Similarly, the initial **offshore** numbers at age, corresponding to the deterministic equilibrium, are:

(A40)
$$\begin{aligned}
&N^O_{0,0} = (1-r_I)R_0 \\
&N^O_{0,a+1} = N^O_{0,a} e^{-M_a} && 0 \le a \le 4 \\
&N^O_{0,a+1} = N^O_{0,a} e^{-M_a} + N^I_{0,a}\rho e^{-M_a} && 5 \le a \le z-2 \\
&N^O_{0,z} = \frac{N^O_{z-1}e^{-M_{z-1}} + \rho\left(N^I_{0,z}e^{-M_z} + N^I_{0,z-1}e^{-M_{z-1}}\right)}{1-e^{-M_z}} && a = z
\end{aligned}$$

It follows from the steady-state solutions to these equations that the inshore and offshore equilibrium plus group mean ages are as follows:

(A41)
$$\begin{aligned}
&\bar{z}^I_0 = z + \frac{(1-\rho)e^{-M_{z-1}}}{1-(1-\rho)e^{-M_z}} \\
&\bar{z}^O_0 = z + \frac{e^{-M_{z-1}}}{1-e^{-M_z}} + \frac{\rho\, e^{-M_{z-1}}}{\left(1-e^{-M_z}\right)\left(1-(1-\rho)e^{-M_z}\right)} \cdot \frac{N^I_{0,z}}{N^O_{0,z}}
\end{aligned}$$

Numbers-at-age for subsequent years are then computed by means of equations (A1)-(A36).

4 Parameter Values

Input parameters:
The following fixed parameter values are used in the model. The three von Bertalanffy parameters are from Tarr (1995) and the two mass-length relationship parameters were computed in this study:

ℓ_∞ = 172.76 mm

κ = 0.186 yr^{-1}

t_0 = 0 yr (and is assumed to correspond to October because Tarr (1995) tagged animals *in situ* in October and November)

$c \quad = 0.000098$ gm/mm$^{3.155}$

$d \quad = 3.1549$

with the computations assuming a plus group at age z = 15 yrs.

The proportion of abalone of age a that are mature is approximated by $f_4 = 0.25$, $f_5 = 0.5$, $f_6 = 0.75$ and $f_a = 1$ for $a \geq 7$ (Tarr 1995).

Moreover, the base-case assumes that h = 0.7. The base-case value of the steepness parameter h corresponds roughly to the median (h = 0.74) of a distribution of h values for stock-recruit functions fitted to the fisheries stock recruitment database developed by R.A. Myers and colleagues (Myers *et al*. 1995a).

Estimable parameters:

The sector-specific fishing selectivities S_a^s (including those for FIAS) are assumed to follow the functional form:

(A42) $$S_a^s = \frac{P \cdot e^{-\mu a}}{1 + e^{-\delta(a - \tilde{a})}}$$

where μ, δ and $\tilde{a}$ are three estimable parameters that control the shape of the function and P is simply a scalar fixed at a value such that S_{11}^s = 1.00. In essence, μ controls the slope of the right hand limb of the function, δ controls the steepness of the ascending left hand limb, and $\tilde{a}$ shifts the function to the left or right, all in relation to age a.

The assumption that commercial selectivity parameters are the same for the inshore and offshore compartments might seem severe, given the greatly different age profiles of abalone in the inshore and offshore areas. Note however that only a small component of the commercial fishing takes place in the inshore region (the numbers of commercially exploitable size in that region being small), so that even if the assumption is in error, the impact on results should not be substantial.

Under the assumption that the sampling methodology is the same inshore and offshore, the same selectivity parameters are used for the inshore and offshore FIAS sectors. A separate selectivity function is used to compute model-predicted catch-at-age when fitting to the "old survey" data and it is again assumed that the same parameters apply to the inshore and offshore regions.

5 The likelihood function

The likelihood function which is maximised in the parameter estimation process is based on equations developed by Geromont and Butterworth (1999). The model is fitted to CPUE and FIAS abundance and catch-at-age data from all sectors (commercial, recreational, poaching, old survey and FIAS) and the contributions by each of these to the negative of the log-likelihood (-*ln L*) calculated as described below.

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

(A43) $$I_y^s = \hat{I}_y^s e^{\varepsilon_y^s} \qquad \text{or} \qquad \varepsilon_y^s = \ln(I_y^s) - \ln(\hat{I}_y^s)$$

where I_y^s is the abundance index for year y and sector s,

$\hat{I}_y^s = q^s B_y^{exp,s}$ is the corresponding model estimated value, where $B_y^{exp,s}$ is the model value for exploitable resource biomass corresponding to sector s, given by equations (A21- A24) (if the index refers to numbers, $B_y^{exp,s}$ is replaced by $N_y^{exp,s}$ - see equation (A25)).

q^s is the constant of proportionality for abundance series corresponding to sector s, and

ε_y^s from $N\left(0,\left(\sigma_y^s\right)^2\right)$.

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

(A44)
$$-\ln L = \sum_s \left[\sum_y \ln \sigma_y^s + \left(\varepsilon_y^s\right)^2 / 2\left(\sigma_y^s\right)^2 \right]$$

Variance unspecified: (CPUE abundance series)

In this case the standard deviation of the residuals for the logarithms of abundance series s is assumed to be independent of y, and is estimated in the fitting procedure by its maximum likelihood value:

(A45)
$$\hat{\sigma}^s = \sqrt{\frac{1}{n_s} \sum_y \left(\ln I_y^s - \ln \hat{I}_y^s\right)^2}$$

where n_s is the number of data points for the abundance series corresponding to sector s.

The catchability coefficient q^s for sector s's abundance index is estimated by its maximum likelihood value:

(A46)
$$\ln \hat{q}^s = \frac{1}{n_s} \sum_y \left(\ln I_y^s - \ln \hat{B}_y^{exp,s}\right)$$

Variance specified: (FIAS data)

The sampling variance estimates available for FIAS are used as inputs in the model, but these estimates fail to include all sources of variability. To take this into account an additional variance component is added to the variance estimates, with a single additional variance parameter, assumed to be the same for each zone, estimated in the minimisation process. This is effected subject to the constraint that the overall variance must be greater than or the same as its externally input component.

The FIAS catchability coefficient q^s is thus estimated by its maximum likelihood value which, for the case of a log-normal error distribution, is given by:

(A47) $$\ln \hat{q}^{s} = \frac{\sum_{y} 1 \Big/ \left(\sigma_{y}^{s}\right)^{2} \left(\ln I_{y}^{s} - \ln \hat{B}_{y}^{exp,s}\right)}{\sum_{y} 1 \Big/ \left(\sigma_{y}^{s}\right)^{2}}$$

where $\left(\sigma_{y}^{FS}\right)^{2} = \left(\sigma_{Add}\right)^{2} + \ln\left(1 + \left(CV_{y}\right)^{2}\right)$ and the coefficient of variation (CV_{y}) of the resource abundance estimate for year y is input.

Catches-at-age:

The likelihood contribution is calculated assuming a log-normal error distribution and by making an adjustment (suggested by A. Punt, pers. commn) to weight in relation to the observed proportions so that undue importance is not attached to poorly represented age classes:

(A48) $$-\ln L = \sum_{s}\sum_{y}\sum_{a}\left[\ln\left(\sigma_{c}^{s} \Big/ \sqrt{p_{y,a}^{s}}\right) + p_{y,a}^{s}\left(\ln(\delta + p_{y,a}^{s}) - \ln(\delta + \hat{p}_{y,a}^{s})\right)^{2} \Big/ 2\left(\sigma_{c}^{s}\right)^{2}\right]$$

where $p_{y,a}^{s} = C_{y,a}^{s} \Big/ \sum_{a'} C_{y,a'}^{s}$ is the observed proportion of abalone caught/sampled by sector s in year y that are of age a,

$\delta = 0.05$ is a constant included because not all of the $p_{y,a}^{s}$ values are nonzero,

σ_{c}^{s} is the standard deviation associated with the catch-at-age data for sector s, estimated in the fitting procedure by:

(A49) $$\sigma_{c}^{s} = \sqrt{\sum_{y}\sum_{a} p_{y,a}^{s}\left(\ln(\delta + p_{y,a}^{s}) - \ln(\delta + \hat{p}_{y,a}^{s})\right)^{2} \Big/ \sum_{y}\sum_{a} 1}$$

and $\hat{p}_{y,a}^{s} = \hat{C}_{y,a}^{s} \Big/ \sum_{a'} \hat{C}_{y,a'}^{s}$ is the model-predicted proportion of abalone caught/sampled by sector s in year y that are of age a.

For subarea CNP, the earliest catch-at-age data are from 1980 and hence correspond to the period during which all commercial catches are assumed taken from the offshore region, so that $\hat{C}_{y,a}^{s}$ is given by:

(A50) $$\hat{C}_{y,a}^{s} = \left(N_{y,a}^{O} + \rho N_{y,a}^{I}\right) e^{-\frac{M_a}{4}} S_{a}^{s} F_{y}^{s}$$

whereas for subarea CP, $\hat{C}_{y,a}^{s}$ is determined as follows:

(A51) $$\hat{C}_{y,a}^{s} = \left(N_{y,a}^{I} + N_{y,a}^{O}\right) e^{-\frac{M_a}{4}} S_{a}^{s} F_{y}^{s}$$

The model-predicted recreational catch-at-age data is based on abalone assumed caught from both the CNP and CP subareas, such that for this sector:

(A52) $$\hat{C}^{s}_{y,a} = \left(\left(1-\rho_{CNP}\right) N^{I_{CNP}}_{y,a} + \left(1-\rho_{CP}\right) N^{I_{CP}}_{y,a} \right) e^{-\frac{M_a}{4}} S^{s}_{a} F^{s}_{y}$$

except in the case of the single year's (1997) recreational catch-at-age data from subarea CP, for which $\hat{C}^{s}_{y,a}$ is computed as:

(A53) $$\hat{C}^{s}_{y,a} = \left(1-\rho\right) N^{I_{CP}}_{y,a}\, e^{-\frac{M_a}{4}} S^{s}_{a} F^{s}_{y}$$

The poached catch is taken primarily from the inshore region of subarea CP and hence Eqn. (A53) above is used to calculate $\hat{C}^{s}_{y,a}$ for the poaching sector.

The FIAS, "old survey" and industry survey catches-at-age are similarly incorporated into the negative of the log-likelihood, except that comparisons with observed proportions are made at mid-year rather than after the first quarter of each Model year. Data from the inshore FIAS stations is assumed to correspond to the inshore model region whereas data from the deep FIAS stations is assumed to correspond to the offshore model region. The 0-5 m and 5-15 m "old survey" data are assumed to respectively correspond to the inshore and offshore model regions. Thus, for each subarea, the inshore FIAS and inshore "old survey" model-predicted numbers of abalone of age *a* sampled are computed as:

(A54) $$\begin{aligned} \hat{C}^{s}_{y,a} &= \left(N^{I}_{y.a} e^{-\frac{M_a}{4}} - C^{I}_{y,a} \right) e^{-\frac{M_a}{4}} S^{s}_{a} F^{s}_{y} & a < 5 \\ \hat{C}^{s}_{y,a} &= \left(\left(1-\rho\right) N^{I}_{y.a} e^{-\frac{M_a}{4}} - C^{I}_{y,a} \right) e^{-\frac{M_a}{4}} S^{s}_{a} F^{s}_{y} & a \geq 5 \end{aligned}$$

and $\hat{C}^{s}_{y,a}$ for the deep FIAS and offshore "old survey" are given by:

(A55) $$\begin{aligned} \hat{C}^{s}_{y,a} &= \left(N^{O}_{y.a} e^{-\frac{M_a}{4}} - C^{O}_{y,a} \right) e^{-\frac{M_a}{4}} S^{s}_{a} F^{s}_{y} & a < 5 \\ \hat{C}^{s}_{y,a} &= \left(\left(N^{O}_{y.a} + \rho\, N^{I}_{y,a} \right) e^{-\frac{M_a}{4}} - C^{O}_{y,a} \right) e^{-\frac{M_a}{4}} S^{s}_{a} F^{s}_{y} & a \geq 5 \end{aligned}$$

Data from the 2002 industry “total population size composition” survey are assumed representative of the entire Zone C area and hence $\hat{C}^{s}_{y,a}$ for the industry survey is computed by summing over mid-year inshore and offshore regions for both CNP and CP.

Inspection of the various –ln *L* contributions has revealed that the catch-at-age –ln *L* contributions are substantially larger than those for CPUE and the FIAS series, in part because they include many more data points as a result of summation over age as well as year. This is questionable as the $p^{s}_{y,a}$ values for a given *y* and *s* are not likely to be independent of each other (as implicitly assumed by equation (A48)), because the cohort-slicing method used to provide the catch-at-age information from length composition data likely introduces positive correlation. The catch-at-age –ln *L* contributions are thus downweighted by a multiplicative factor of 0.1, thereby downscaling these contributions to a similar order of magnitude as the CPUE and FIAS contributions.

References

Geromont, H.F. and D.S. Butterworth 1997. Assessments of West Coast hake using an age-structured production model to provide a basis for simulation testing of a revised Operational Management Procedure. Unpublished report, MCM, South Africa. WG/08/97/D:H35: 24 pp.

Geromont, H.F. and D.S. Butterworth 1999. A fleet-disaggregated age-structured production model for application to Atlantic bluefin tuna. *Int. Commn Cons. Atl. Tuna.*, *Coll. Vol. Sci. Pap.* **47**: 403-415 (SCRS/98/77).

Appendix 2 – Incorporating the "ecosystem-change"effect

Method for modelling increased juvenile mortality

1. The following formulation was used to model age-dependent natural mortality rates M_a :

$$M_a = \mu + \frac{\lambda}{a+1} \qquad \text{(A2.1)}$$

where parameter μ was estimated in the model-fitting process and λ was either estimated or set equal to a constant (e.g. 0.2 for all cases shown here).

2. The number of new recruits to the population from 1994 onwards is no longer reduced to 10% of the 1993 level as in previous model versions, but is instead determined in the same way as for the earlier years, i.e. by using the Beverton – Holt stock-recruit function.

3. To model the rate and extent of the "recruitment failure" effect, two new parameters were introduced: a steepness of recruitment failure parameter ν and a maximum increase in mortality parameter M_{max}. An exponential increase in the M_0 mortality rate is assumed to have occurred as from year *y*, where different values of the starting year *y* were tried and the rate of increase in M_0 is determined by parameter ν . M_0 is assumed to increase continuously up to a maximum value M_{max} and then remains constant at this value from years y_{Mmax} forwards. For example, Combined B&C Model I in 2002 was as follows: μ = 0.138 (estimated), λ = 0.2 (fixed), first year with increase M_0 is 1990, ν = 0.227 (estimated) and M_{max} = 3.856 (estimated).

As *M* values are more easily understandable when converted to survival rates *S* (= the proportion of that age-class surviving from one year to the next), M_0 values will be discussed in terms of S_0 instead. The above parameter values thus translate into a situation where currently only 2.1% of abalone recruits survive into the second year compared to 71% in the absence of this "recruitment failure" effect.

Table 1. Summary description of model parameters and definitions of other abbreviated terms utilised in the text.

Parameter	Description	Units
$B_0^{sp} = K$	Pre-exploitation (assumed to be 1951) spawning biomass	MT
$B^{sp}, B_{insh}^{sp}, B_{offsh}^{sp}$	Spawning biomass (total per zone), Inshore spawning biomass, Offshore spawning biomass	MT
ρ	Rate at which inshore animals move offshore at the start of each Model year	yr^{-1}
r_I	Proportion of the recruits which settle inshore	-
$CP_{\max}$ (number) (zone)	The total number of abalone poached in the year corresponding to the poaching maximum for the zone under consideration	no.
$CP_{\max}$ (MT) (zone)	The poaching maximum in terms of mass	MT
C_{mult}	Historic catch multiplier for Zone A	-
p_{poach}	Parameter that specifies the relative exploitation rate effected by poachers in subareas CP and CNP	-
$M_a : \mu$ $(\lambda = 0.2)$ $\left(M_a = \mu + \frac{\lambda}{a+1}\right)$	Age-dependent mortality rate parameters; M_0 is the mortality rate of 0-yr old animals; M_{15} is the plus group mortality rate etc.	yr^{-1}
υ	Parameter that controls the steepness of the function describing an increase in 0-yr old mortality due to the ecosystem-change effect	-
$M_{\max}$	Maximum increase in 0-yr old mortality rate due to the ecosystem-change effect	yr^{-1}
$\hat{a}$ (sector)	Selectivity parameter for sector as indicated; shifts the selectivity function to the left or right	-
μ (sector)	Selectivity parameter that controls the slope of the right hand limb of the function	-
δ (sector)	Selectivity parameter that controls the steepness of the ascending left hand limb of the selectivity function.	-

Other definitions		
Zone	Fishery area / management unit: Zones A-G	
CNP, CP	Two subareas comprising Zone C, with CNP subject to less poaching historically than CP	
FIAS	Fishery Independent Abalone Survey	
FIAS N_{2006}/N_{1951}	FIAS depletion statistics expressing depletion in terms of *number* rather than mass	
CS	Commercial sector	
RS	Recreational sector	
PS	Poaching sector (corresponding to illegal catches)	
FS	Parameters pertaining to FIAS	
OS	Parameters pertaining to the Old Surveys conducted during the 1980's	
IS	Industry/MCM joint full population surveys conducted in 2002	
Co/Po_{yr}	Confiscations (i.t.o. number) as a proportion of the model-estimated number of animals poached in year *yr*.	
CI	Confidence Interval (typically 95% CI) determined by likelihood profile method	
MSY	Maximum Sustainable Yield	
MSYL	Maximum Sustainable Yield Level	
TAC	Total Allowable Catch (annual catch allocation)	

Table 2. Comparison of the uncertainty associated with key model results when using the 2008 Reference Case assessment model.

Parameter	Value	90% Confidence Interval	
$B(2009)^{sp}/B(0)^{sp}$ (zone A)	0.33	0.26	0.39
$B(2009)^{sp}/B(0)^{sp}$ (zone B)	0.25	0.19	0.30
$B(2009)^{sp}/B(0)^{sp}$ (zone C)	0.04	0.01	0.06
$B(2009)^{sp}/B(0)^{sp}$ (zone D)	0.12	0.08	0.16
$B(0)^{sp}$ (A)	9759	6056	13461
$B(0)^{sp}$ (B)	5843	5405	6282
$B(0)^{sp}$ (C)	7292	7055	7529
$B(0)^{sp}$ (D)	9647	6441	12853
$B(current)^{sp}$ (A)	3205	1567	4842
$B(current)^{sp}$ (B)	1441	1078	1804
$B(current)^{sp}$ (C)	314	210	419
$B(current)^{sp}$ (D)	1130	435	1824

Table A.1. Best fit estimates of the pre-exploitation spawning biomass B_0^{sp} (or *K*) for the "poached" CP and "nonpoached" CNP areas of Zone C, and for each of Zones A, B and D, the estimated natural mortality estimates M_a, the inshore-offshore migration parameters ρ (yr^{-1}), the proportions of recruitment in each subarea that occur inshore versus offshore r_I, and the poaching maximum $CP_{\max}$ (i.t.o. NUMBERS). The $CP_{\max}$ estimates are also shown in terms of biomass and the years to which these estimates apply are given in the row below. Minimum values of the negative of the log-likelihood function are also shown. The estimated selectivity parameters are shown for the commercial sector (CS), recreational sector (RS), poaching sector (PS), FIAS (FS) and the old 1980's survey (OS). Note that for the 2002 industry survey (IS), $S_a^{IS} = 1$. Note also that all -*ln*L contributions from catch-at-age data have been multiplied by 0.1 as an *ad hoc* adjustment to compensate for likely positive correlation in these data.

Model	a) Base-case					b) OLD REF CASE-ZONE B POACHING ESTIMATE					c) Combined inshore and offshore regions				
No. parameters			31					31					28		
Zone	**A**	**B**	**CNP**	**CP**	**D**	**A**	**B**	**CNP**	**CP**	**D**	**A**	**B**	**CNP**	**CP**	**D**
Ave confiscation %	18%	25%	8%		7%	19%	26%	9%		8%	18%	30%	11%		7%
$B(0)^{sp}$	9759	5843	2981	4311	9647	8469	5811	2496	4310	9286	7205	5749	1202	4426	7472
ρ	0.029	0.029	0.029	0.015	0.029	0.037	0.037	0.037	0.018	0.037	0.000	0.000	0.000	0.000	0.000
r^I	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9					
Cpmax (no.)	2284770	7.95E+05		561627	757621	1649240	7.04E+05		546372	680564	1421110	6.39E+05		535829	685149
Cpmax (MT)	741	379		271	456	524	342		273	419	440	310		257	388
Cpmax (YEAR)	2006	2002		1995	2002	2006	2002		1995	2002	2006	2002		1995	2002
CP(2008) (MT)	536	274		0	53	495	306		0	1	495	322		156	190
Cmult (Zone A)	2.62					2.22					2.15				
Ppoach			0.90					0.90					0.80		
M_0			0.326					0.327					0.315		
M_{15}			0.139					0.139					0.127		
ν (steepness of recruitment failure)			0.2567					0.2690					0.2185		
Mmax (Recruitment failure scale parameter|)			13.9536					13.9546					13.9685		
a(CS)			8.99943					8.99916					8.99935		
a(RS)			8.99802					8.99743					8.9969		
a(PS)			4.9035					4.90401					4.90554		
a(FS)			6.50921					6.10419					6.71512		
a(OS)			4.67808					5.15731					4.75827		
a(IS)			-					-					-		
μ(CS)			0.000404376					0.000326802					4.56912E-13		
μ(RS)			0.00147504					0.00108153					0.00193256		
μ(PS)			0.000371529					2.65288E-13					0.000811239		
μ(FS)			0.00195037					0.00137293					0.00250421		
μ(OS)			1.63665E-12					9.49973E-13					3.88234E-12		
μ(IS)			-					-					-		
δ(CS)			896.457					640.349					989.104		
δ(RS)			135.3					129.36					68.0937		
δ(PS)			306.198					306.199					306.204		
δ(FS)			0.87247					0.916378					0.793031		
δ(OS)			0.649333					0.576726					0.649558		
δ(IS)			-					-					-		

Model	a) Base-case					b) OLD REF CASE-ZONE B POACHING ESTIMATE					c) Combined inshore and offshore regions				
	A	**B**	**CNP**	**CP**	**D**	**A**	**B**	**CNP**	**CP**	**D**	**A**	**B**	**CNP**	**CP**	**D**
-*ln* L CPUE	-50.201	-49.728	-34.388	-45.222	-33.826	-50.016	-50.359	-35.189	-44.821	-34.138	-49.701	-50.758	-33.152	-46.046	-36.380
-*ln* L FIAS	-0.730	-3.558	-4.089	4.883	-4.168	0.281	-3.629	-3.683	4.651	-3.890	-0.293	-1.998	-4.359	4.831	-3.736
-*ln* L age CS	-15.679	-19.415	-8.290	-10.166	-11.661	-16.536	-19.387	-8.670	-10.081	-11.503	-15.772	-18.542	16.537	-9.531	-11.779
-*ln* L age RS	-1.707	-7.933	-6.866	0.006	-9.013	-1.666	-8.101	-7.076	0.027	-8.604	-1.716	-7.861	-7.007	-0.047	-9.227
-*ln* L age PS	-4.756	-3.646		-0.920	-3.049	-4.234	-4.177		-0.693	-3.080	-3.996	-4.066		-2.185	-3.446
-*ln* L age FIAS	-3.353	-10.514	-4.391	-0.386	-4.953	-3.351	-9.960	-4.738	-0.436	-4.898	-2.576	-10.686	-4.124	-0.265	-4.949
-*ln* L age OS inshore	-3.464	-1.016		-1.305	-0.846	-3.575	-1.043		-1.267	-0.837	-3.048	-0.922		-1.219	-0.645
-*ln* Lage OS offsh.	-3.634	-1.776		-1.159	-1.928	-3.562	-1.729		-1.380	-1.758	-0.962	-1.065		-0.361	-0.159
-*ln* L age IS insh+offsh.		-0.931	-0.857				-0.933	-0.990				-0.859	-0.439		
-*ln* L zone subtotal	-83.525	-98.517	-113.151		-69.444	-82.659	-99.319	-114.344		-68.708	-78.065	-96.757	-87.347		-70.321
-*ln* L TOTAL & AIC			-364.637	**-667.274**				-365.030	**-668.060**				-332.489	**-608.978**	
σ CPUE	0.096	0.098	0.156	0.063	0.177	0.097	0.096	0.151	0.065	0.174	0.098	0.094	0.164	0.061	0.161
σ age CS	0.086	0.072	0.116	0.097	0.098	0.081	0.072	0.113	0.097	0.099	0.085	0.076	0.580	0.101	0.097
σ age RS	0.112	0.058	0.061	0.205	0.058	0.113	0.057	0.059	0.211	0.062	0.111	0.059	0.059	0.190	0.056
σ age PS	0.098	0.127		0.172	0.111	0.105	0.120		0.178	0.111	0.108	0.122		0.145	0.104
σ age FIAS	0.112	0.071	0.085	0.130	0.092	0.112	0.074	0.080	0.128	0.093	0.125	0.069	0.090	0.135	0.092
σ OS insh.	0.036	0.066		0.051	0.080	0.035	0.064		0.053	0.081	0.044	0.072		0.056	0.096
σ OS offsh.	0.038	0.040		0.063	0.033	0.039	0.042		0.053	0.038	0.106	0.070		0.116	0.130
σ IS		0.039	0.061				0.039	0.052				0.043	0.103		
Additional variance	0.386					0.410					0.418				
q CPUE	0.000255	0.00061	0.00306728	0.0010372	0.000252	0.000293	0.00061	0.00356598	0.001025	0.000263	0.000392	0.000671	0.000670824	0.001015	0.0003789
<u>Confiscation percentage</u>			<u>Zone C</u>					Zone C					Zone C		
$\%Co/Po_{2006}$	0.15	0.30	0.08		0.08	0.15	0.34	0.09		0.08	0.18	0.35	0.12		0.08
$\%Co/Po_{2007}$	0.24	0.26	0.07		0.06	0.25	0.27	0.07		0.07	0.29	0.29	0.09		0.07
$\%Co/Po_{2008}$	0.16	0.19	0.09		0.06	0.16	0.17	0.10		0.07	0.19	0.18	0.12		0.07
Ave prop over last 5 yrs	**0.18**	**0.25**	**0.08**		**0.07**	**0.19**	**0.26**	**0.09**		**0.08**	0.18	0.30	0.11		0.07
<u>Catches</u>															
Ccomm(2008)	0	24	0	0	0	0	24	0	0	0	0	24	0	0	0
Cpoa(2008)	536.5	274.2	0.1	0.1	53.4	495.3	305.7	0.0	0.0	1.2	495.4	321.5	39.4	116.9	190.3
Catch total (2008) MT	536.5	298.2	0.1	0.1	53.4	495.3	329.7	0.0	0.0	1.2	495.4	345.5	39.4	116.9	190.3
	A	**B**	**CNP**	**CP**	**D**	**A**	**B**	**CNP**	**CP**	**D**	**A**	**B**	**CNP**	**CP**	**D**
<u>Depletion comp. yr</u>	1986/87	1982		1981	1983	1986/87	1982		1981	1983	1986/87	1982		1981	1983
Insh OBS	0.33	0.67		0.33	0.36	0.33	0.67		0.33	0.36	0.33	0.67		0.33	0.36
Insh PRED	0.74	0.54		0.44	0.72	0.75	0.55		0.45	0.71	0.58	0.42		0.38	0.54
Offsh OBS	0.20	0.54		0.24	0.50	0.20	0.54		0.24	0.50	0.20	0.54		0.24	0.50
Offsh PRED	0.59	0.36		0.25	0.60	0.60	0.37		0.25	0.60	0.60	0.44		0.39	0.59

Table 1 continued. Depletion statistics.

Model	a) Base-case				
Depletion Statistics	A	B	CNP	CP	D
$B^{sp}(2008)/K$ (Insh. + Offsh)	0.33	0.25	0.06	0.03	0.12
$B^{sp}(2008)/K$ (Insh.)	0.21	0.18	0.00	0.00	0.01
$B^{sp}(2008)/K$ (Offsh.)	0.60	0.39	0.18	0.20	0.35
$B^{total}(2008)/K$	0.38	0.30	0.05	0.03	0.11
$B^{commercial}(2008)/K$	0.28	0.18	0.07	0.04	0.14
FIAS N_{2008}/N_{1951}	0.21	0.22	0.00	0.00	0.00
Projections	A	B	CNP	CP	D
Ccomm(2008)	0.0	0.0	0.0	0.0	0.0
Cpoa(2008) (NUMBERS)	1520860	814562	105067	99890	207209
Cpoa(2008) (MT)	570	296.6	0.0	0.0	8
Catch total (2008) MT	569.8	296.6	0.0	0.0	7.8
$B^{sp}(2013)/K$	0.24	0.21	0.03	0.02	0.06
$B^{sp}(2028)/K$	0.12	0.11	0.00	0.00	0.01
$B^{sp}(2013)/Bsp(2008)$	0.73	0.83	0.54	0.53	0.50
$B^{sp}(2028)/Bsp(2008)$	0.35	0.43	0.07	0.07	0.06

Model	b) OLD REF CASE-ZONE B POACHING ESTIMATE				
Depletion Statistics	A	B	CNP	CP	D
$B^{sp}(2008)/K$ (Insh. + Offsh)	0.33	0.27	0.05	0.04	0.13
$B^{sp}(2008)/K$ (Insh.)	0.16	0.18	0.00	0.00	0.00
$B^{sp}(2008)/K$ (Offsh.)	0.61	0.41	0.15	0.20	0.35
$B^{total}(2008)/K$	0.38	0.32	0.05	0.03	0.12
$B^{commercial}(2008)/K$	0.29	0.19	0.07	0.05	0.16
FIAS N_{2008}/N_{1951}	0.14	0.19	0.00	0.00	0.00
Projections	A	B	CNP	CP	D
Ccomm(2008)	0.0	0.0	0.0	0.0	0.0
Cpoa(2008) (NUMBERS)	1481840	828885	91984	91477	186134
Cpoa(2008) (MT)	512	296.6	0.0	0.0	0
Catch total (2008) MT	512.3	296.6	0.0	0.0	0.1
$B^{sp}(2013)/K$	0.23	0.22	0.03	0.02	0.07
$B^{sp}(2028)/K$	0.16	0.15	0.00	0.00	0.01
$B^{sp}(2013)/Bsp(2008)$	0.70	0.82	0.54	0.53	0.50
$B^{sp}(2028)/Bsp(2008)$	0.47	0.56	0.07	0.07	0.06

Model	c) Combined inshore and offshore regions				
Depletion Statistics	A	B	CNP	CP	D
$B^{sp}(2008)/K$ (Insh. + Offsh)	0.22	0.20	0.06	0.04	0.09
$B^{sp}(2008)/K$ (Insh.)	0.22	0.20	0.06	0.04	0.09
$B^{sp}(2008)/K$ (Offsh.)					0.38
$B^{total}(2008)/K$	0.27	0.25	0.06	0.04	0.08
$B^{commercial}(2008)/K$	0.17	0.12	0.00	0.05	0.11
FIAS N_{2008}/N_{1951}	0.23	0.28	0.01	0.00	0.02
Projections	A	B	CNP	CP	D
Ccomm(2008)	0.0	0.0	0.0	0.0	0.0
Cpoa(2008) (NUMBERS)	1276870	788753	36463	111217	187388
Cpoa(2008) (MT)	526	317.0	22.9	38.7	183
Catch total (2008) MT	526.2	317.0	22.9	38.7	183.2
$B^{sp}(2013)/K$	0.07	0.12	0.00	0.00	0.00
$B^{sp}(2028)/K$	0.00	0.00	0.00	0.00	0.00
$B^{sp}(2013)/Bsp(2008)$	0.33	0.62	0.00	0.01	0.01
$B^{sp}(2028)/Bsp(2008)$	0.00	0.00	0.00	0.00	0.00

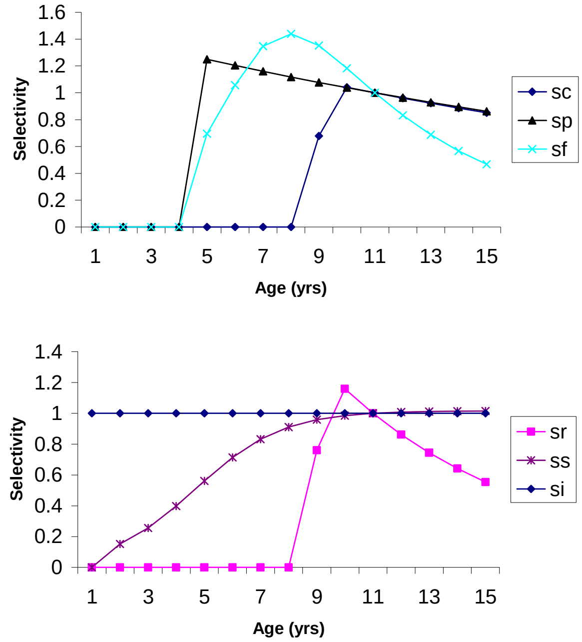


Fig. 1a. Plots of the Reference-case combined ABCD model selectivity functions estimated for the commercial (sc), recreational (sr) and poaching (sp) fishery sectors, and for FIAS (sf) and the old 1980's surveys (ss). A description of the general functional form used is given in Appendix 1 and the fitted parameter values are listed in Table A1. A uniform value is assumed for the industry/MCM survey (si) because of the extractive nature of the sampling methodology used.

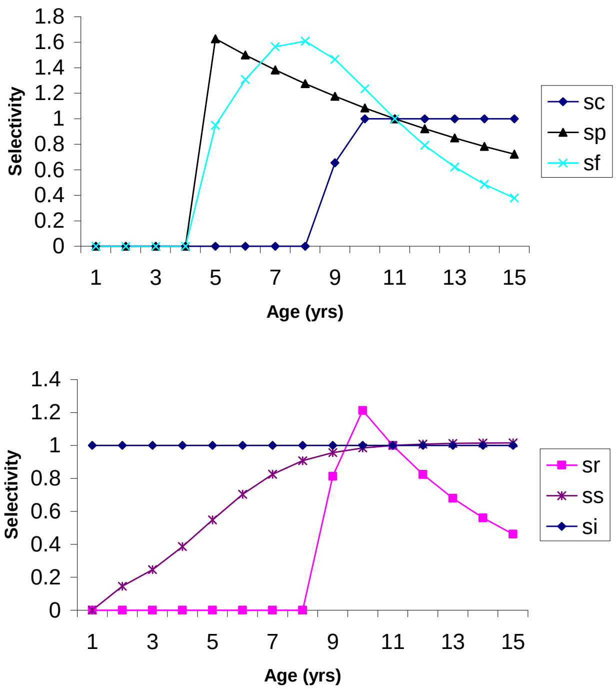
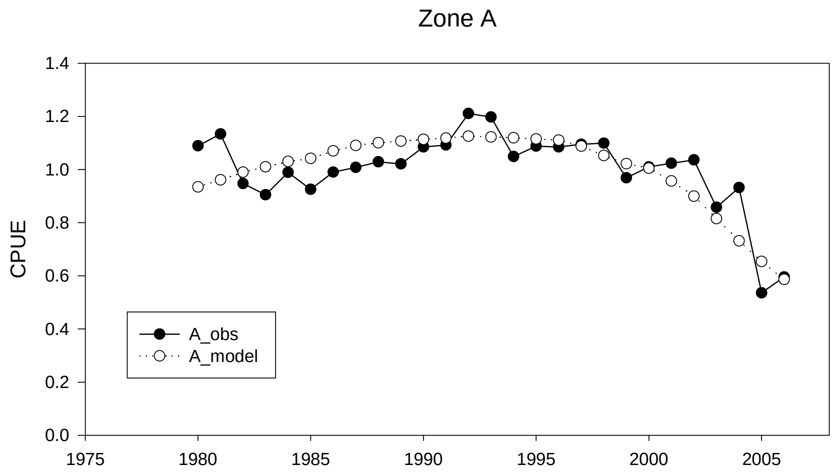
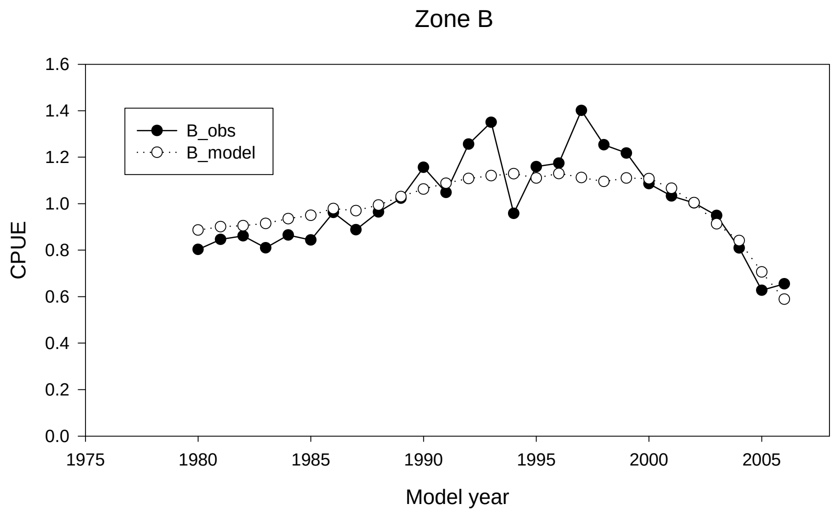


Fig. 1b. Plots of the model selectivity functions estimated for Model version d) which assumes a combined inshore/offshore region.





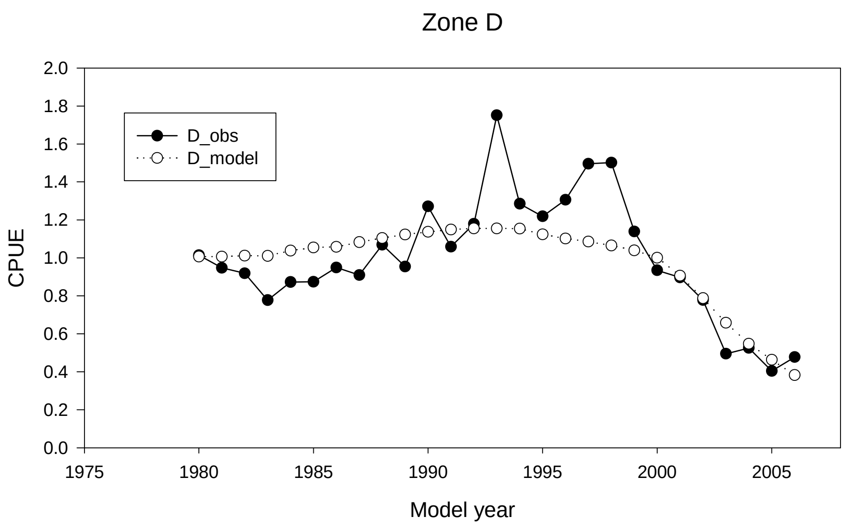
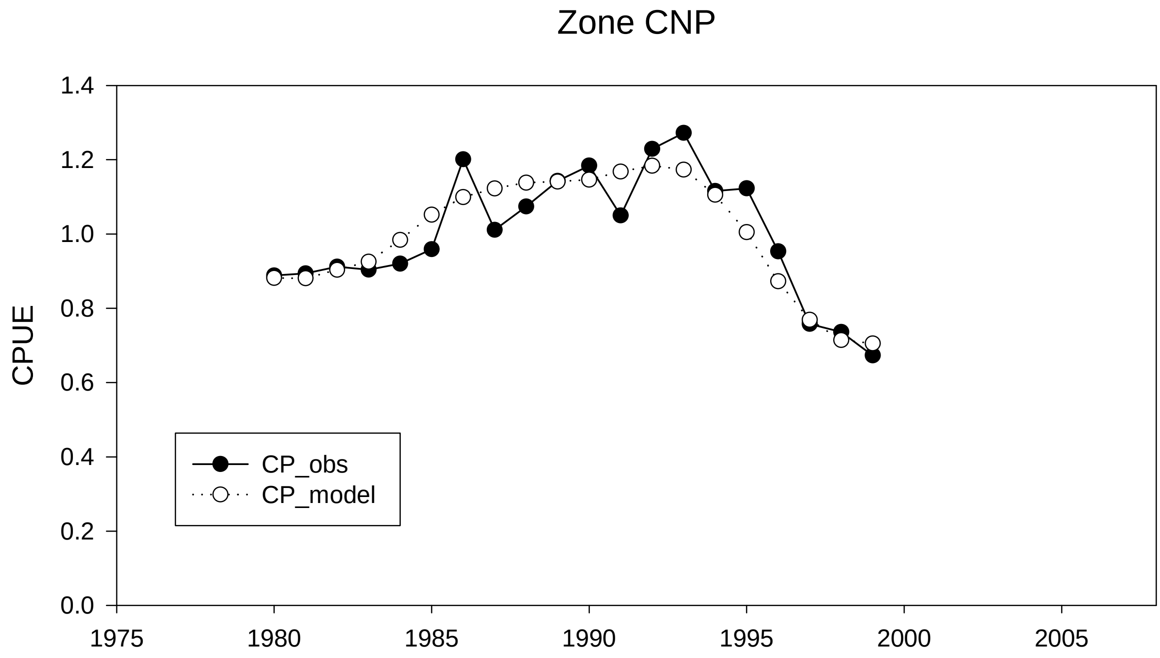


Fig. 2. Comparisons between the standardised CPUE and model-predicted CPUE values (for the Reference-case combined ABCD model) for each of Zones A, B and D.



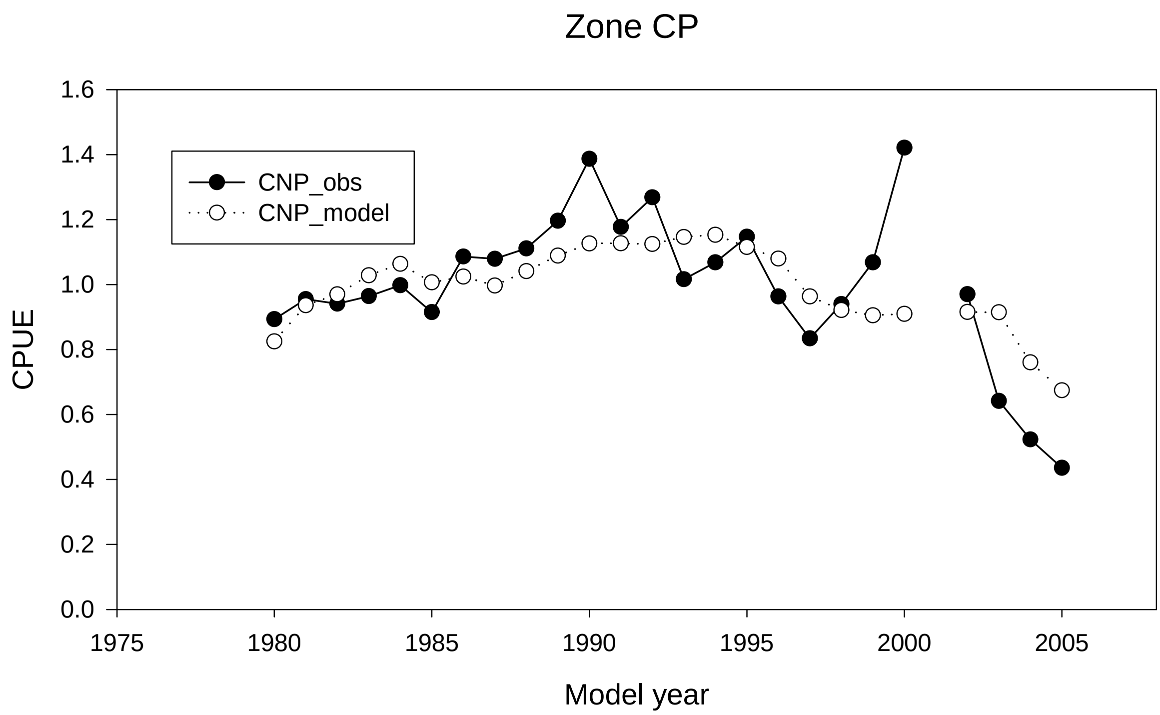


Fig. 3. Comparisons between the standardised CPUE and model-predicted CPUE values (for the Reference-case combined ABCD model) for each of Zones CNP and CP.

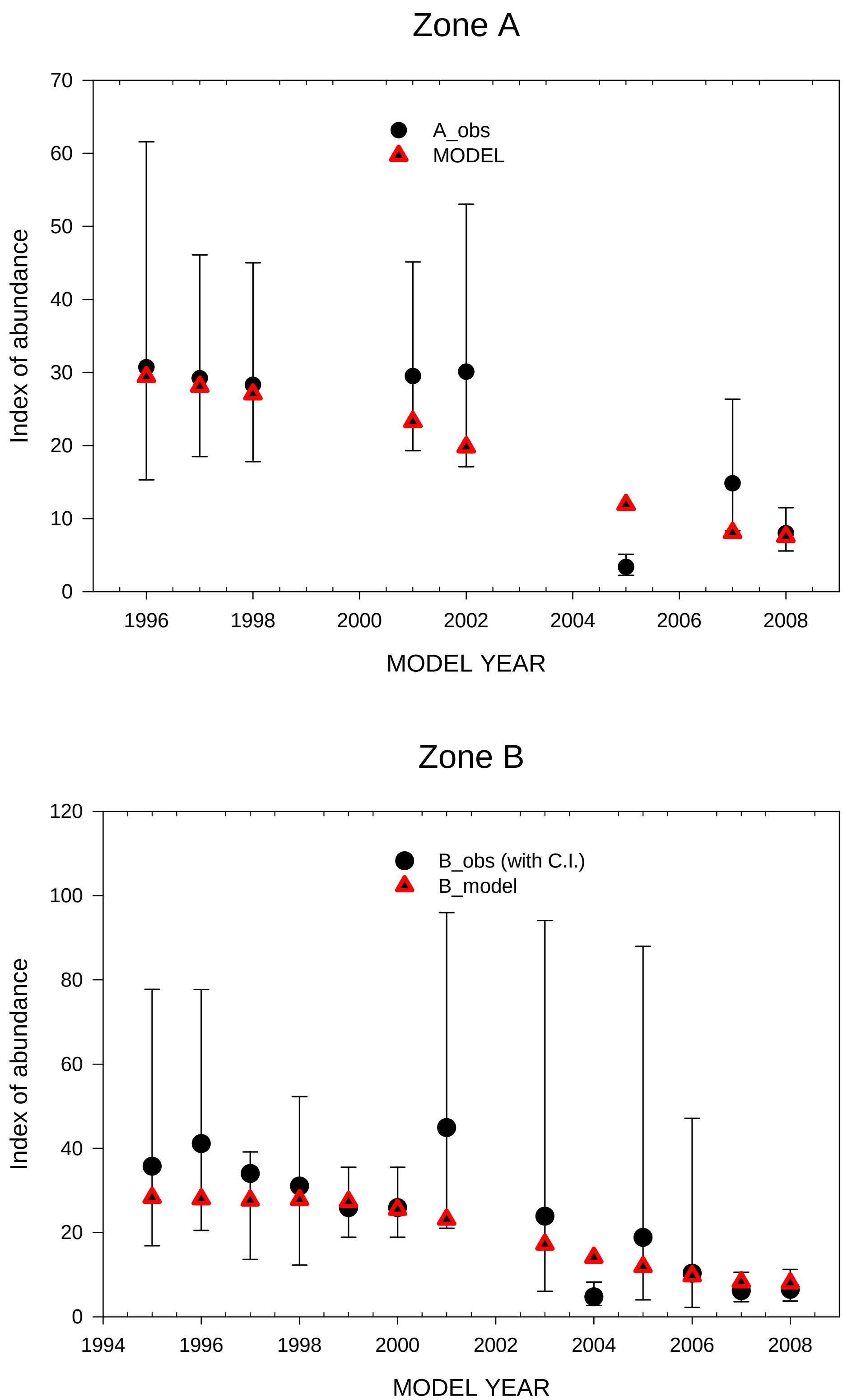


Fig. 4 Comparison of model-predicted (NEW Reference-case combined ABCD model) and observed FIAS trends for each of Zones A and B. Note that 95% confidence intervals have been computed as estimate*exp(±1.96*CV).

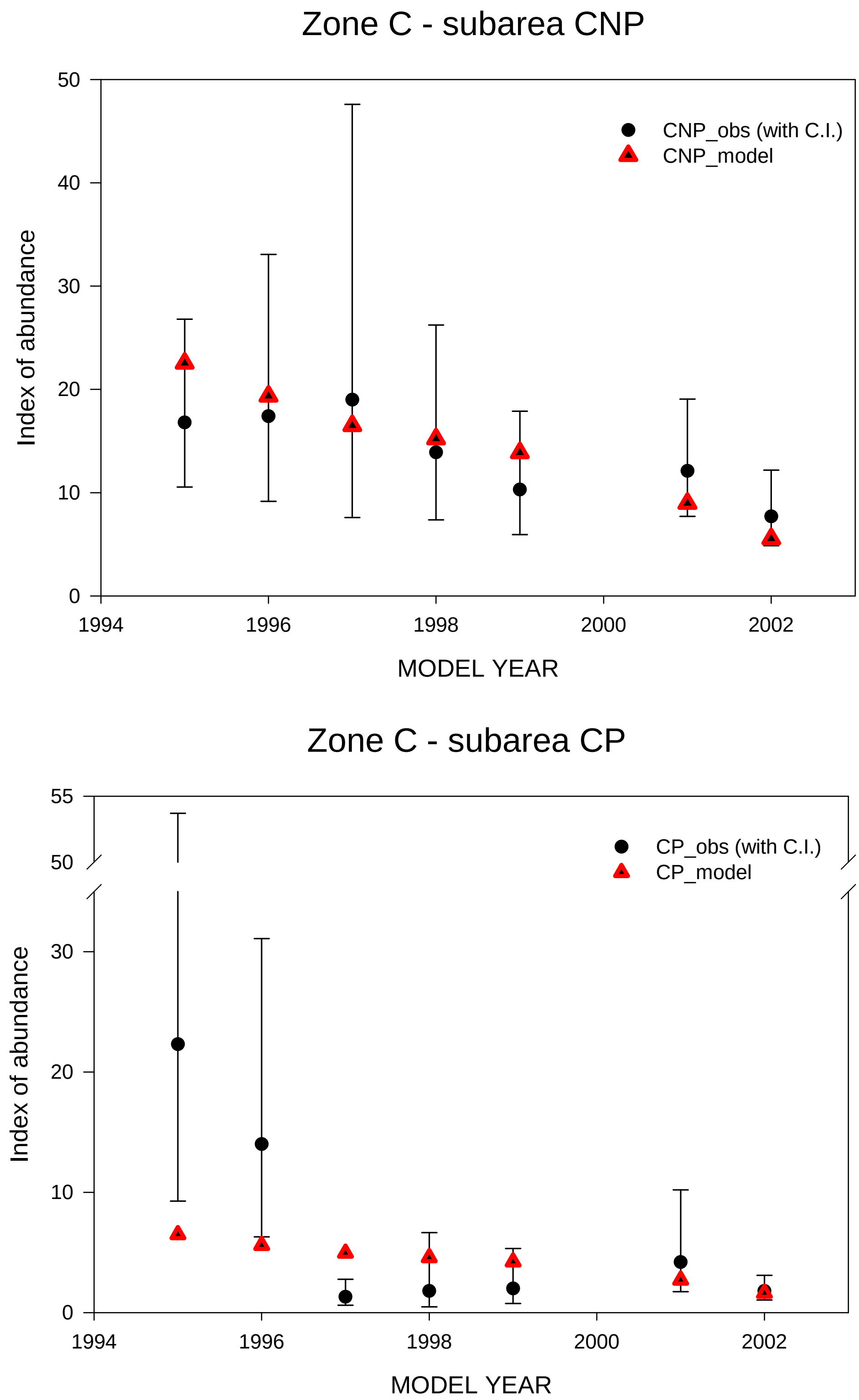


Fig. 5. Comparison of model-predicted (Reference-case combined ABCD model) and observed FIAS trends for each of subareas CNP and CP in Zone C. Note that 95% confidence intervals have been computed as estimate*exp(±1.96*CV). Note the break inserted on the y-axis for subarea CP for ease of viewing purposes (because it allows amplification of the rest of the figure).

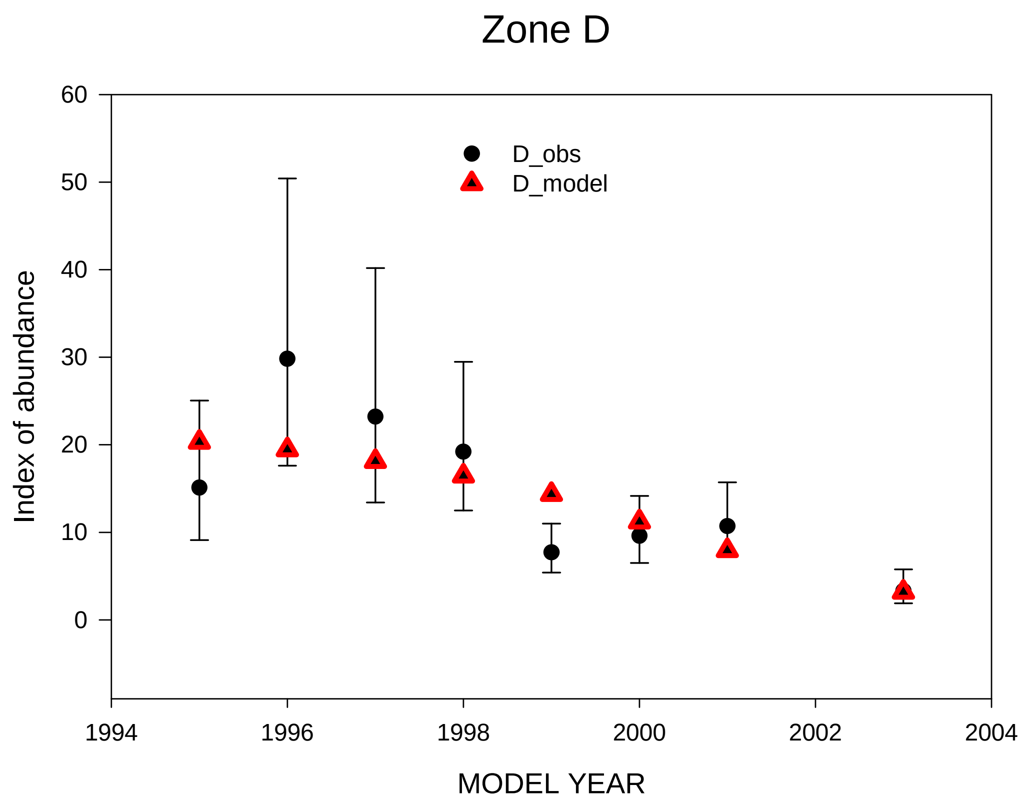


Fig. 6. Comparison of model-predicted (Reference-case combined ABCD model) and observed FIAS trends for each of Zone D. Note that 95% confidence intervals have been computed as estimate*exp(±1.96*CV).

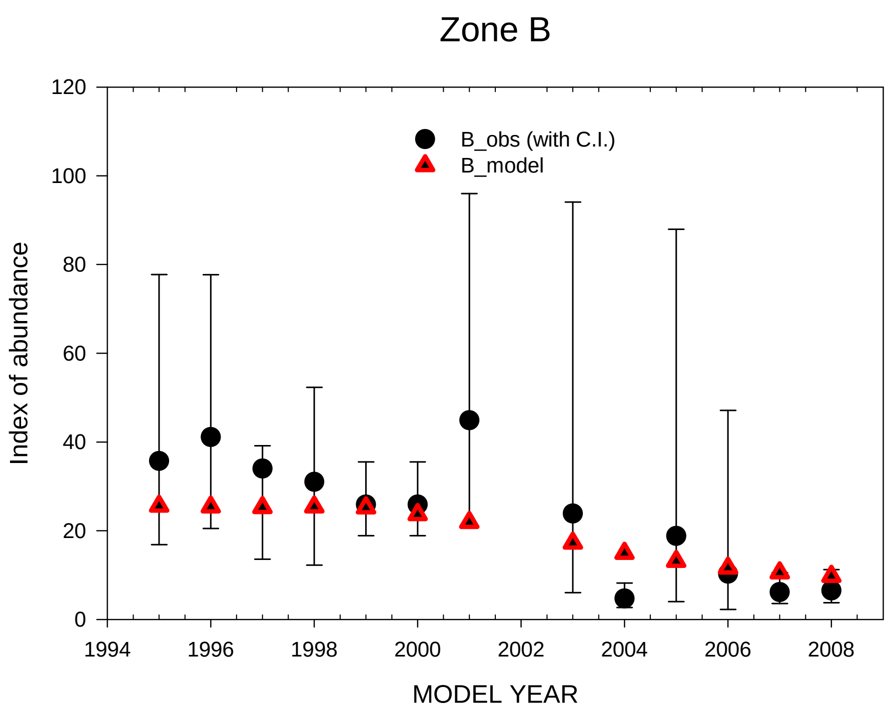


Fig. 7. Zone B fit to FIAS when using the combined inshore/offshore model version.

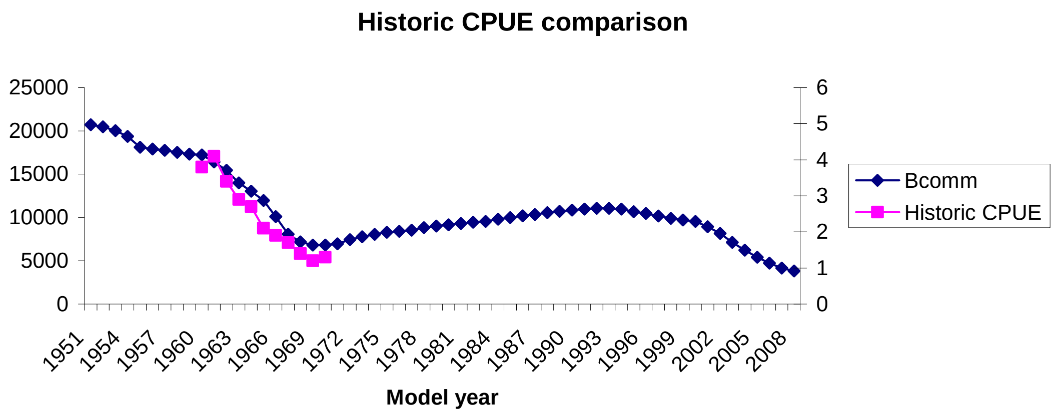


Fig. 8. Historic CPUE Comparison with Zones A-D combined commercial exploitable biomass trajectory.

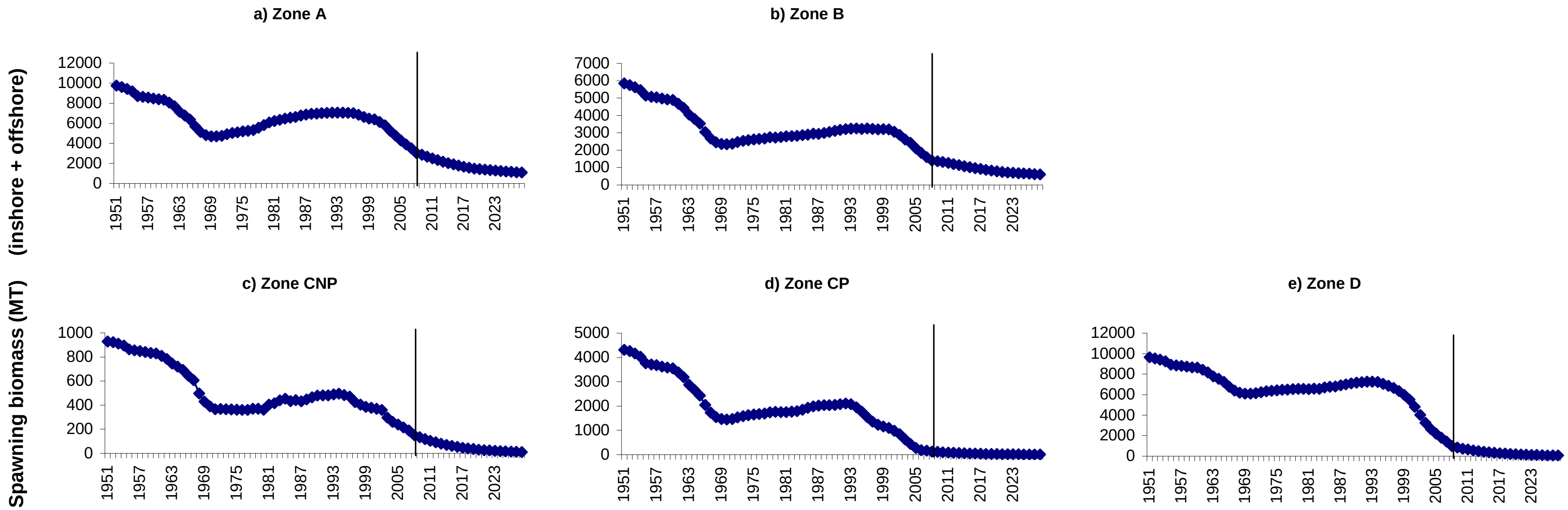


Fig. 9. Reference-case combined ABCD model total (inshore + offshore) spawning biomass trajectories shown for Zones A to D. Note that the 20-yr projections shown (indicated by vertical bar) represent scenarios under which future poaching levels are assumed to remain at the current estimated level (average of 2007 and 2008) and future commercial catches are set to zero.

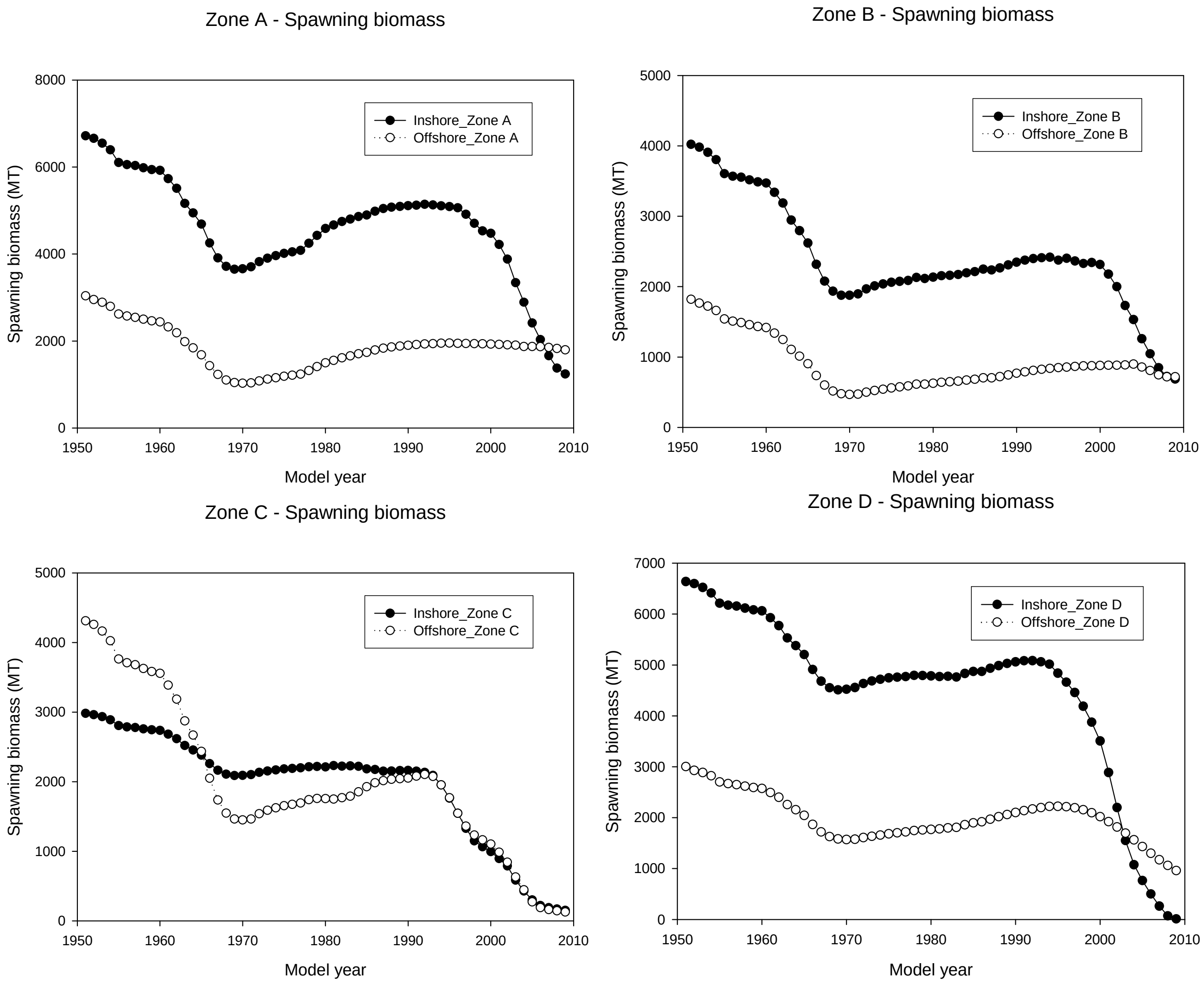
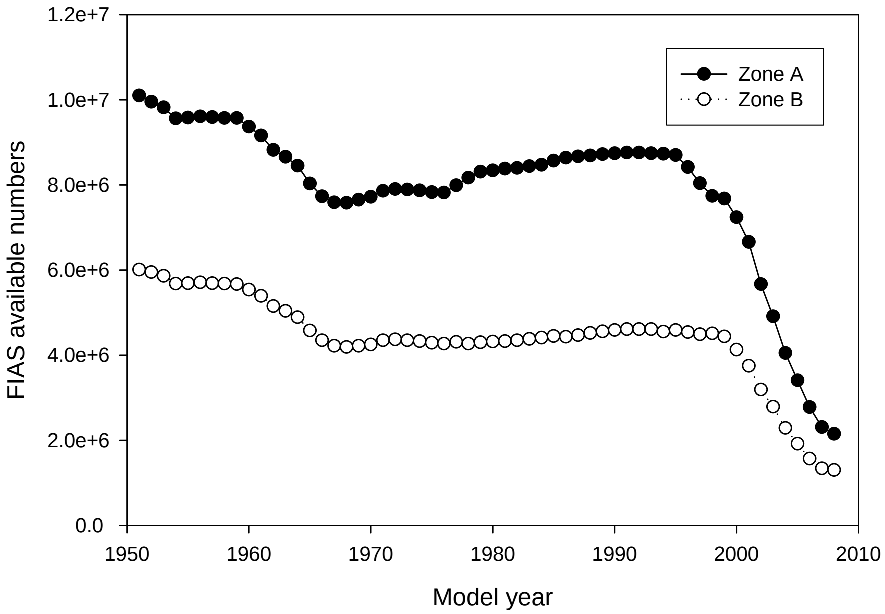


Fig. 10. Spawning biomass trajectories for the inshore and offshore components of Zones A, B, C and D from the Reference-case model.



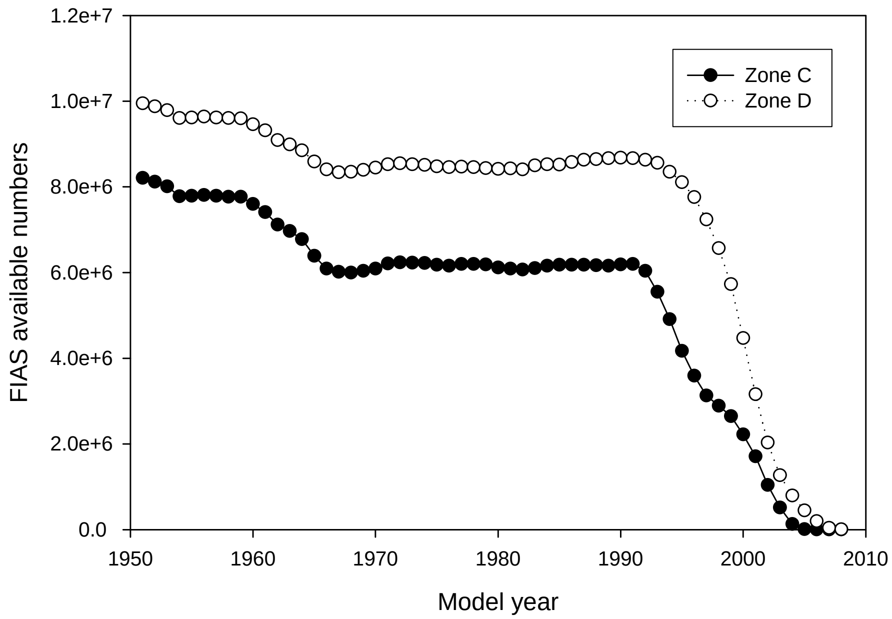


Fig. 11. Reference-case model estimates of the numbers of abalone available to the FIAS sector in Zones A, B, C and D.

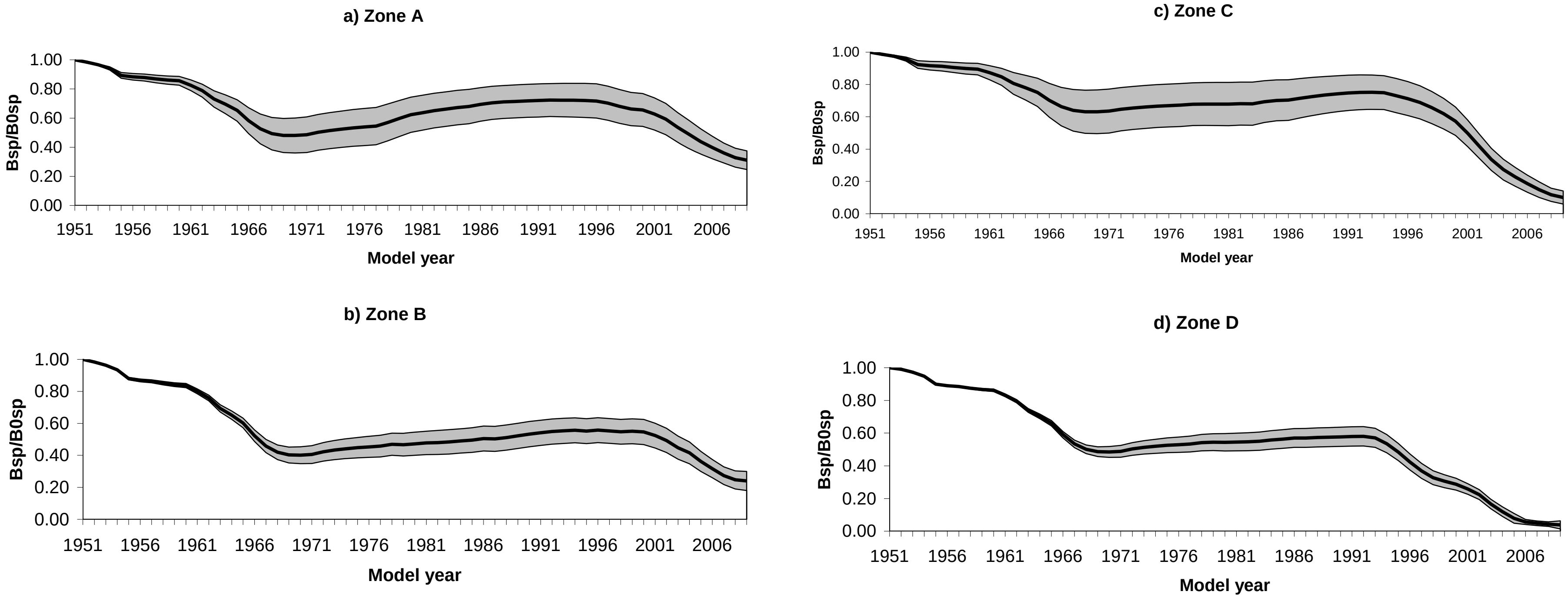


Fig. 12. Total spawning biomass trajectories (inshore and offshore combined shown as a proportion of the pre-exploitation level) for a) Zone A, b) Zone B, c) Zone C and d) Zone D when using the 2008 Reference Case model. The shaded areas represent the associated Hessian-based 90% probability intervals.

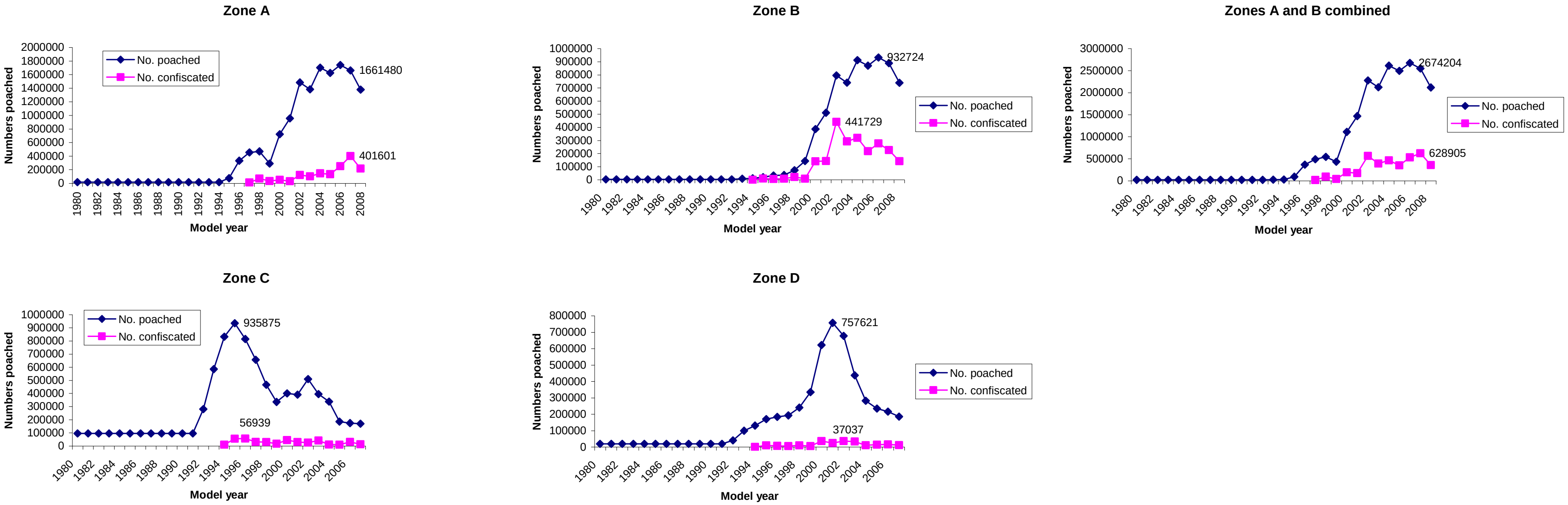


Fig . 13. Comparison of model-predicted numbers of abalone poached per Zone A and B with “observed” numbers confiscated (after allocating confiscated abalone from the Unknown category to each of Zones A-D). The numerical value (units are numbers) corresponding to selected points on the graph is given.

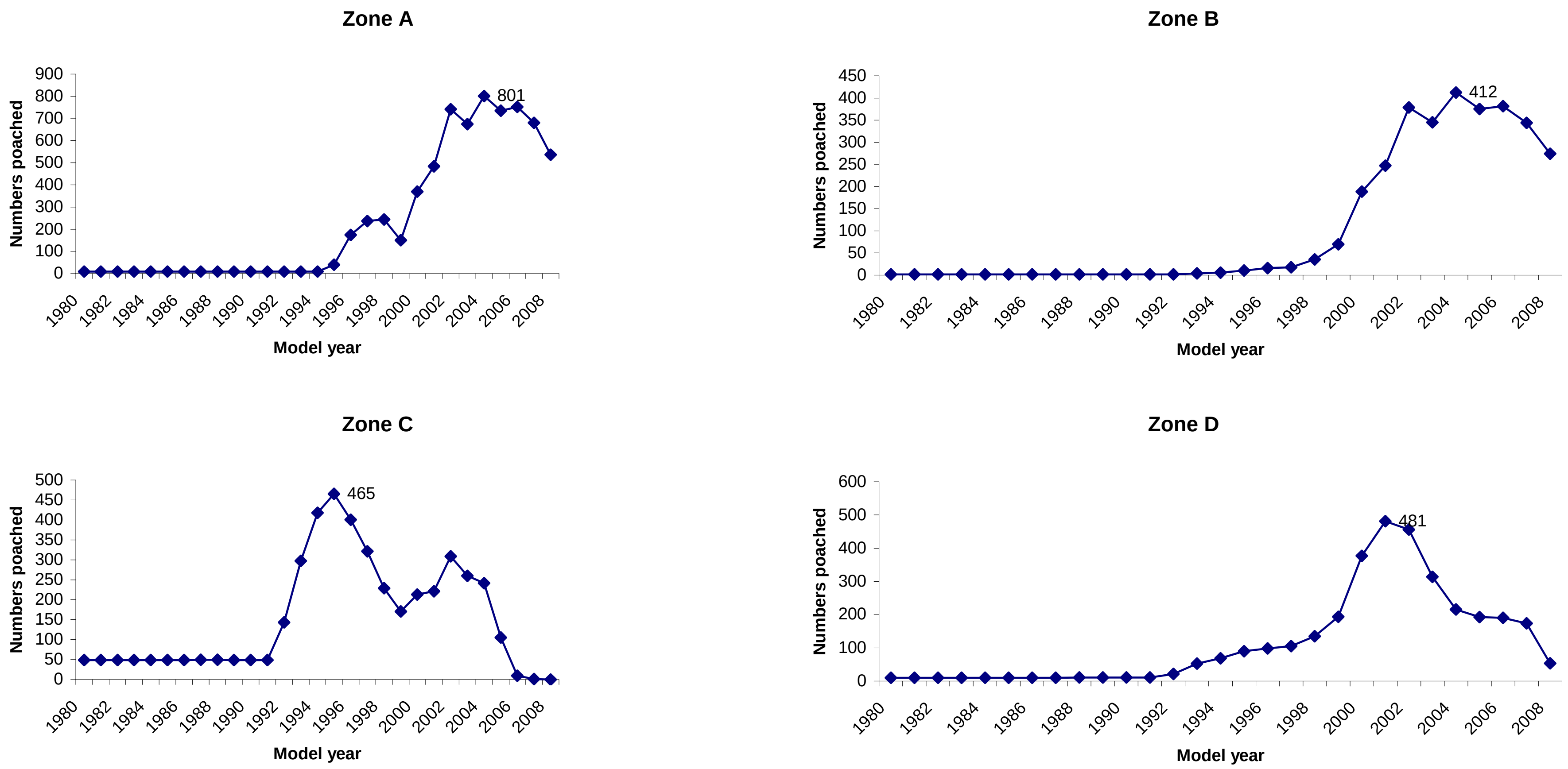


Fig . 14. Model-predicted **biomass (in MT)** of abalone poached per Zones A-D.

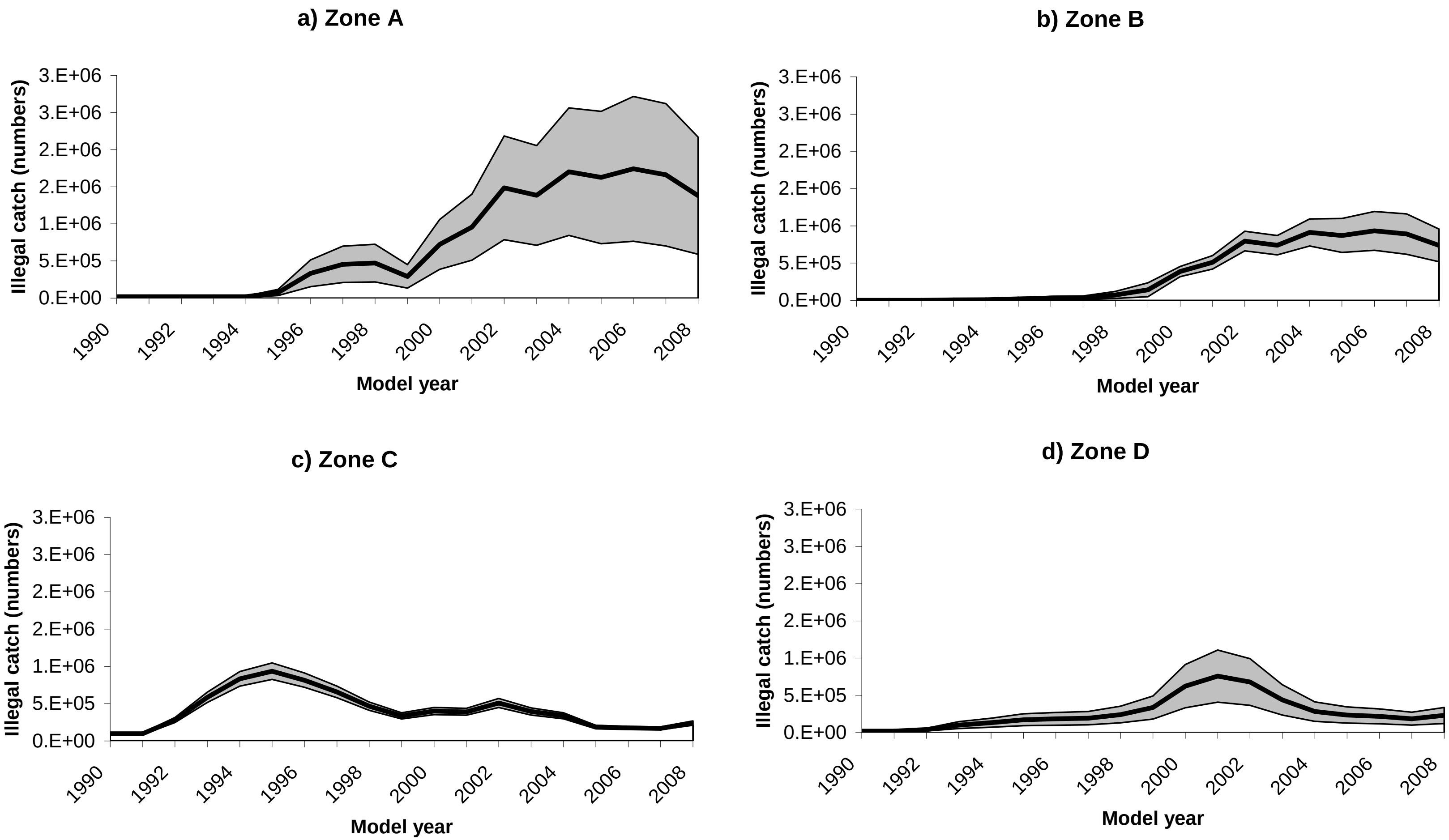


Fig. 15. Reference-case model results showing the uncertainty associated with estimates of the total numbers of abalone poached for years 1990 to present and for a) Zone A, b) Zone B, c0 Zone C and d) Zone D. The y-axis scale is the same in all plots for purposes of comparing amongst Zones. The shaded areas represent the associated Hessian-based 90% probability intervals.

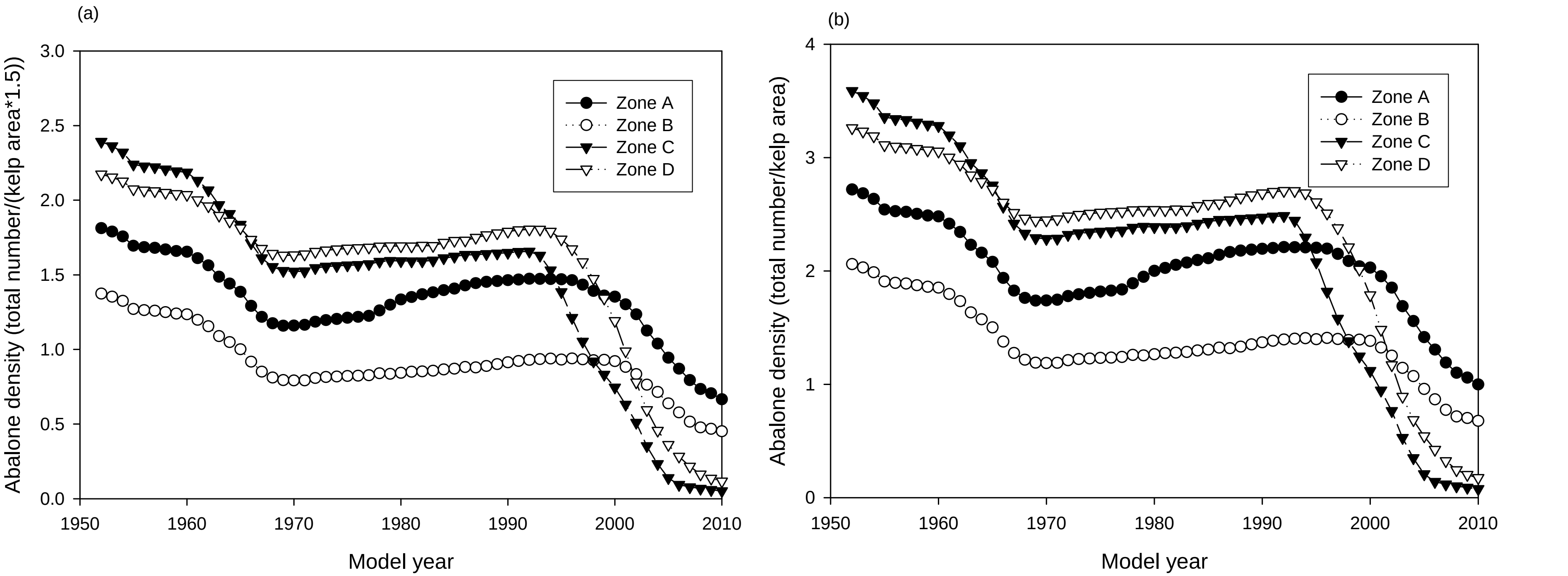


Fig. 16. Reference-case model estimated abalone density per Zones A-D. Density is computed as the total number of abalone (inshore and offshore combined) divided by the habitat area, which is measured either as a) kelp area multiplied by a scaling factor of 1.5 or b) kelp area.