Abalone spatial- and age-structured assessment model preliminary results for Zones A, B, C and D in 2007

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SUMMARY

A summary is presented of the results obtained from the 2007 Reference-case model 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 Appendix 1.

Model results estimate a pristine spawning biomass, B_0^{sp} (in tonnes), of 9330, 6050, 6820 and 12120 for Zones A, B, C and D respectively. The current (inshore+offshore) spawning biomasses of abalone in Zones A, B and D are estimated at ca. 39 %, 38 % and 18 % respectively of their pre-exploitation levels. The "nonpoached" CNP and "poached" CP areas of Zone C are estimated at ca. 9 % and 7 % 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. 0.32 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 2006/07 poaching estimate of 783 MT (corresponding to the assumption that, on average, 20% of all poached abalone are confiscated) is more than ten times the legal 2006 commercial TAC for these zones.

INTRODUCTION

This document provides **preliminary** 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 2007 data. The full details of the spatial- and age-structured production model are provided in Appendix 1 and 2 of this document (see also WG/AB/07/Jun/01). A summary of model parameters and some of the basic features of the model are given in Tables 1 and 2.

Parameters

The Reference-case ABCD model estimates the following 29 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) $M_a : \mu$ $(\lambda = 0.2)$ where the formulation to model age-dependent mortality rates is $M_a = \mu + \frac{\lambda}{a+1}$. Natural mortality parameter assumed common to all Zones [1 parameter]
6) 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]
7) Three parameters for each of five selectivity functions (assumed common to all Zones) [15 parameters]

RESULTS

Model parameter estimates as well as log-likelihood contributions for the Reference case combined ABCD model and some sensitivities are summarised in Tables 3 and 4. The model selectivity functions and fits to the abundance indices are presented in Figs. 1 to 7.

Model results for the case presented are similar to last year’s assessment except that the resource in Zone A is estimated to be much more depleted following the inclusion of more recent FIAS data and as a consequence of high poaching estimates. The model shows generally reasonable fits to all indices.

Parameter estimates

Model results suggest a pristine spawning biomass, B_0^{sp}, of 2340 and 4480 tonnes respectively for subareas CNP and CP, and hence a total Zone C spawning biomass of ca. 6820 tonnes. The difference in the pristine spawning biomass estimates $B_0^{sp}[CNP]$ and $B_0^{sp}[CP]$ are in the main due to the partitioning of the historic zone C catch data between the two subareas. The pristine spawning biomass estimates for the other zones are on a similar scale to the Zone C estimates, with 9330, 6050 and 12120 tonnes estimated for Zones A, B and D respectively (Table 3). These values are similar to those used in last year’s assessment, and once again the Zone D estimate is perhaps too high, possibly because poaching is overestimated in this zone.

The Reference-case selectivity estimates are illustrated in Fig. 1. 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. However, the Reference case model estimates that relatively few 3 and 4 year old animals are caught by the poaching sector (Fig. 1). The estimated FIAS selectivity function reflects the fact that the FIAS transects are situated inshore where smaller animals occur (Fig. 1).

Based on the results of the Reference-case model, the current spawning biomasses of abalone in Zones A, B and D are estimated at ca. 39 %, 38 % and 18 % respectively of their pre-exploitation levels (Table 4, Fig. 7). The “nonpoached” CNP and “poached” CP areas of Zone C are estimated at ca. 9 % and 7 % (Table 4, Fig. 7) respectively of their pre-exploitation levels. The inshore region is particularly depleted, with the model predicting zero remaining abalone in the inshore Zone C and D areas (Table 4).

Catch-at-age comparisons

To assist in identifying potential yearly patterns in the catch-at-age residuals, selected standardized residuals ($\varepsilon_{y,a} \rightarrow \frac{\left(\ell n\, p^{i}_{y,a} - \ell n\, \hat{p}^{i}_{y,a}\right)}{\sigma^{i} / \sqrt{\hat{p}^{i}_{y,a}}}$) have been plotted for Zones A and B (Fig. 8). Some indications of systematic effects in the residuals are evident. For example, the model systematically predicts too many too many age 14-15+ abalone corresponding to the recent commercial catch-at-age data for Zones A. This may reflect errors with the cohort slicing or that the model overestimates the number of older abalone. The fits to the Zone A catch-at-age data corresponding to the FIAS sector are particularly poor, with the model consistently tending to over-estimate the proportion of animals in the larger age classes and *vice versa* for the smaller age classes.

In general, the patterns of residuals do not indicate any very obvious model-misspecification. However, the selectivity functions may warrant some further exploration to see whether it is possible to improve the residuals for the fits to the proportions-at-age data to reflect better randomness and homoscedasticity. Although the poaching sector is thought to have possibly changed its mode of fishing during recent years by moving into deeper waters, there are no obvious indications from the residuals of any changes in selectivity over time for the poaching sector.

Poaching estimates

Figures 9 and 10 respectively show the model-predicted numbers and biomass of poached abalone in each Zone. The numbers poached are compared with the numbers confiscated, suggesting that the numbers poached may be overestimated in Zones C and D. The combined Zones A-D model-predicted 2006/07 poaching estimate of 783 MT (corresponding to the assumption that, on average, 20% of all poached abalone are confiscated) is more than ten times the legal 2006 commercial TAC for these zones.

Projections

Preliminary 20-yr projection results are given at the end of Table 4 for a single scenario that assumes future commercial catches stay constant at the current levels (with recreational catches set at zero) and that future poaching is the average of the 2006 and 2007 estimated poaching levels (assumed to remain at this level for all future years).

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

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

from which it follows that:

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

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

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 catchability coefficient q^s for such a sector's abundance index is 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 $\left(\sigma_y^s\right)^2 = \ln\left(1+\left(CV_y\right)^2\right)$ 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)
$$\hat{C}^s_{y,a} = \left(N^I_{y.a} e^{-\frac{M_a}{4}} - C^I_{y,a} \right) e^{-\frac{M_a}{4}} S^s_a F^s_y \qquad a < 5$$
$$\hat{C}^s_{y,a} = \left(\left(1-\rho\right) N^I_{y.a} e^{-\frac{M_a}{4}} - C^I_{y,a} \right) e^{-\frac{M_a}{4}} S^s_a F^s_y \qquad a \geq 5$$

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

(A55)
$$\hat{C}^s_{y,a} = \left(N^O_{y.a} e^{-\frac{M_a}{4}} - C^O_{y,a} \right) e^{-\frac{M_a}{4}} S^s_a F^s_y \qquad a < 5$$
$$\hat{C}^s_{y,a} = \left(\left(N^O_{y.a} + \rho\, N^I_{y,a} \right) e^{-\frac{M_a}{4}} - C^O_{y,a} \right) e^{-\frac{M_a}{4}} S^s_a F^s_y \qquad a \geq 5$$

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. The parameters listed in the Table are defined in more detail in Appendix 1.

Parameter	Description	Units
$B_0^{sp} = K$	Pre-exploitation (assumed to be 1951) spawning biomass	MT
$B^{sp}, B^{sp}_{insh}, B^{sp}_{offsh}$	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.	-
<u>Other definitions</u>		
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. Summary of model assumptions and structure pertaining to the base-case combined ABCD model that simultaneously fits the model to the data for all the zones. All zones are assumed to comprise an inshore and offshore compartment and Zone C is further subdivided into a "poached" subarea CP and "nonpoached" subarea CNP. Parameter values are either fixed externally, "fixed" based on the Zone C values estimated in the model fit, or are estimated simultaneously for all zones.

	Common	Zone A	Zone B	Zone C – subareas CNP & CP	Zone D
B_0^{sp}		Estimate	Estimate	Estimate (2 par)	Estimate
M	Estimate (1 par)				
Estimate p_{poach}		n/a	n/a	Estimate (1 par)	n/a
Include catch multiplier parameter C_{mult}?		Yes – fix = 1.5	No	No	No
Poaching amount fixed or estimated in model-fitting process? Does it hit the constraint?		Estimate	Estimate (hits 50% constraint)	Estimate (1 par)	Estimate
Year poaching increase assumed to start		1997	1995	1994	1994
Year poaching at maximum level		2004	2002	1995	2002
Migration parameter ρ fixed or estimated in model-fitting process?	Estimate 1 common par for A, B, CNP and D			$\rho_{CP} = 0.5\,\rho_{CNP}$	
Proportion of recruitment occurring inshore fixed or estimated?		Fix = 0.9	Fix = 0.9	Fix = 0.9	Fix = 0.9
Downweight catch-at-age data?		Yes	Yes	Yes	Yes
Model ecosystem-change effect?		No	No	Yes (2 pars)	Yes – fix using Zone C parameter estimates
Selectivity parameters	Estimate 15 parameters simultaneously for all zones				

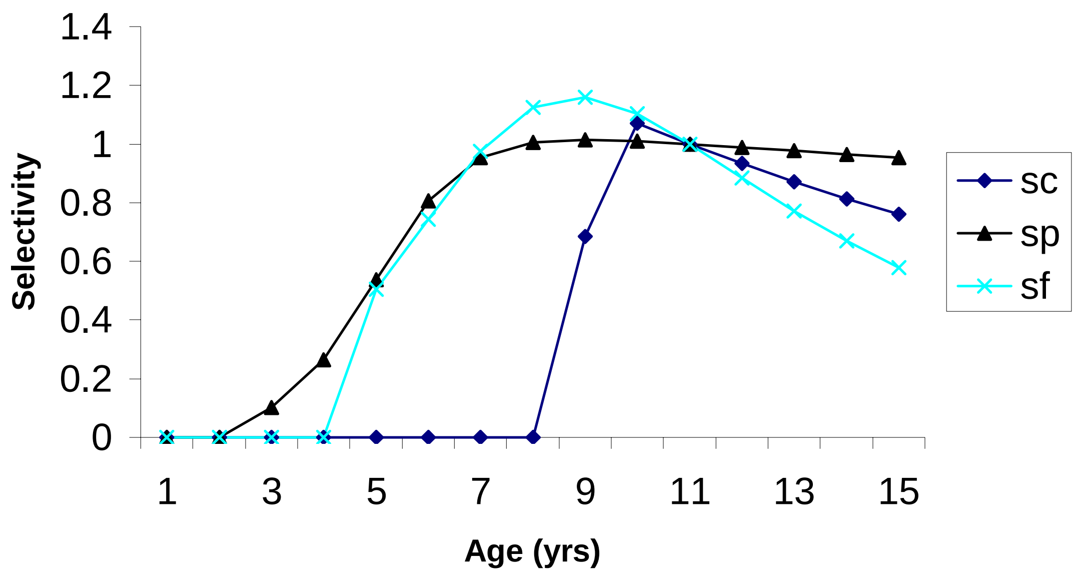
Table 3. Best fit estimates of the pre-exploitation spawning biomass B_0^{sp} (or K) for the "poached" CP and "nonpoached" CNP areas of Zone C, and for each of Zones A, B and D, the estimated natural mortality estimates M_a, the inshore-offshore migration parameters ρ (yr^{-1}), the proportions of recruitment 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) Ref. case					b) Confis prop = 0.5					c) Stratified estimates for ZoneB FIAS data				
No. parameters			30					30					30		
Zone	**A**	**B**	**CNP**	**CP**	**D**	**A**	**B**	**CNP**	**CP**	**D**	**A**	**B**	**CNP**	**CP**	**D**
Ave confiscation %	16%	40%	17%		6%	7%	27%	15%		11%	12%	18%	15%		5%
$B(0)^{sp}$	9332	6049	2337	4477	12122	14953	6451	2109	4690	12068	9292	6362	2186	4683	11269
ρ	0.000495	0.000495	0.000495	0.000247	0.000495	0.000765	0.000765	0.000765	0.000383	0.000765	0.000578	0.000578	0.000578	0.000289	0.000578
r^I	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Cpmax (no.)	1741720	7.93E+05		544271	856666	3027840	1.00E+06		623174	393898	1883250	1.53E+06		624503	834271
Cpmax (MT)	410	363		275	551	685	445		314	254	349	504		264	486
Cpmax (YEAR)	2004	2002		1995	2002	2004	2002		1995	2002	2004	2002		1995	2002
Cmult (Zone A)	1.50					1.50					1.50				
Ppoach			0.64					0.64					0.60		
M_0			0.322					0.349					0.313		
M_1			0.222					0.249					0.213		
M_2			0.189					0.216					0.179		
M_3			0.172					0.199					0.163		
M_4			0.162					0.189					0.153		
M_5			0.156					0.183					0.146		
M_6			0.151					0.178					0.141		
M_7			0.147					0.174					0.138		
M_8			0.144					0.172					0.135		
M_9			0.142					0.169					0.133		
M_{10}			0.140					0.167					0.131		
M_{11}			0.139					0.166					0.129		
M_{12}			0.138					0.165					0.128		
M_{13}			0.136					0.164					0.127		
M_{14}			0.136					0.163					0.126		
M_{15}			0.135					0.162					0.125		
□□steepness of recruitment failure)			0.2352					0.2544					0.2194		
Mmax (Recruitment failure scale parameter|)			10.0003					9.99998					10.0237		
h	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
a(CS)			8.99924					8.99901					8.99951		
a(RS)			8.99954					8.99926					8.99958		
a(PS)			4.99941					5.21118					14.9887		
a(FS)			6.94021					5.33804					7.14365		
a(OS)			5.12146					6.72718					5.11012		
a(IS)			-					-					-		
□(CS)			0.000687					0.000568					0.000943		
□(RS)			0.001032					0.00043					0.000969		
□(PS)			0.000121					0.000213					0.0407		
□(FS)			0.001491					7.87E-05					0.001376		
□(OS)			0.000344					0.001239					0.000348		
□(IS)			-					-					-		
□(CS)			516.874					498.529					694.577		
□(RS)			643.465					499.232					685.631		
□(PS)			1.13889					1.47575					4.10293		
□(FS)			0.726992					1.74354					0.817154		
□(OS)			0.668038					0.69304					0.668356		
□(IS)			-					-					-		

Model	a) Ref. case					b) Confis prop = 0.5					c) Stratified estimates for ZoneB FIAS data				
	A	**B**	**CNP**	**CP**	**D**	**A**	**B**	**CNP**	**CP**	**D**	**A**	**B**	**CNP**	**CP**	**D**
-*ln* L CPUE	-42.256	-46.205	-33.460	-47.513	-31.319	-45.220	-43.507	-36.325	-43.562	-29.460	-43.853	-36.424	-34.110	-44.576	-31.937
-*ln* L FIAS	13.954	-4.572	-5.961	9.121	-2.620	13.361	-4.463	-4.139	10.530	-2.225	13.904	6.134	-5.581	10.100	-2.489
-*ln* L age CS	-16.625	-19.627	-8.692	-10.245	-11.888	-16.454	-20.077	-8.885	-10.909	-10.777	-16.436	-19.089	-8.969	-10.705	-11.862
-*ln* L age RS	-1.587	-8.073	-7.059	-0.023	-8.664	-1.633	-8.199	-7.203	-0.118	-7.863	-1.567	-8.122	-7.195	-0.032	-8.123
-*ln* L age PS	-2.794	-3.953		-1.985	-4.543	-2.230	-2.329		-1.079	-2.404	-0.693	1.357		-1.570	-2.405
-*ln* L age FIAS	-2.709	-9.968	-3.860	-0.174	-5.571	-3.021	-8.474	-4.928	-0.315	-4.467	0.147	-8.501	-3.565	-0.182	-5.978
-*ln* L age OS inshore	-3.217	-1.113		-1.394	-1.043	-1.896	-1.323		-1.622	-1.367	-3.194	-1.088		-1.342	-1.100
-*ln* Lage OS offsh.	-3.270	-1.424		-0.982	-2.285	-2.288	-0.958		-1.252	-0.744	-2.934	-1.228		-1.159	-2.336
-*ln* L age IS insh+offsh.		-0.914	-0.589				-1.090	-0.734				-0.777	-0.481		
-*ln* L zone subtotal	-58.505	-95.850	-112.816		-67.933	-59.382	-90.420	-110.541		-59.309	-54.627	-67.739	-109.367		-66.230
-*ln* L TOTAL			-335.105					-319.652					-297.963		
□□CPUE	0.129	0.112	0.162	0.056	0.194	0.116	0.123	0.145	0.069	0.208	0.122	0.160	0.158	0.065	0.189
□□age CS	0.081	0.068	0.113	0.096	0.097	0.082	0.067	0.111	0.092	0.103	0.082	0.071	0.111	0.093	0.097
□□age RS	0.116	0.057	0.059	0.197	0.061	0.115	0.056	0.057	0.172	0.068	0.117	0.056	0.057	0.194	0.066
□□age PS	0.121	0.121		0.149	0.085	0.131	0.148		0.169	0.125	0.162	0.234		0.156	0.125
□□age FIAS	0.116	0.069	0.094	0.139	0.084	0.111	0.081	0.078	0.133	0.099	0.185	0.081	0.099	0.139	0.078
□□OS□insh.	0.041	0.061		0.047	0.067	0.074	0.050		0.039	0.050	0.041	0.062		0.050	0.064
□□OS offsh.	0.044	0.053		0.072	0.025	0.064	0.076		0.059	0.083	0.050	0.061		0.063	0.024
□□□S		0.040	0.085				0.032	0.071				0.048	0.098		
q CPUE	0.000256	0.000605	0.00313	0.000967	0.000196	0.000138	0.000461	0.00251	0.000709	0.000181	0.000268	0.000627	0.003379	0.000941	0.000226
Confiscation percentage			Zone C					Zone C					Zone C		
$\%Co/Po_{1994}$		0.24	0.08		0.03		0.19	0.07		0.06		0.13	0.07		0.03
$\%Co/Po_{1995}$		0.09	0.07		0.02		0.07	0.06		0.04		0.05	0.06		0.02
$\%Co/Po_{1996}$		0.08	0.05		0.01		0.06	0.04		0.03		0.04	0.04		0.01
$\%Co/Po_{1997}$	0.10	0.18	0.05		0.02	0.06	0.14	0.05		0.05	0.09	0.09	0.05		0.02
$\%Co/Po_{1998}$	0.05	0.05	0.04		0.01	0.03	0.04	0.04		0.02	0.04	0.02	0.03		0.01
$\%Co/Po_{1999}$	0.11	0.27	0.17		0.04	0.06	0.21	0.16		0.10	0.10	0.14	0.15		0.05
$\%Co/Po_{2000}$	0.04	0.16	0.05		0.02	0.02	0.12	0.05		0.05	0.04	0.08	0.05		0.02
$\%Co/Po_{2001}$	0.17	0.38	0.15		0.04	0.10	0.30	0.14		0.09	0.16	0.19	0.14		0.04
$\%Co/Po_{2002}$	0.10	0.24	0.11		0.05	0.06	0.19	0.10		0.12	0.09	0.12	0.10		0.06
$\%Co/Po_{2003}$	0.17	0.23	0.16		0.03	0.10	0.18	0.15		0.06	0.16	0.12	0.14		0.03
$\%Co/Po_{2004}$	0.15	0.32	0.12		0.05	0.07	0.21	0.10		0.09	0.11	0.13	0.09		0.04
$\%Co/Po_{2005}$	0.22	0.83	0.32		0.12	0.05	0.50	0.28		0.18	0.08	0.33	0.28		0.08
Ave prop over last 5 yrs	**0.16**	**0.40**	**0.17**		**0.06**	**0.07**	**0.27**	**0.15**		**0.11**	0.12	0.18	0.15		0.05
Mean CS Fishing mortality	0.03	0.11	0.13	0.15	0.02	0.02	0.08	0.12	0.12	0.04	0.04	0.12	0.14	0.14	0.03
Catches	782.6	75	10.43406			1466.3	75	19.55015			675.2	75	9.002407		
Ccomm(2005)	0	75	0	0	0	0	75	0	0	0	0	75	0	0	0
Cpoa(2005)	671.8	105.6	0.6	0.7	3.8	1142.8	130.9	0.1	0.2	192.3	556.0	117.0	0.2	0.2	1.8
Catch total (2005) MT	671.8	180.6	0.6	0.7	3.8	1142.8	205.9	0.1	0.2	192.3	556.0	192.0	0.2	0.2	1.8
	A	**B**	**CNP**	**CP**	**D**	**A**	**B**	**CNP**	**CP**	**D**	**A**	**B**	**CNP**	**CP**	**D**
Depletion comp. yr	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	0.83	0.58		0.47	0.78	0.92	0.72		0.62	0.84	0.82	0.58		0.47	0.76
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	0.70	0.36		0.29	0.67	0.84	0.50		0.42	0.72	0.68	0.36		0.28	0.62

Table 4. Illustrative model depletion statistics for each of Zones A, B, CNP, CP and D

Model	a) Ref. case					b) Confis prop = 0.5					c) Stratified estimates for ZoneB FIAS data				
Depletion statistics															
$B^{sp}(2005)/K$ (Insh. + Offsh)	0.39	0.38	0.09	0.07	0.18	0.50	0.48	0.10	0.09	0.22	0.39	0.22	0.10	0.08	0.18
$B^{sp}(2005)/K$ (Insh.)	0.25	0.37	0.00	0.00	0.00	0.31	0.45	0.00	0.00	0.05	0.24	0.14	0.00	0.00	0.00
$B^{sp}(2005)/K$ (Offsh.)	0.59	0.40	0.22	0.26	0.44	0.70	0.50	0.21	0.26	0.41	0.56	0.29	0.21	0.25	0.37
$B^{total}(2005)/K$	0.44	0.42	0.08	0.07	0.17	0.55	0.53	0.09	0.08	0.20	0.42	0.25	0.09	0.08	0.16
$B^{commercial}(2005)/K$	0.35	0.29	0.11	0.09	0.21	0.45	0.37	0.13	0.11	0.29	0.38	0.17	0.11	0.09	0.23
FIAS N_{2005}/N_{1951}	0.21	0.49	0.00	0.00	0.00	0.23	0.52	0.00	0.00	0.01	0.19	0.18	0.00	0.00	0.00
Projections	**A**	**B**	**CNP**	**CP**	**D**	**A**	**B**	**CNP**	**CP**	**D**	**A**	**B**	**CNP**	**CP**	**D**
Ccomm(2006)	0.0	75.0	0.0	0.0	0.0	8.0	0.0	4.0	4.0	8.0	0.0	75.0	0.0	0.0	0.0
Cpoa(2006) (NUMBERS)	1660730	256406	49371	92555	484445	2887040	324472	35019	115701	222749	1795680	496281	45371	109575	471781
Cpoa(2006) (MT)	662	106.9	2.4	1.9	16	1121	132.1	0.3	0.6	190	550	117.4	0.0	0.6	7
Catch total (2006) MT	661.9	181.9	2.4	1.9	16.3	1128.8	132.1	4.3	4.6	197.7	550.0	192.4	0.0	0.6	7.4
$B^{sp}(2010)/K$	0.25	0.44	0.05	0.04	0.10	0.33	0.57	0.05	0.04	0.10	0.23	0.23	0.06	0.05	0.12
$B^{sp}(2025)/K$	0.15	0.54	0.01	0.01	0.01	0.20	0.72	0.00	0.00	0.01	0.10	0.28	0.01	0.01	0.02
$B^{sp}(2025)/Bsp(2005)$	0.64	1.15	0.57	0.56	0.53	0.66	1.20	0.44	0.46	0.44	0.59	1.07	0.59	0.59	0.66
$B^{sp}(2025)/Bsp(2005)$	0.38	1.41	0.08	0.08	0.07	0.40	1.50	0.00	0.00	0.02	0.27	1.31	0.09	0.09	0.10



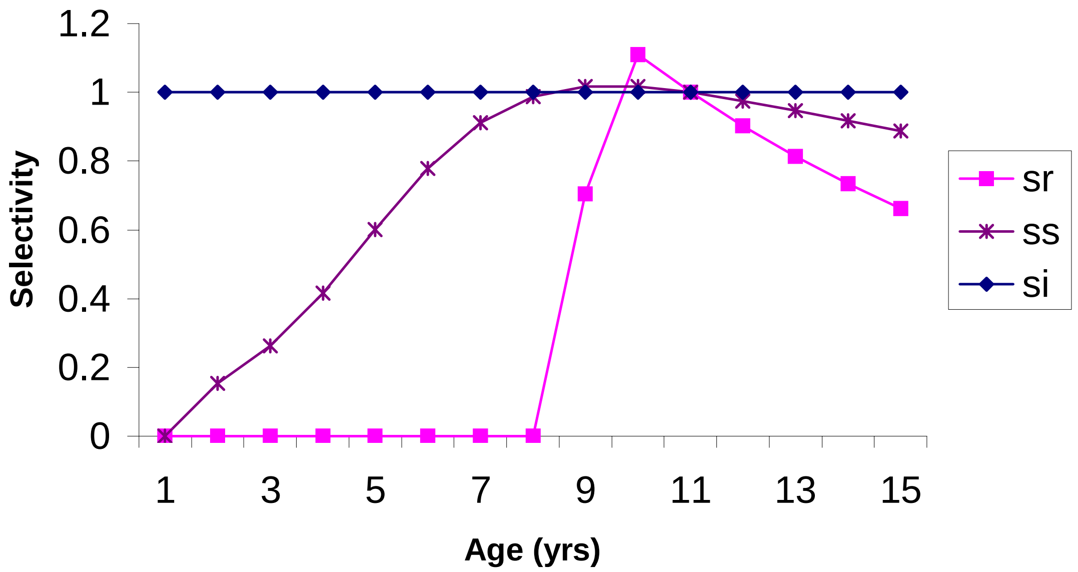


Fig. 1. Plots of the Reference-case combined ABCD model selectivity functions estimated for the commercial (sc), recreational (sr) and poaching (sp) fishery sectors, and for FIAS (sf) and the old 1980's surveys (ss). A description of the general functional form used is given in Appendix 1 and the fitted parameter values are listed in Table 4. A uniform value is assumed for the industry/MCM survey (si) because of the extractive nature of the sampling methodology used.

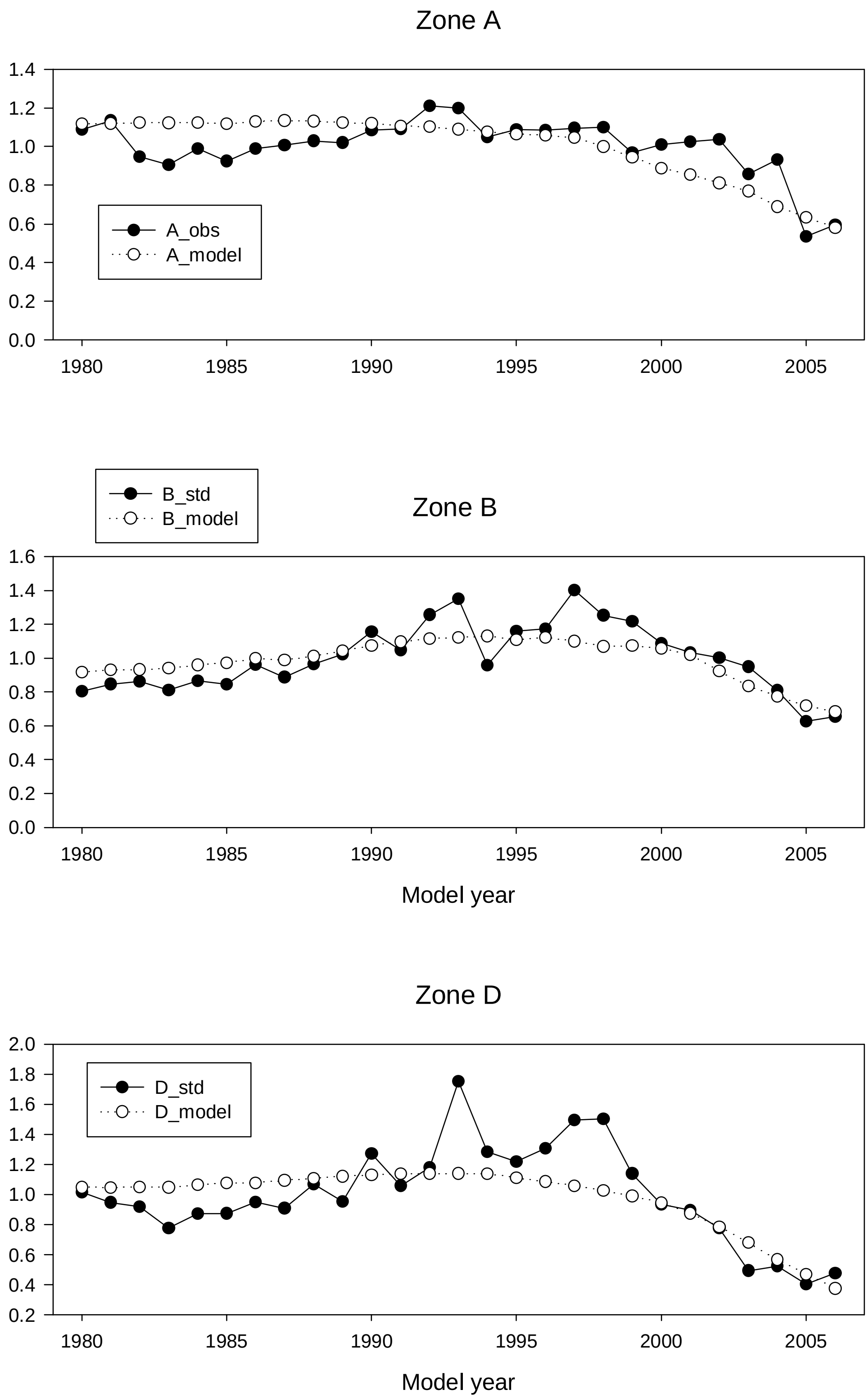
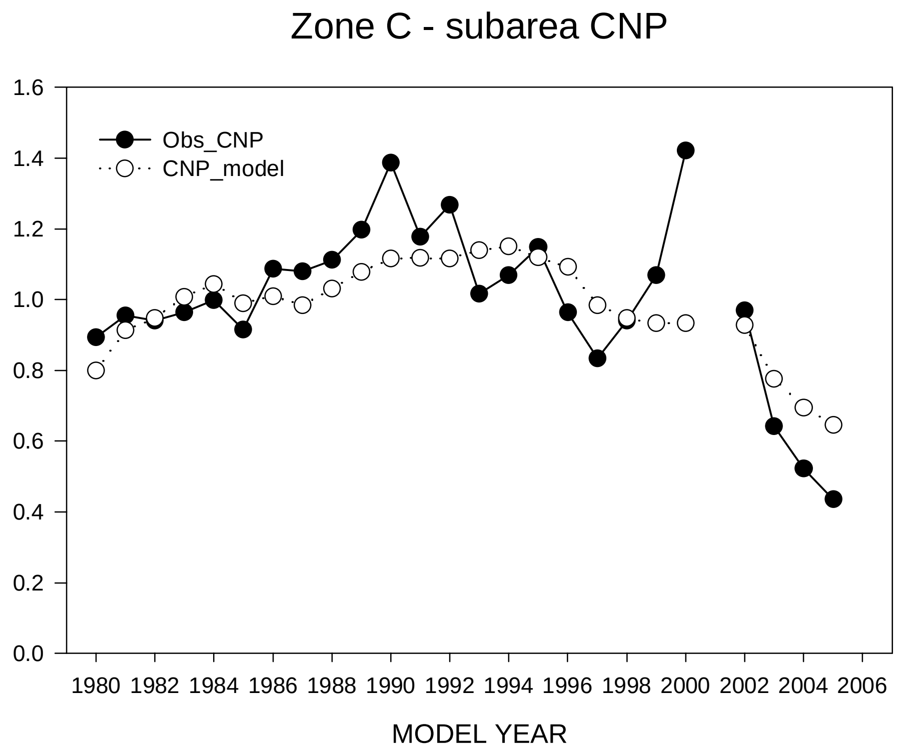


Fig. 2. Comparisons between the standardised CPUE and model-predicted CPUE values (for the Reference-case combined ABCD model) for each of Zones A, B and D.



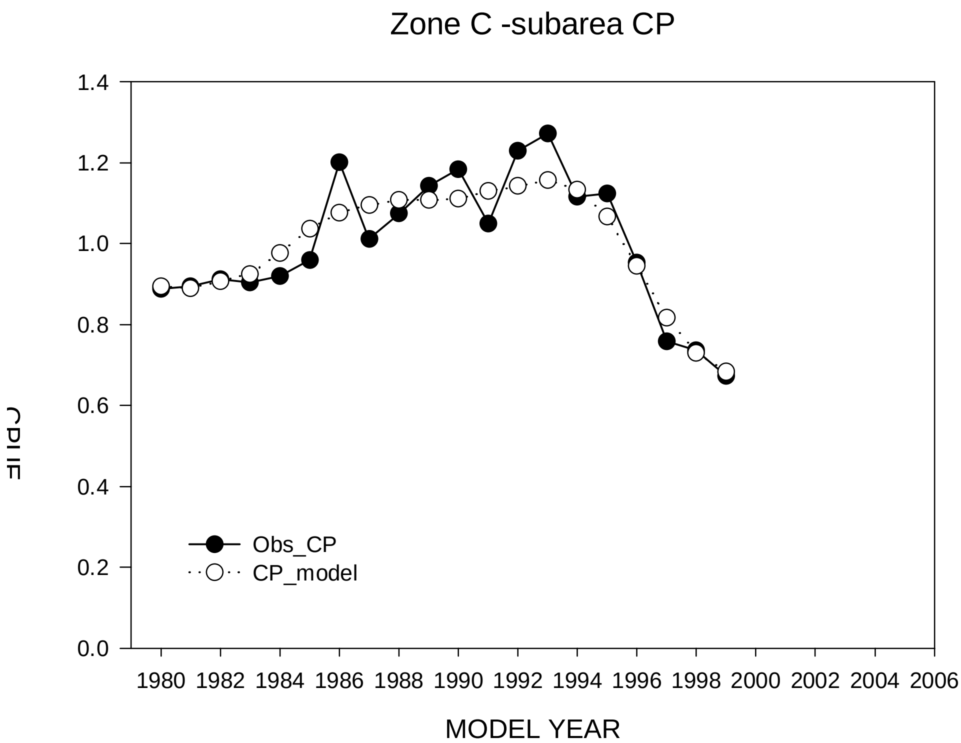
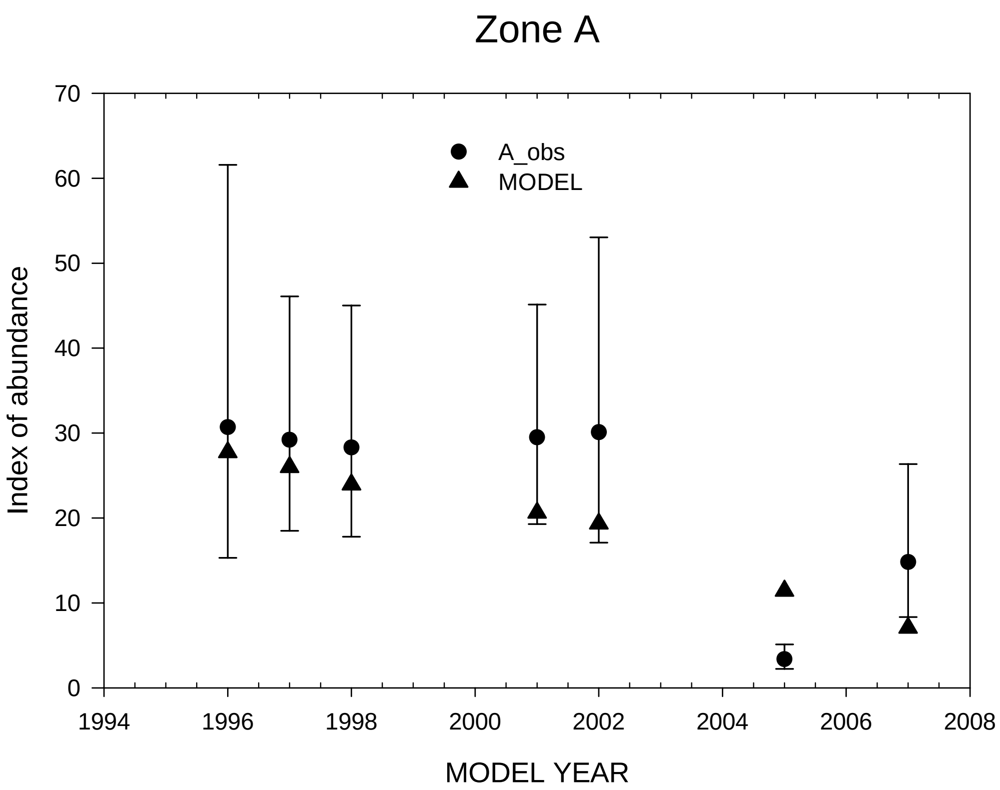


Fig. 3. Comparisons between the standardised CPUE and model-predicted CPUE values (for the Reference-case combined ABCD model) for each of Zones CNP and CP.



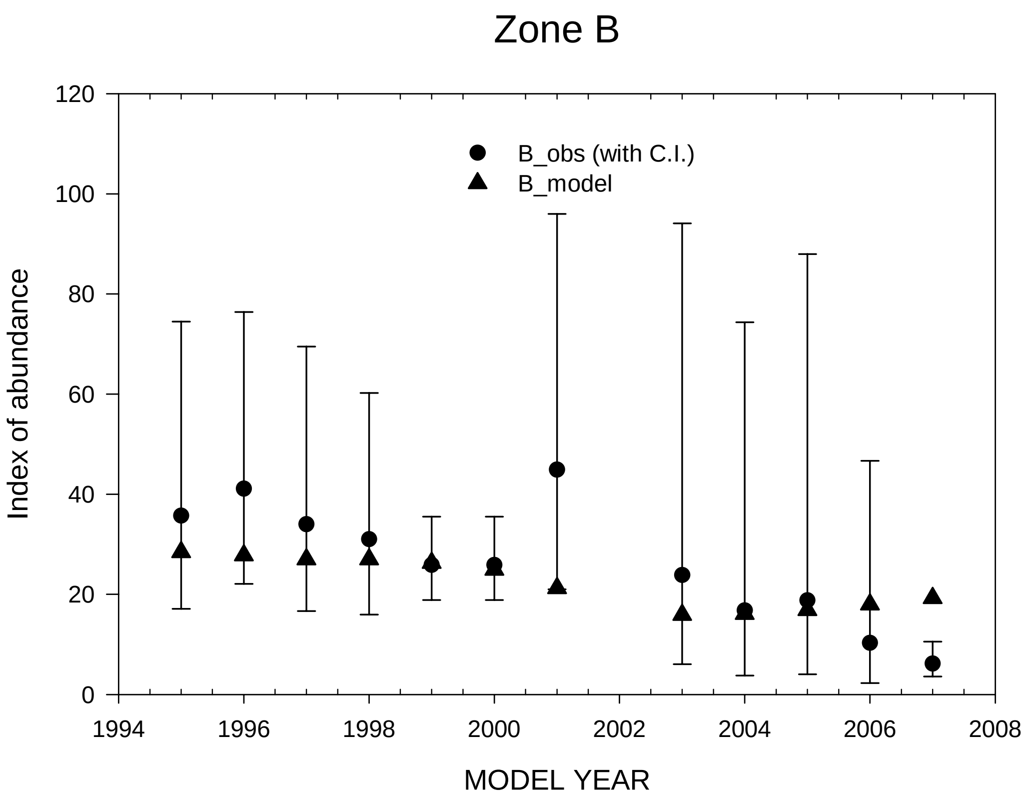
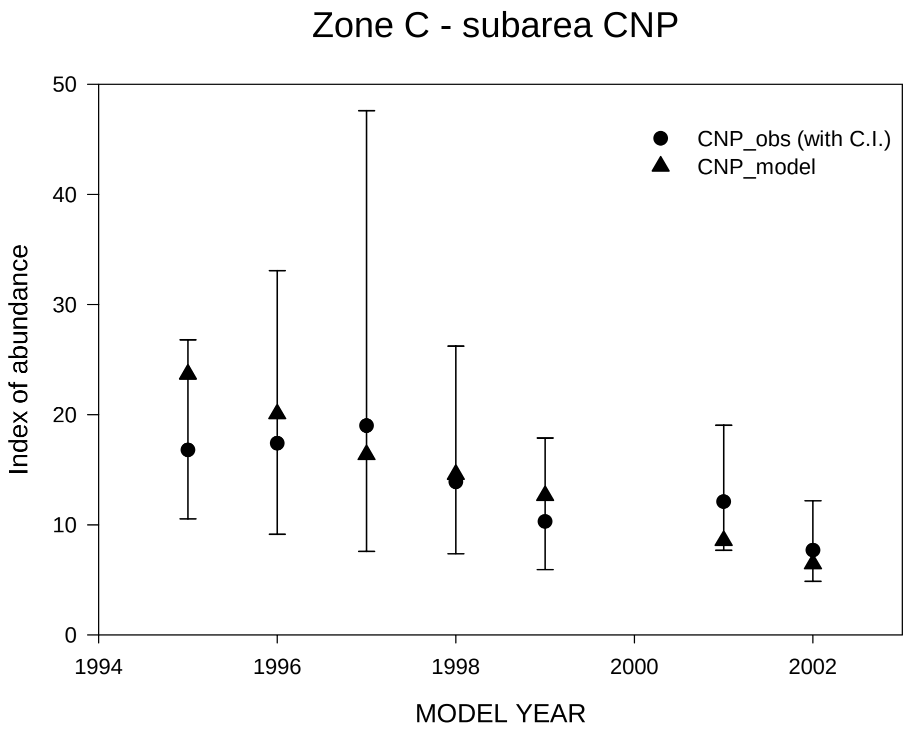


Fig. 4 Comparison of model-predicted (Reference-case combined ABCD model) and observed FIAS trends for each of Zones A and B. Note that 95% confidence intervals have been computed as estimate*exp(±1.96*CV).



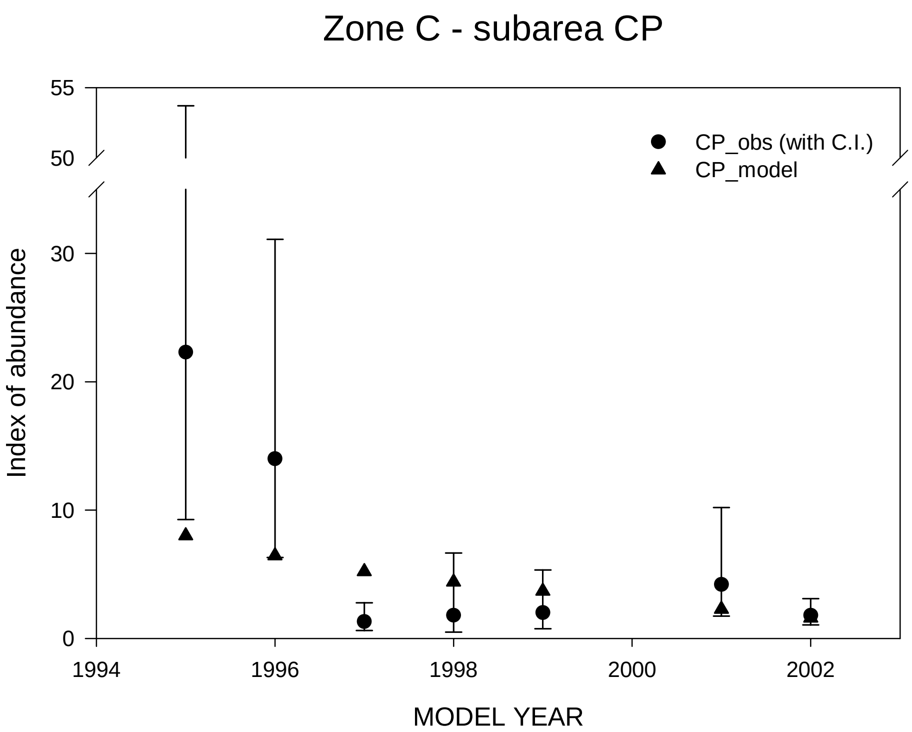


Fig. 5. Comparison of model-predicted (Reference-case combined ABCD model) and observed FIAS trends for each of subareas CNP and CP in Zone C. Note that 95% confidence intervals have been computed as estimate*exp(±1.96*CV). Note the break inserted on the y-axis for subarea CP for ease of viewing purposes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

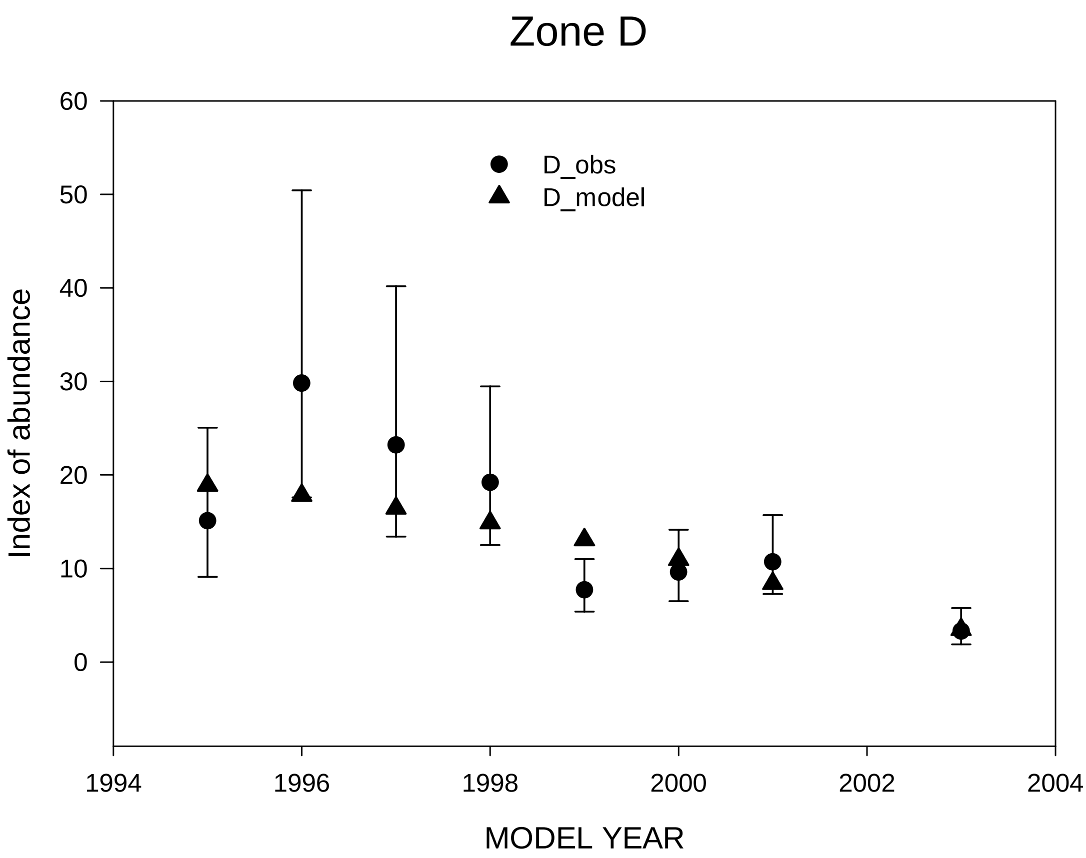


Fig. 6. Comparison of model-predicted (Reference-case combined ABCD model) and observed FIAS trends for each of Zone D. Note that 95% confidence intervals have been computed as estimate*exp(±1.96*CV).

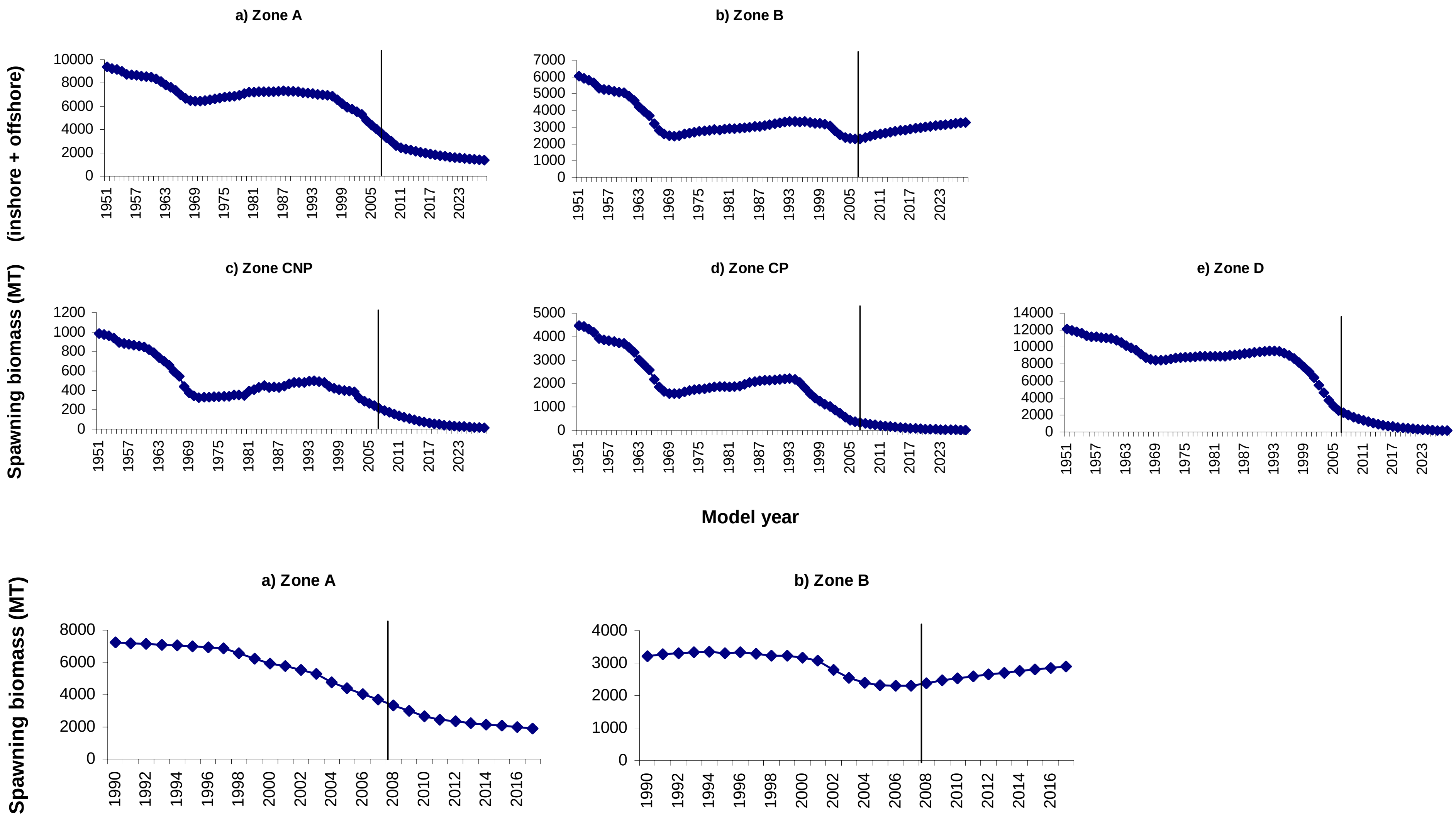


Fig. 7. Reference-case combined ABCD model total (inshore + offshore) spawning biomass trajectories shown for Zones A to D. Note that the 20-yr projections shown (indicated by vertical bar) represent scenarios under which future poaching levels are assumed to remain at the current estimated level (average of 2005 and 2006) and future commercial catches remain constant at the current level (Zone A: 0 t; Zone B: 75 t). The bottom panel shows an expanded version of the top panel.

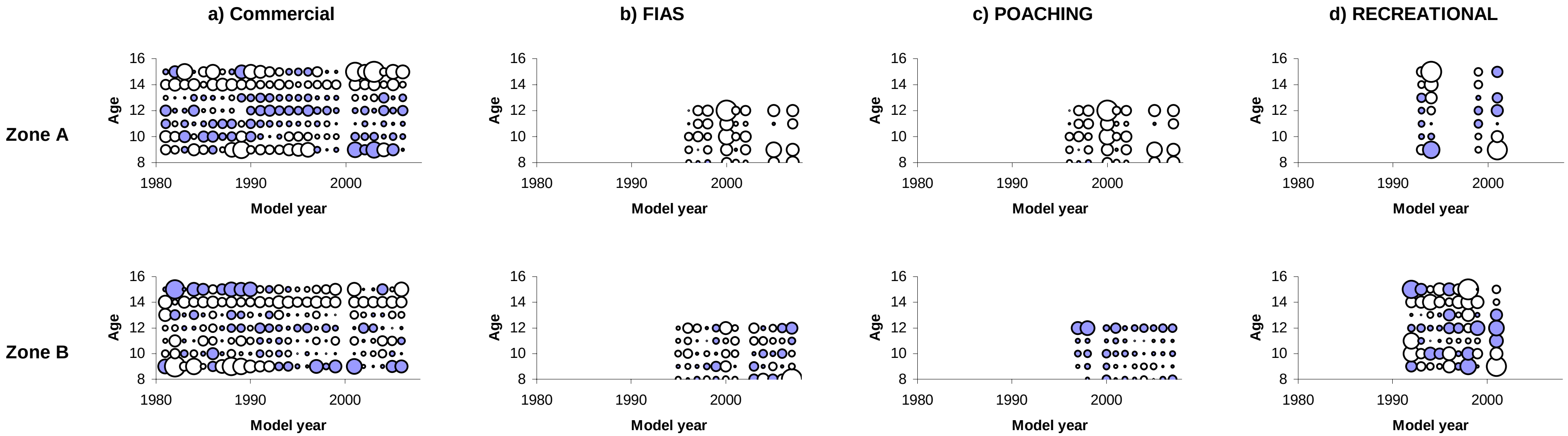


Fig . 8. Catch-at-age residuals for Zones A and B for a) the commercial data, b) the FIAS data, c) the recreational data and d) the poached sector (based on confiscation data) for the base-case combined ABCD model. The size (radius) of the "bubble" in the plots is proportional to the corresponding standardized residual ((ln(obs)-ln(pred))/(sigma/sqrt(pred))). White bubbles represent negative residuals and grey bubbles represent positive residuals.

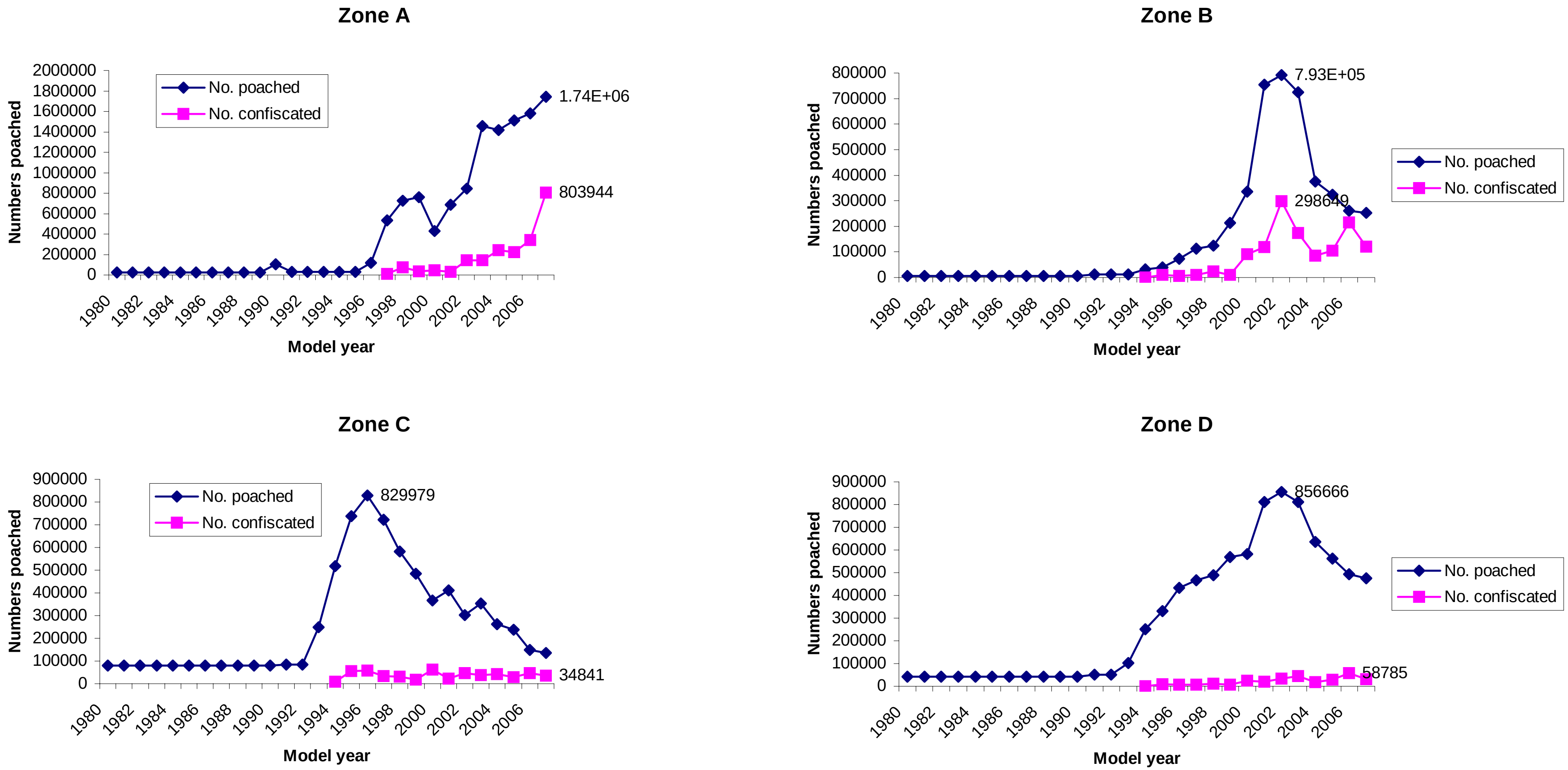


Fig . 9. Comparison of model-predicted numbers of abalone poached per Zone with “observed” numbers confiscated (after allocating confiscated abalone from the Unknown category to each of Zones A-D). The numerical value (units are numbers) corresponding to selected points on the graph is given.

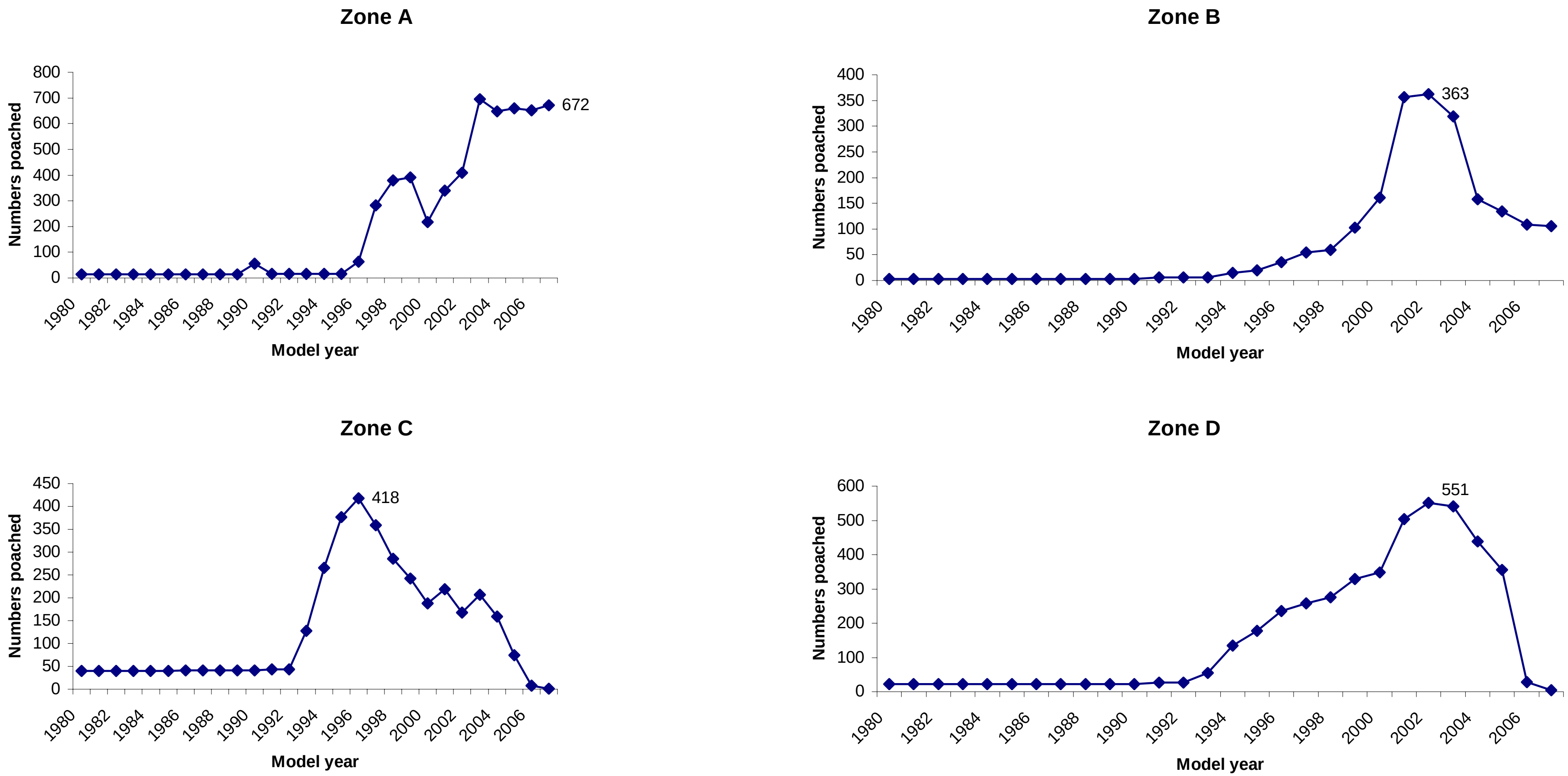


Fig . 10. Model-predicted **biomass** of abalone poached per Zone.