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André E. Punt & David Hobday

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Management strategy evaluation for rock lobster, *Jasus edwardsii*, off Victoria, Australia: accounting for uncertainty in stock structure

ANDRÉ E. PUNT
School of Aquatic and Fishery Sciences
Box 355020
University of Washington
Seattle, WA 98195–5020, United States

CSIRO Marine and Atmospheric Research
GPO Box 1538
Hobart, TAS 7001, Australia
email: aepunt@u.washington.edu

DAVID HOBDAY
Marine and Freshwater Fisheries Research Institute
Department of Primary Industries
P.O. Box 114
Queenscliff, VIC 3225, Australia

Abstract The management strategy evaluation (MSE) approach was used to evaluate management strategies based on the current method of stock assessment for rock lobster (*Jasus edwardsii*) off Victoria, Australia, and decision rules inferred from the management plan for Victorian rock lobster and past practice when selecting total allowable catches, TACs. The results are expressed in terms of whether it is possible to keep stocks above limit reference points with high probability and recover over-exploited stocks to the target level. Three categories of management strategy were examined using the MSE, which differed in whether assessments were conducted, and TACs set, by management zone or by region within management zone. A management strategy based on conducting assessments and setting TACs by management zone is most similar to the way assessments are currently conducted and management regulations implemented for rock lobster off Victoria. However, this management strategy performed poorest in recovering stocks to target levels. Alternative management strategies which involved conducting assessments and setting TACs by region performed better, but may have practical limitations. The assessment method was found to be generally relatively accurate and precise, although estimation performance was poor/imprecise on occasion.

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INTRODUCTION

Management strategies, also referred to as "decision rules" (Starr et al. 1997), "management procedures" (Breen et al. 2003), "operational management procedures" (Johnston & Butterworth 2005), "harvest algorithms" (Cooke 1999), and "harvest control rules" (Kell et al. 1999) are "fully-specified feedback control systems applied as a part of a fishery management system" (McAllister et al. 1999). A management strategy therefore includes specifications related to: (1) what data will be collected; (2) how those data will be processed; (3) what estimates will be made from the data; and (4) how those estimates will be used to determine management actions (Breen et al. 2003). The performance of a management strategy can be evaluated using Monte Carlo simulation (Punt & Donovan 2007). There are several advantages to using management strategies rather than the conventional approach of conducting assessments and then attempting to interpret their management implications (Punt & Donovan 2007). Specifically: there is increased transparency in how management decisions are made; the management strategy's likely trade-offs among the management objectives is known; and management strategies are applied in a feedback control manner so that management can respond to future data as they become available, thereby self-correcting to some extent for the consequences of having had to base previous management decisions on incomplete information (Punt & Donovan 2007).

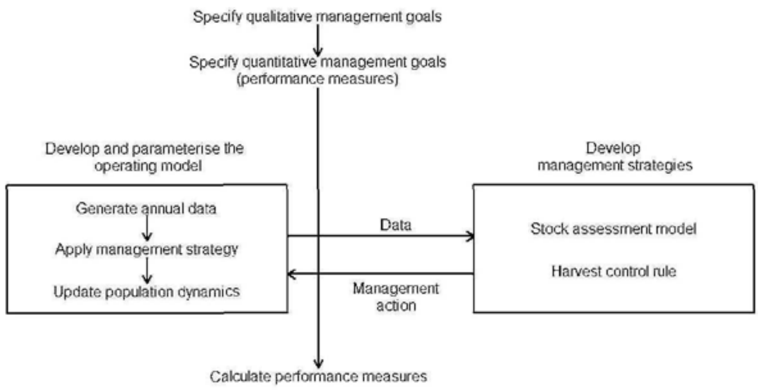


Fig. 1 Flow chart of the approach used to evaluate management strategies.

The use of simulation-tested management strategies provides certainty to different stakeholders in different ways. For example, industry members consider that one of the advantages of using management strategies is that management arrangements will not be changed arbitrarily given a slight drop in, for example, an abundance index. In contrast, conservation stakeholders are given greater certainty that reductions in, for example, total allowable catch (TAC) will occur if there are signs of resource depletion (or lack of sufficient increase in biomass for depleted resources). Specifically, the use of a management strategy replaces the "default" of "no change" by a pre-specified reduction in, for example, the TAC if there are signs of reductions in abundance, but there is no scientific consensus on whether abundance has really declined. Use of management strategies to determine management actions is therefore pro-active rather than the norm for fisheries management which has generally been re-active (Punt 2006).

The development and testing of management strategies is often referred to as the management strategy evaluation (or MSE) approach (Smith 1994; Punt et al. 2001). Management strategies have been evaluated for many fisheries and, in recent years, for ecosystem objectives (e.g., Fulton et al. 2007; Dichmont et al. 2008). In particular, they have been evaluated (and implemented) for several species of rock lobster (Bentley et al. 2003; Breen et al. 2003; Johnston & Butterworth 2005). The advantages of the MSE approach include: (1) uncertainty in the entire management system (including process, observation, model, estimation and implementation uncertainty—Francis & Shotton (1997)) can be taken into account; (2) finding a management strategy that is robust to uncertainty rather than a management strategy that performs optimally if reality is known; (3) development of management strategies leads to the specification of management objectives using quantifiable performance measures; and (4) the nature of the evaluation forces consideration of a longer-term view of the exploitation of the resource.

The MSE approach can be used to evaluate both the performance of management strategies and stock assessment methods (e.g., Punt et al. 2002; Dichmont et al. 2005).

It is necessary to evaluate management strategies against a wide range of uncertainties. Examples of the types of uncertainties considered when evaluating management strategies include the extent of productivity, errors when sampling catches, the form of the stock-recruitment relationship and whether this relationship is stationary, and errors when implementing management actions. In this study, we developed an MSE framework for rock lobster *Jasus edwardsii* off Victoria, Australia, which allows for multiple stocks, and used this framework to determine the implications of stock structure on the performance of the current assessment approach as well as on management strategies based on the current assessment approach and derived from the management plan for the fishery.

MATERIALS AND METHODS

Overview of the MSE approach

The MSE approach involves several steps to evaluate a set of candidate management strategies (Punt et al. 2001; Punt 2006; Fig. 1). First, the management objectives are identified and quantified using a set of performance measures. Second, a set of alternative structural models (called operating models) which represent the "true" system being managed are developed and parameterised. Third, following specification of the set of alternative management

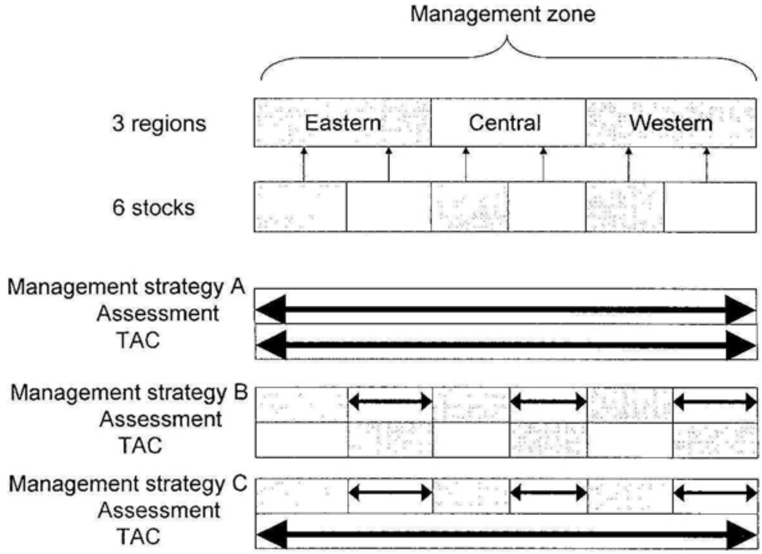


Fig. 2 Outline of the structure of the operating model, highlighting the relationship between the regions (eastern, central, and western) within each management zone and the stocks on which the dynamics of the operating model were based, and the three categories of management strategy based on the spatial scale at which assessments were conducted and total allowable catches (TACs) were set. Upper box for each management strategy indicates the spatial scale at which assessments were conducted and the lower box the spatial scale at which TACs were set (e.g., management zone for both assessments and TACs for management strategy A).

strategies to be evaluated, each management strategy is simulated into the future. For each year of the projection period, this last step involves generating the data available for assessment purposes, analysing those data to determine a management action (in general by applying a method of stock assessment and then a harvest control rule), and determining the biological implications of the management action (in this study, annual catch limits at various spatial scales) by setting the removals from true stocks represented in the operating model based on those catch limits.

Biological component of the operating model

The operating model forms the "truth" for the simulations and needs to be able to represent all key alternative hypotheses for the dynamics of the resource and to generate the data used by the management strategies. In the context of this study, the operating model was a stock-, size- and sex-structured population dynamics model. It represented the population dynamics at a finer spatial resolution than that on which conventional stock assessments are based (region), so that it was possible to evaluate the implications of not adequately capturing the true underlying stock structure correctly. Therefore, in the operating model, each of the regions considered in the assessments (see Hobday & Punt 2009, this issue) may include more than one stock (see Fig. 2), where a "stock" is defined as a group of animals which do not mix with other such groups, except through larval dispersal. It is not implausible that there are a number of rock lobster stocks off Victoria given the limited rates of movement of adult southern rock lobster (e.g., Pearn 1994; Gardner et al. 2003).

Basic dynamics

The number of animals of sex s in size class l in stock z (divided into areas open to fishing, $A = 1$, and those in marine protected areas, MPAs, $A = 0$) at the start of year t, $N^{s,z,A}_{t,l}$ was determined by the effects of natural mortality, fishing mortality, growth, recruitment, and MPAs:

$$N^{s,z,A}_{t+1,l} = \sum_{l'} X^{s,z}_{l',l,t} \left(\sum_{A'} \Omega^{z,A,A'} N^{s,z,A'}_{t,l'} \right) e^{-M} \{1 - \ddot{S}^{s}_{l'} F^{z,A}_{t}\} + 0.5\lambda^{z,A}_{t} R^{z}_{t,l} \tag{1}$$

where $X^{s,z}_{l',l,t}$ is the fraction of the animals of sex s in size class l' in stock z that grow into size class l at the end of year t;

M is the instantaneous rate of natural mortality (assumed to be independent of size, stock, and time);

$\ddot{S}^{s}_{l}$ is the selectivity of the gear on animals of sex s in size class l, given the implications of minimum legal size limits:

$$\vec{S}_l^s = \begin{cases} \omega S_l^s & \text{if } L_l^s + \Delta L^s < \text{LML}^s \\ S_l^s & \text{if } L_l^s > \text{LML}^s \\ S_l^s[\omega + (1-\omega)(L_l^s + \Delta L^s - \text{LML}^s) / \Delta L^s & \text{otherwise} \end{cases} \quad (2)$$

L_l^s is the lower limit of size class l for sex s;

ΔL^s is the width of a size class for sex s;

LML^s is the legal minimum length for sex s (110 mm carapace length (CL) males; 105 mm CL females);

ω is the discard mortality rate;

S_l^s is the selectivity of the gear on animals of sex s in size class l;

$F_t^{z,A}$ is the exploitation rate on fully-selected (i.e., $\vec{S}_l^s = 1$) animals in the open/closed parts of the area in which stock z is found during year t (the exploitation rate in the closed part is assumed to be zero);

$\Omega^{z,A,A'}$ is the fraction of animals in stock z that move from area A to area A' (i.e., from the closed to the open part);

$\lambda_t^{z,A}$ is the fraction of the area in which stock z is found that is open/closed during year t (the dependence of λ on time allows the introduction of MPAs to be modelled—Hobday et al. (2005)); and

$R_{t,l}^z$ is the recruitment of animals (both sexes combined) to size class l in stock z at the end of year t (recruitment is assumed to occur to the first size class (80 mm CL) only).

Recruitment dynamics

Two hypotheses related to recruitment dynamics were considered. The hypotheses examined the questions whether: (1) recruitment is density-dependent (dependent on local egg production) or density-independent (independent of local egg production); and (2) whether recruitment is correlated among stocks.

$$R_{t,l}^z = \begin{cases} \bar{R}^z e^{\varepsilon_t^z - \sigma_R^2/2} \\ \dfrac{4hR_0^z B_{t-L}^{\prime z} / B_0^{\prime z} e^{\varepsilon_t^z - \sigma_R^2/2}}{(1-h)+(5h-1)B_{t-L}^{\prime z} / B_0^{\prime z}} \end{cases} \quad (3A,B)$$

where $\bar{R}^z$ is mean recruitment to stock z;

R_0^z is the recruitment to stock z at pre-exploitation equilibrium;

h is the steepness of the (Beverton-Holt) stock-recruitment relationship (assumed to be independent of stock);

$B_t^{\prime z}$ is the egg production in stock z during year t:

$$B_t^{\prime z} = \sum_l Q_l^z \sum_A N_{t,l}^{f,z,A} \quad (4)$$

Q_l^z is the number of eggs produced by a female in size class l and stock z;

$B_0^{\prime z}$ is the egg production in stock z at pre-exploitation equilibrium;

L is the time between spawning and recruitment to 80 mm CL;

ε_t^z is the "recruitment residual" for region z and year t:

$$\varepsilon_t^z = \rho_R^z \varepsilon_{t-1}^z + \sqrt{1-(\rho_R^z)^2}\, \varphi_t^z$$

ρ_R^z determines the extent of temporal correlation in the recruitment residuals within region z;

φ_t^z is generated from a multivariate normal distribution with diagonal elements, σ_R^2; and

σ_R is the extent of variation in recruitment about the deterministic component of the stock-recruitment relationship.

The assumption that recruitment is independent of egg production (Equation 3A) represents the hypothesis that recruitment is not driven by factors local to a stock, whereas allowing for a Beverton-Holt stock-recruitment relationship (Equation 3B) allows the amount of egg production in a stock to determine future recruitment success.

Catches

The value of $F_t^{z,1}$ is computed by assuming that the catch from stock z, which includes commercial and recreational removals, is taken instantaneously in the middle of the year (after half of the annual natural mortality):

$$F_t^{z,1} = \frac{C_t^{\mathrm{comm},z} + C_t^{\mathrm{rec},z}}{\sum_l \sum_s S_l'^s \, W_l^s \, N_{t,l}^{s,z,1} \, e^{-M/2}} \tag{5}$$

where $C_t^{\mathrm{comm},z}$ is the commercial catch from stock z during year t;

$C_t^{\mathrm{rec},z}$ is the recreational catch from stock z during year t;

$S_l'^s$ is the selectivity of the gear on animals of sex s in size class l, restricted to legal-sized animals; and

W_l^s is the weight of an animal of sex s in size class l.

Equation 5 implies that selectivity for commercial and recreational fishers is the same. The historical catches are recorded by region and the management strategies operate at the region (or zone) level (see Fig. 2). It is therefore necessary to allocate catches by region (or zone) to stock. The allocation scheme on which the calculations of this study were based assumed that catches are allocated to stocks in proportion to the exploitable biomass within each region, subject to process error in availability (Equation 6A), while accounting for the historical distribution of catches when allocating catches for a zone to regions (Equation 6B):

$$C_t^z = C_t^q \frac{B_t'^{e,z} e^{\varsigma_t^z}}{\sum_{j \in q} B_t'^{e,j} e^{\varsigma_t^j}} \quad \varsigma_t^z \sim N(0;\sigma_B^2) \tag{6A}$$

$$C_t^q = C_t^v \frac{\tau^q \sum_{z \in q} B_t'^{e,z}}{\sum_{q' \in v} \tau^{q'} \sum_{z' \in q'} B_t'^{e,z'}} \tag{6B}$$

where C_t^z is the catch from stock z during year t;

C_t^q is the catch for region q during year t;

C_t^v is the catch for zone v during year t;

$j \in q$ denotes the set of stocks which are found in region q;

$q \in v$ denotes the set of regions which constitute zone v;

$B_t'^{e,z}$ is the exploitable biomass in the open part of the area in which stock z is found at the start of year t:

$$B_t'^{e,z} = \sum_s \sum_l S_l'^s \, W_l^s \, N_{t,l}^{s,z,1} \tag{7}$$

τ^q is the relative attractiveness of region q, i.e.:

$$\tau^q = \sum_{t=1999}^{2004} C_t^q \Big/ \sum_{t=1999}^{2004} \sum_{z \in q} B_t'^{e,z} \tag{8}$$

σ_B determines the extent of inter-annual variation in availability among stocks.

Given how Equation 8 is defined, Equation 6B weights the exploitable biomass by region so that the historical catches by zone between 1999 and 2004 (the 5 years before the first application of a management strategy) are allocated correctly to region on average. The catches by the recreational sector were assumed to be proportional to the commercial catch in expectation, but to be log-normally distributed about the expected value, i.e.:

$$C_t^{\mathrm{rec},z} = \gamma^z C_t^{\mathrm{comm},z} e^{\xi_t^z - \sigma_\varsigma^2/2} \qquad \xi_t^z \sim N(0;\sigma_\xi^2) \tag{9}$$

where γ^z is the fraction which, in expectation, the recreational catch from stock z is of the commercial catch from that stock (2.2% in the western zone and 9.9% in the eastern zone); and

σ_ξ is the extent to which recreational catches vary about their expected values.

Initial conditions

The operating model was initialised by assuming that each stock was at its pre-exploitation equilibrium level at the start of 1905, with the corresponding size structure. The first year for which recruitment was stochastic was therefore 1906. Catches (equal to those for 1945, the first year for which catch information was available) were assumed to start in 1930, so that the stock was not at its pre-exploitation size when the observed catch series began, although the probability distribution of numbers by size class would be stationary by this time.

Data generation

Data available for stock assessment purposes and hence on which any management measures could be based were: catches, catch-rates, catch size-composition data, and research size-composition data.

The commercial catches were assumed to be known without error after 1945 (pre-1945 catches were not provided to the stock assessment). Catches were aggregated by region to reflect the accuracy to which estimates of historical removals were known. The annual catches by the recreational sector on which stock assessments were based were assumed to be a fixed proportion (2.2% for the western zone and 9.9% for the eastern zone) of those for the commercial sector even though these proportions varied over time (Equation 9).

Catch-rate data were assumed to be available by region (or zone) from 1951. For region (or zone) q, the catch-rate index for year t is given by:

$$I_t^q = q'^q \left(\sum_{z \in q} B_t^{e,z} \right)^\beta e^{\varphi_t^q - \sigma_q^2/2} \tag{10}$$

where $B_t^{e,z}$ is the exploitable biomass in stock z in the middle of year t:

$$B_t^{e,z} = \sum_s \sum_l S_l'^s W_l^s N_{t,l}^{s,z,1} e^{-M/2}(1 - F_t^{z,1}/2) \tag{11}$$

ϕ_z^q are residuals generated from a multivariate normal distribution with mean 0 and variance-covariance matrix with diagonal elements, σ_q^2;

β is a parameter that determines whether catch-rates are related linearly to abundance;

q'^q is the catchability coefficient for region q, i.e.:

$$q'^q = I'^q_{2004} / \left(\sum_{z \in q} B_{2004}^{e,z} \right)^\beta \tag{12}$$

I'^q_t is the actual catch-rate for region q in year t; and

σ_q is the extent of inter-annual variation in catchability.

The catch rate index for zone v was therefore calculated as:

$$I_t^v = \sum_{q \in v} C_t^{\text{comm},q} / \sum_{q \in v} E_t^{\text{comm},q} \tag{13}$$

where $E_t^{\text{comm},q}$ is the effort applied by commercial fishers in region q during year t:

$$E_t^{\text{comm},q} = \frac{\sum_{z \in q} C_t^{\text{comm},z}}{q'^q (\sum_{z' \in q} B_t^{e,z'})^\beta e^{\varphi_t^q - \sigma_q^2/2}} \tag{14}$$

The observed commercial catches in numbers by region were assumed to be lognormally distributed, whereas the size-composition data available for assessment purposes were generated under the assumption that the length-frequency data were multinomially distributed.

Model parameterisation

Maturity and growth were assumed to be region-specific (Punt et al. 2006a,b), whereas the relationship between egg production and length was assumed to be independent of region (Hobday & Ryan 1997). The rate of natural mortality, M, was assumed to be 0.1 yr^{-1} for the baseline analyses for consistency with the assumption underlying the stock assessment, but the implications of the true value being lower or higher than this value were examined in the tests of sensitivity. The recruitment residuals from the assessments of the six regions were positively correlated (Hobday & Punt 2009). This correlation was modelled by:

$$\rho_{i,j} = 0.55^{x_{i,j}} \tag{15}$$

where $\rho_{i,j}$ is the correlation in the recruitment residuals between stocks i and j; and

$x_{i,j}$ is the "distance" between stocks i and j (the distance between the centres of the regions in which each stock is found).

Selectivity as a function of length was set using the relationships obtained by Treble et al. (1998), whereas the specifications for the MPAs off Victoria and the rates of movement out of them were based on the analyses conducted by Hobday et al. (2005).

The value for R_0 for each stock and simulation was set so that if the operating model was projected from 1905 to 2004, the depletion in 2004, the last year before a management strategy is used to determine management measures, equalled a pre-specified value (Table 1; the baseline values in this table reflect the outcomes of the application of the stock assessment method to the actual data for the six regions). This process involved generating the recruitment residuals for all years of the projection period (1906 onwards) as well as the relative number of recruits to each of the stocks which are found in region q, i.e.:

$$\omega_0^z = e^{\upsilon_z} / \sum_{z' \in q} e^{\upsilon_{z'}} \qquad \upsilon_z \sim N(0;\sigma_\upsilon^2) \tag{16}$$

where ω_0^z is the fraction which recruitment to stock z constitutes of total recruitment in region q (stock z is located in region q); and

σ_υ determines the extent of spatial variation in average recruitment levels among stocks within a region.

Data generation

The values for the quantities that determine the data available for assessment purposes for the baseline analyses (Table 2) were set to those on which the actual assessments were based (Hobday & Punt 2006). The correlations among the residuals for different regions can be summarised by the equations $\rho_{i,j} = 0.45^{x_{i,j}}$ (catch-rates) and $\rho_{i,j} = 0.89^{x_{i,j}}$ (catch-in-numbers), respectively.

Scenarios

The scenarios considered in the simulations (Table 3) examined the implications of: (1) uncertainty in stock structure (i.e., the true number of stocks being managed); (2) uncertainty in the values for some of the key biological parameters, including the form of the relationship between egg production and subsequent recruitment; (3) uncertainty in the data available for assessment purposes; and (4) uncertainty in whether the catches are allocated spatially in the anticipated ratio when management is based on setting TACs by management zone.

The management strategies

The management strategies considered in this study consisted of two components: (1) a stock assessment method; and (2) a harvest control rule. The stock assessment method used the data generated by the operating model to determine the status of the resource relative to target and limit reference points, and the size-structure of the stock at the start of the year for which a TAC recommendation is needed. The harvest control rule used the results from the stock assessment to determine TACs, with the objective of leaving all stocks at or above 40% of the 1951 stock size (in both exploitable biomass and egg production) and avoiding dropping stocks below 20% of the 1951 level.

Table 1 Values for the biological parameters of the operating model. Values for the baseline analyses are shown in bold. Sensitivity tests explored the implications of the other values for the biological parameters.

Parameter	Value	Source
No of size classes	**12**, 48 (M); **17**, 26 (F)	
Width of each size class, ΔL^S	**10 mm**, 2.5 mm (M); **5 mm**, 2.5 mm (F)	
Rate of natural mortality, M	**0.1 yr^{-1}**, 0.08 yr^{-1}, 0.15 yr^{-1}	Hobday & Punt (2001)
Recruitment variability, σ_R	**0.5**, 0.4, 0.6	Hobday & Punt (2001)
Depletion of the exploitable biomass in the middle of 2004 relative to 1951		
Western Zone		
Portland region	**0.343**; 0.257; 0.429	Hobday & Punt (2006)
Warrnambool region	**0.270**; 0.203; 0.338	Hobday & Punt (2006)
Apollo Bay region	**0.218**; 0.164; 0.273	Hobday & Punt (2006)
Eastern zone		
Queenscliff region	**0.226**; 0.170; 0.284	Hobday & Punt (2006)
San Remo region	**0.242**; 0.182; 0.303	Hobday & Punt (2006)
Lake Entrance region	**0.325**; 0.244; 0.206	Hobday & Punt (2006)
Steepness, h	**1.0**, 0.8	Assumed
Lag between spawning and recruitment, L	3	Assumed
Variability in recruitment among stocks in a region, σ_υ	0.2	Assumed
Variability in the spatial split of the catch, σ_B	**0.0**, 0.1, 0.3	Assumed
Variability in the recreational catch about its expectation, σ_ξ	0.2	Assumed
Discard mortality rate, ω	**0**, 0.1	Assumed
Recreational catch, γ (fraction commercial catch)		
Western zone	**0.022**; 0.044	Hobday & Punt (2001)
Eastern zone	**0.099**; 0.198	Hobday & Punt (2001)
Catch-rate non-linearity factor, β	**1.0**, 0.5	Assumed

Table 2 Baseline specifications related to the generation of future data. σ_q is the coefficient of variation of catchability, σ_N is the coefficient of variation of the sampling error associated with estimating catch-in-numbers, and N^{eff} is the effective sample size for the size-composition data. Years in parentheses indicate the years for which the data were assumed to be available.

Region	Catch rate	Catch in numbers	Catch size-composition	Research size composition
Western zone				
Portland	$\sigma_q = 0.2$ (1951+)	$\sigma_N = 0.11$ (1951+)	$N^{eff} = 25$ (1961–64; 78–85; 93+)	$N^{eff} = 60$ (1989; 94+)
Warrnambool	$\sigma_q = 0.2$ (1951+)	$\sigma_N = 0.11$ (1951+)	$N^{eff} = 25$ (1961–63; 95+)	$N^{eff} = 60$ (1995+)
Apollo Bay	$\sigma_q = 0.2$ (1951+)	$\sigma_N = 0.11$ (1951+)	$N^{eff} = 25$ (1961–63; 95)	$N^{eff} = 60$ (1995+)
Eastern zone				
Queenscliff	$\sigma_q = 0.25$ (1951+)	$\sigma_N = 0.18$ (1951+)	$N^{eff} = 20$ (1995–97)	$N^{eff} = 25$ (1994+)
San Remo	$\sigma_q = 0.25$ (1951+)	$\sigma_N = 0.18$ (1951+)	$N^{eff} = 20$ (1961–64; 95)	$N^{eff} = 25$ (1995; 2005+)
Lakes Entrance	$\sigma_q = 0.25$ (1951+)	$\sigma_N = 0.18$ (1951+)	$N^{eff} = 20$ (1963; 2002)	$N^{eff} = 25$ (2005+)

Table 3 Scenarios considered as part of the management strategy evaluation. (Run B-9 was parameterised so that the variances of the length-frequency data were the same as those for the baseline operating model, but with positive rather than negative correlation between the frequencies for size classes that are close together, to reflect a lack of independence when sampling for length-frequency.)

Run no.	Stock structure	Other specifications/comments
Biological characteristics		
A-1	6 stocks	Baseline operating model
A-2	12 stocks	12 stock baseline run
A-3	18 stocks	18 stock baseline run
A-4	6 stocks	Initial depletion = 0.75 reference level
A-5	6 stocks	Initial depletion = 1.25 reference level
A-6	6 stocks	More smaller size classes in the operating model
A-7	6 stocks	Lower natural mortality; $M = 0.08\ \mathrm{yr}^{-1}$
A-8	6 stocks	Higher natural mortality; $M = 0.15\ \mathrm{yr}^{-1}$
A-9	6 stocks	Lower recruitment variability; $\sigma_R = 0.4$
A-10	6 stocks	Higher recruitment variability; $\sigma_R = 0.6$
A-11	6 stocks	Beverton-Holt recruitment; Steepness = 0.8
Data generation		
B-1	6 stocks	Non-linear catch-rate-abundance relationship, $\beta = 0.5$
B-2	6 stocks	Catchability q has been increasing at 2% per annum since 1985
B-3	6 stocks	Effective sample sizes are twice the baseline values
B-4	6 stocks	Effective sample sizes are half the baseline values
B-5	6 stocks	Less variation in catchability (the σ_q^2s are half the baseline values)
B-6	6 stocks	More variation in catchability (the σ_q^2s are double the baseline values)
B-7	6 stocks	Less variation in catch-in-numbers (the σ_N^2s are half the baseline values)
B-8	6 stocks	More variation in catch-in-numbers (the σ_N^2s are double the baseline values)
B-9	6 stocks	Multivariate normal generation
Catches		
C-1	12 stocks	Less variation in the spatial split of the catch, $\sigma_B = 0.1$
C-2	12 stocks	More variation in the spatial split of the catch, $\sigma_B = 0.3$
C-3	6 stocks	No Marine Protected Areas
C-4	6 stocks	Recreational catch is twice the baseline level (but this is not known when assessments are conducted)
C-5	6 stocks	Discard mortality is 0.1

Stock assessment

The method of stock assessment was identical to that applied to rock lobster stocks off Victoria (see Hobday & Punt 2001, 2009). It involved fitting a size- and sex-structured population dynamics model to catch, catch-rate, catch-in-numbers, and length-frequency data by maximising a penalised likelihood function. The values for several of the parameters of the stock assessment model were pre-specified: selectivity, $M = 0.1\ \text{yr}^{-1}$, σ_R, $\sigma_q = 0.19/0.25$ (western and eastern zones), and $\sigma_N = 0.11/0.18$. The annual recruitments (numbers entering the first size class) were estimated subject to a penalty on their deviations from mean recruitment. The effective sample sizes for the catch size-composition data were assumed to be 27 and 21 (western and eastern zones, respectively), whereas the effective sample sizes for the research size-composition data were assumed to be 65 and 25, respectively.

Harvest control rule

The harvest control rule depends on $P(SB_y > 0.xSB_{1951})$, the probability that the egg production in year y exceeds x % of the 1951 egg production, and $P(EB_y > 0.xEB_{1951})$, the probability that the exploitable biomass in year y exceeds x % of the 1951 exploitable biomass. These probabilities were estimated based on the asymptotic sampling distributions for the ratios $SB_y\ /\ 0.xSB_{1951}$ and $EB_y\ /\ 0.xEB_{1951}$ (c.f. Maunder et al. 2006). Projections into the future were based on the assumption that recruitment is independent of the amount of egg production, i.e., the same assumption on which the bulk of the operating model scenarios were based. Year n denotes the current year (the last year for which information on catches is available); year $n+1$ is therefore the year for which a TAC recommendation is needed. Separate harvest control rules were specified for the eastern and western zones. The harvest control rule imposes a maximum (Δ base case 0.1) inter-annual proportional change in TAC.

The algorithm used to determine the TAC for a region in the western zone for year $n+1$, TAC_{n+1}, based on an assessment conducted in year n first involved computing $P(SB_{n+5} > 0.4SB_{1951})$, $P(SB_{n+5} > 0.2SB_{1951})$, and $P(EB_{n+5} > 0.2EB_{1951})$ when future catches were set equal to TAC_n. The TAC needed to be reduced to the level at which all three of these criteria was satisfied if $P(SB_{n+5} > 0.4SB_{1951}) < 0.5$, $P(SB_{n+5} > 0.2SB_{1951}) < 0.75$, or $P(EB_{n+5} > 0.2EB_{1951}) < 0.75$. However, if none of these three criteria was satisfied, the stock was above both egg production reference points and above the limit reference point for exploitable biomass. In this instance, the TAC was set to the maximum of TAC_n and the constant future catch over the next 5 years so that $P(EB_{n+5} > 0.4EB_{1951}) = 0.5$. Finally, the TAC was constrained to lie between $(1-\Delta)\text{TAC}_n$ and $(1+\Delta)\text{TAC}_n$.

The harvest control rule for the eastern zone was the same as that for the western zone, except that the TAC was only reduced when $P(EB_{n+5} > 0.4EB_{1951}) < 0.5$ or when $P(SB_{n+5} > 0.4SB_{1951}) < 0.5$ if the egg production/available biomass in 5 years was predicted to be below the current level.

Management strategy variants

There is no formally adopted management strategy for rock lobsters off Victoria, nor are there plans to adopt a management strategy. However, the process that leads to management decisions tends to follow the concepts outlined in the previous section. There are many ways in which management decisions could be made, and it was necessary to select only a few so that they could be adequately evaluated given the computational demands of the calculations. Therefore, the management strategies considered in this study were selected to address the following questions (see Table 4; Fig. 2): (1) what is the appropriate spatial resolution at which TACs should be set (zone or region); (2) what is the appropriate spatial resolution at which assessments should be conducted (zone or region); and (3) what are the implications of allowing different constraints on interannual variation in catches ($\Delta = 0.1/0.2$)?

Table 4 Management strategies considered in the present study. Each management strategy was based on specifications for: (1) the spatial scale at which assessments are conducted; (2) the spatial scale at which total allowable catches, TACs, are set; and (3) the allowable extent of inter-annual variation in TACs (Δ).

Management strategy	Assessment by	TAC by	Δ
A	Zone	Zone	0.1
B	Region	Region	0.1
C	Region	Zone	0.1
D	Zone	Zone	0.2
E	Region	Region	0.2
F	Region	Zone	0.3

Performance measures

The performance measures were based on the three goals of the rock lobster fishery management plan: (1) sustainability of the rock lobster resource; (2) resource access and use; and (3) effective fishery management (Anon. 2003). In relation to the sustainability of stocks, these goals include rebuilding stocks to 40% of the 1951 biomass. The rebuilding target is defined as both the egg production (referred to as the "spawning biomass" in the plan), and the biomass available to the fishery. The limit reference point represents a "conservation bottom line" so the plan also includes a performance measure that "there be a 75% probability that the stock is above 20% of B_{51}" (Anon. 2003). In contrast, the performance measure related to the target reference point is that "there be a 50% probability that the stock is above 40% of B_{51}" (Anon. 2003). The performance of management strategies relative to these target and limit reference points can be evaluated using the following three probabilities: (1) the probability that the egg production in 2025 exceeds 40% of the 1951 egg production, $P(SB_{2025} > 0.4SB_{1951})$; (2) the probability that the exploitable biomass in 2025 exceeds 20% of the exploitable biomass in 1951, $P(EB_{2025} > 0.2EB_{1951})$; and (3) the probability that the exploitable biomass in 2025 exceeds 40% of the exploitable biomass in 1951, $P(EB_{2025} > 0.4EB_{1951})$.

Performance measures were defined for 2025 to capture the medium-term (20 years) performance of the management strategies. These three performance measures can be computed by stock, region, or zone. In general, results are only reported here by zone. However, detailed results are presented for a small subset of the combinations of operating model and management strategy. Results are not shown for the probability of being below 20% of the 1951 egg production because this probability was low for almost all management strategies and scenarios.

The three performance measures listed above capture the conservation performance of a management strategy. The performance of a management strategy's resource use and industrial stability was quantified by the following four performance measures (with their abbreviations): (1) the median (over simulations) average catch over 2005–14, $\bar{C}_{2005\text{–}14}$; (2) the lower 5th percentile (over simulations) of the average catch over 2005–14, $\tilde{C}_{2005\text{–}14}$; (3) the probability of a reduction in TAC between 2005 and 2014, P_{cat}; and (4) the absolute annual variation (AAV) in catches between 2005 and 2014, i.e., the median over simulations of:

$$AAV = 100\frac{\sum_{t=2005}^{2014}|C_t - C_{t-1}|}{\sum_{t'=2005}^{2014} C_{t'}} \qquad (17)$$

These performance measures can be calculated by stock, region or zone, but are here only reported by zone. The catch-related performance measures focus on the first 10 years of the projection period because 10 years is sufficiently long for the management strategy to substantially change catch limits, but not so long that economic discounting would be substantial.

RESULTS

Selection of a preferred variant

The results for three operating models based on the baseline values for the biological and data-related parameters were used to select a reference management strategy for further evaluation. The three operating models (A-1, A-2, and A-3) differed in the number of stocks that were included in the operating model (6, 12, or 18; i.e., one, two, or three stocks in each of the six regions; Table 3). The three management strategies considered differed in relation to the spatial resolution at which assessments were conducted (by zone or by region) and whether TACs were set by zone or region. The value that determines the extent to which TACs can be changed from one year to the next, Δ, was set to 0.1, and the results were based on 100 simulations of a 21-year (2005–25) projection period.

Exploitable biomass by zone was maintained above 20% of the 1951 level with high probability ($P(EB_y > 0.2EB_{1951}) > 0.9$) for most combinations of an operating model and a management strategy (Table 5). The exception was management strategy A (stock assessments by zone and TACs by zone) for the eastern zone for which the probability of the exploitable biomass exceeding 20% of the 1951 level was 0.78–0.85. The probability of being above the other reference points was lower. For example, $P(EB_y > 0.4EB_{1951})$ was often much lower than 0.5 for management strategies B and C.

The average catches, and particularly the lower 5% limit for the average catch ($\tilde{C}_{2005\text{–}14}$ in Table 5) for the western zone, were lower for management strategy A. Management strategy A also led to more variable catches, particularly for operating model A–1. The probability of a reduction in TAC in some future year was higher for management strategies B and C. In contrast to the situation for the western zone, the average catches in the eastern zone for management strategy A were higher than those for management strategies B and C. However, the lower 5% limit of the average catch was similar among management strategies. The average catch in the eastern zone exceeded the current TAC for this zone, and the probability of reductions in catch in the eastern zone was less than for the western zone. As for the western zone, management strategy A led to the highest levels of inter-annual variation in catches for the eastern zone.

All three management strategies were able to keep the egg production by stock above 40% of the 1951 level with high probability (Table 6). Management strategy A again performed more poorly than the other management strategies in leaving resources above this target reference point. The management strategies aimed to move the resource towards 40% of the 1951 exploitable biomass, but were not constructed to achieve this goal with high probability. In general, the exploitable biomass was left below 40% of the 1951 level and, in some instances, well below this level. Management strategy B (assessments and TACs by region) performed best in avoiding any stock being well below 40% of the 1951 level on average, even for operating model A-3 which had 18 stocks (three in each region) (Table 6). In contrast, management strategies A and C both performed relatively poorly for some stocks (generally, but not always, the same stocks).

The remaining calculations of this study focused on management strategy C because it achieved noticeably higher average catches than management strategy A (particularly for the western zone; Table 5) and because it did not perform more poorly than management strategy A in conserving the resource. The focus was on management strategy C rather than management strategy B because it does not seem likely that it will be feasible to set TACs by region for Victorian rock lobster in the short to medium term.

Management performance—selected management strategy

There was some recovery of exploitable biomass in the western zone and substantial increases in exploitable biomass in the eastern zone (Fig. 3).

Table 5 Performance measures for three management strategies (A, B, C) for the three baseline operating models (A-1, A-2, and A-3). $P(> ySB_{1951})$ is the probability in 2025 of being above y times the 1951 egg production, $P(> yEB_{1951})$ is the probability in 2025 of being above y times the 1951 exploitable biomass, $\bar{C}_{2005\text{–}14}$ is the median average catch (t) over 2005–14, $\tilde{C}_{2005\text{–}14}$ is the lower 5th percentile of the average catch (t) over 2005–14, P_{cat} is the probability of a reduction in TAC between 2005 and 2014, and AAV is the absolute annual variation in catches (%) between 2005 and 2014.

Strategy	Operating model	Western zone $P(> 0.4SB_{1951})$	Western zone $P(> 0.2EB_{1951})$	Western zone $P(> 0.4EB_{1951})$		Eastern zone $P(> 0.4SB_{1951})$	Eastern zone $P(> 0.2EB_{1951})$	Eastern zone $P(> 0.4EB_{1951})$	
Conservation-related performance measures (%)									
A	A-1	100	100	60		66	84	34	
B	A-1	95	99	27		74	95	47	
C	A-1	93	98	26		74	95	47	
A	A-2	97	100	54		67	85	35	
B	A-2	94	97	23		77	94	50	
C	A-2	93	97	25		76	92	50	
A	A-3	98	98	60		65	78	35	
B	A-3	96	98	28		80	93	45	
C	A-3	97	98	31		74	93	41	
		$\bar{C}_{2005\text{–}14}$	$\tilde{C}_{2005\text{–}14}$	AAV	P_{cat}	$\bar{C}_{2005\text{–}14}$	$\tilde{C}_{2005\text{–}14}$	AAV	P_{cat}
Utilisation-related performance measures									
A	A-1	338	274	3.59	30	76	51	6.16	7
B	A-1	381	308	2.73	54	63	48	4.27	17
C	A-1	381	304	2.55	54	65	49	5.37	14
A	A-2	349	290	3.27	27	67	52	4.40	8
B	A-2	394	313	2.67	54	59	49	4.04	22
C	A-2	396	309	2.30	52	60	50	4.30	19
A	A-3	357	296	3.17	27	64	49	4.45	11
B	A-3	390	306	2.81	54	57	47	3.48	26
C	A-3	390	301	2.48	52	58	47	3.70	23

Table 6 Ratio of the egg production and exploitable biomass in 2025 to that in 1951 (expressed as a percentage) by stock for three management strategies (A, B, C) and for the three baseline operating models (A-1, A-2, and A-3). Values less than 40% are in bold and those less than 30% are in italics. Acronyms for the stocks are as follows: zone-region-stock within region (if there are any) so "W-Warrnambool-2" is the 2nd stock within the Warrnambool region of the western zone.

	Management strategy					
	A		B		C	
Stock	Egg	Exploit	Egg	Exploit	Egg	Exploit
Operating model A-1 (6 stocks)						
West	59	42	53	**34**	53	**34**
East	46	**35**	53	**39**	54	**39**
W-Portland	64	48	53	**33**	55	**36**
W-Warrnambool	54	**36**	50	**32**	53	**35**
W-Apollo Bay	50	**33**	56	**38**	51	**32**
E-Queenscliff	**36**	*25*	53	**39**	52	**38**
E-San Remo	51	**37**	51	**34**	49	**34**
E-Lake Entrace	71	49	64	40	67	44
Operating model A-2 (12 stocks)						
West	60	41	54	**35**	53	**34**
East	49	**34**	55	40	54	40
W-Portland-1	64	46	55	**34**	58	**37**
W-Portland-2	64	44	52	**31**	55	**34**
W-Warrnambool-1	56	**35**	56	**36**	54	**34**
W-Warrnambool-2	53	**35**	54	**36**	53	**34**
W-Apollo Bay-1	56	**34**	58	**36**	53	**31**
W-Apollo Bay-2	50	**34**	53	**36**	49	**31**
E-Queenscliff-1	42	*26*	56	43	51	**36**
E-Queenscliff-2	41	*27*	54	43	51	**37**
E-San Remo-1	52	**38**	50	**34**	51	**38**
E-San Remo-2	55	**39**	54	**35**	57	**38**
E-Lake Entrance-1	63	41	52	*29*	66	46
E-Lake Entrance-2	75	48	63	**32**	78	49
Operating model A-3 (18 stocks)						
West	62	42	58	**35**	59	**35**
East	48	**31**	55	**39**	55	**37**
W-Portland-1	75	50	62	**37**	68	42
W-Portland-2	70	48	59	**34**	62	**37**
W-Portland-3	66	44	57	**33**	59	**35**
W-Warrnambool-1	61	**38**	61	40	59	**36**
W-Warrnambool-2	63	**38**	62	**39**	60	**36**
W-Warrnambool-3	55	**37**	53	**37**	52	**34**
W-Apollo Bay-1	56	**34**	56	**34**	53	**30**
W-Apollo Bay-2	53	**34**	55	**36**	50	**32**
W-Apollo Bay-3	49	**32**	54	**35**	47	*29*
E-Queenscliff-1	41	*26*	55	**38**	49	**33**
E-Queenscliff-2	40	*27*	55	40	47	**33**
E-Queenscliff-3	40	*26*	54	**37**	47	**32**
E-San Remo-1	55	40	57	**39**	60	43
E-San Remo-2	52	**37**	54	**36**	57	40
E-San Remo-3	53	**36**	55	**35**	57	40
E-Lake Entrance-1	61	**34**	53	*27*	62	42
E-Lake Entrance-2	60	**36**	58	*29*	71	46
E-Lake Entrance-3	70	44	65	**34**	84	56

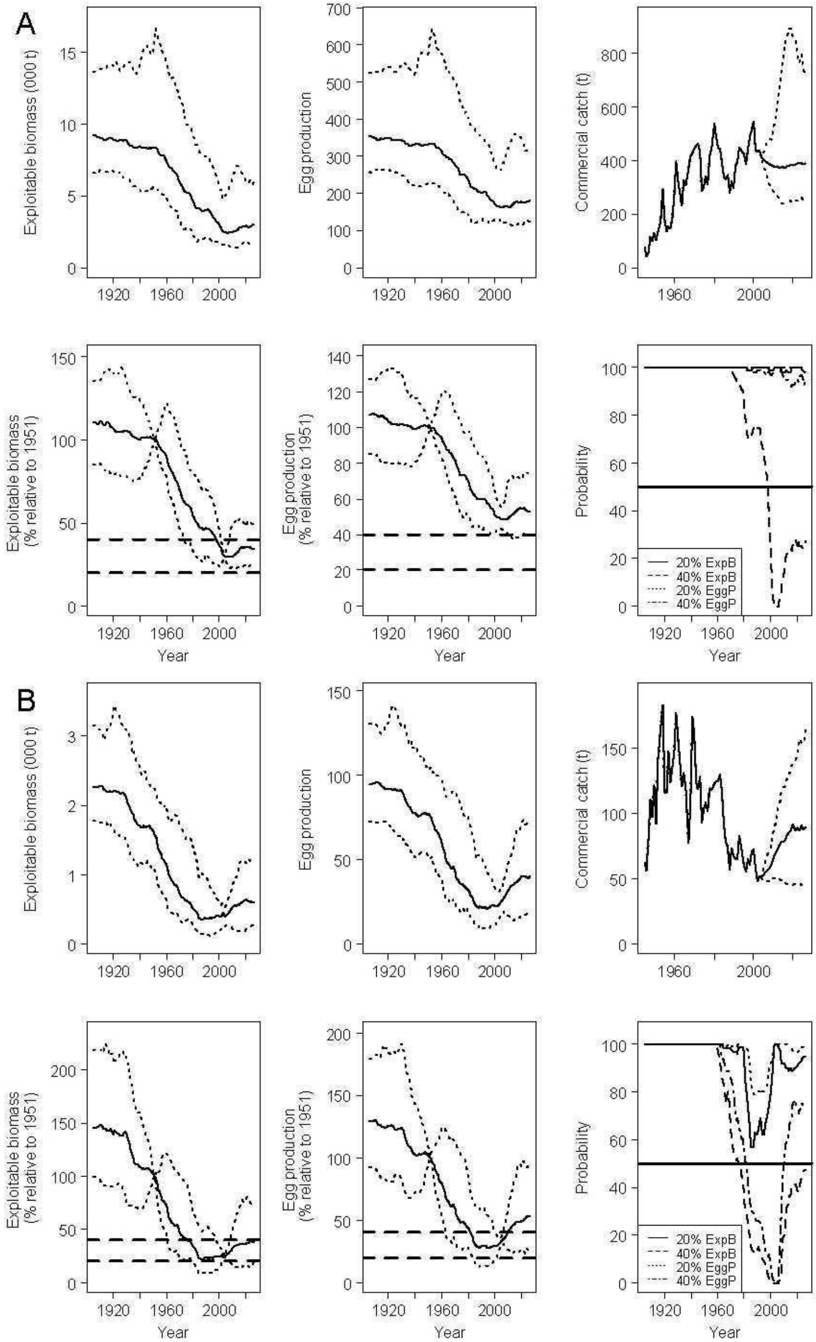


Fig. 3 Time-trajectories of exploitable biomass and egg production (in absolute terms and relative to 1951), the time-trajectory of the catch by the commercial fishery, and the time-trajectories of the probabilities of being above different target and limit reference points for the **A**, western and **B**, eastern zones for management strategy C and operating model A-1. Horizontal lines in the lower two panels for each zone denote the target and limit reference points. Horizontal lines in the lower right panels for each zone indicate a probability of 0.5. Results for each zone were obtained by summing model outcomes across the regions which constitute each zone.

Although management strategy C (i.e., assessments at the level of the biological stocks represented in the operating model) performed adequately at the zonal level for operating model A-1 (Fig. 3), conservation performance was not as good for this operating model when the results were analysed by region (Fig. 4). Specifically, the Apollo Bay region did not recover to nearly the same extent as the other regions (Fig. 4). The time-trajectories of catch (Fig. 4) differ among regions even though the TACs were set by management zone, because effort responds to changes in abundance and hence catch-rate (Equation 6).

Estimation performance—selected management strategy

The estimates of exploitable biomass and egg production in absolute terms were close to unbiased in median terms for all six stocks, except in recent years (Fig. 5). Nevertheless, there was still considerable uncertainty, depending on region. For example, estimates of exploitable biomass and egg production for the Portland, Warrnambool, Queencliff and Lakes Entrance regions tended to be within 20% of the true values for most years. In contrast, there were markedly positively biased estimates for the Apollo Bay and San Remo regions. The estimates of exploitable biomass and egg production were not much better estimated when they were expressed relative to the abundance in 1951, perhaps because the 1951 abundance was itself not well determined (Fig. 5). The poor precision of the estimates of 1951 abundance can be attributed in large part to the lack of data on the size-composition of the catches for the early years of the fishery (Table 2).

There was evidence that additional data led to improved estimation performance; estimates based on data until 2014 were less biased than those based on data until 2009, which were less biased than those based on data until 2004. This effect was only evident for recent years because additional data provide an improved ability to estimate the strength of recent year-classes; there was little or no evidence that additional data led to improved estimates of historical abundance. It can be concluded that historical abundance can only be estimated better if new data on the size-structure of the early catches can be obtained.

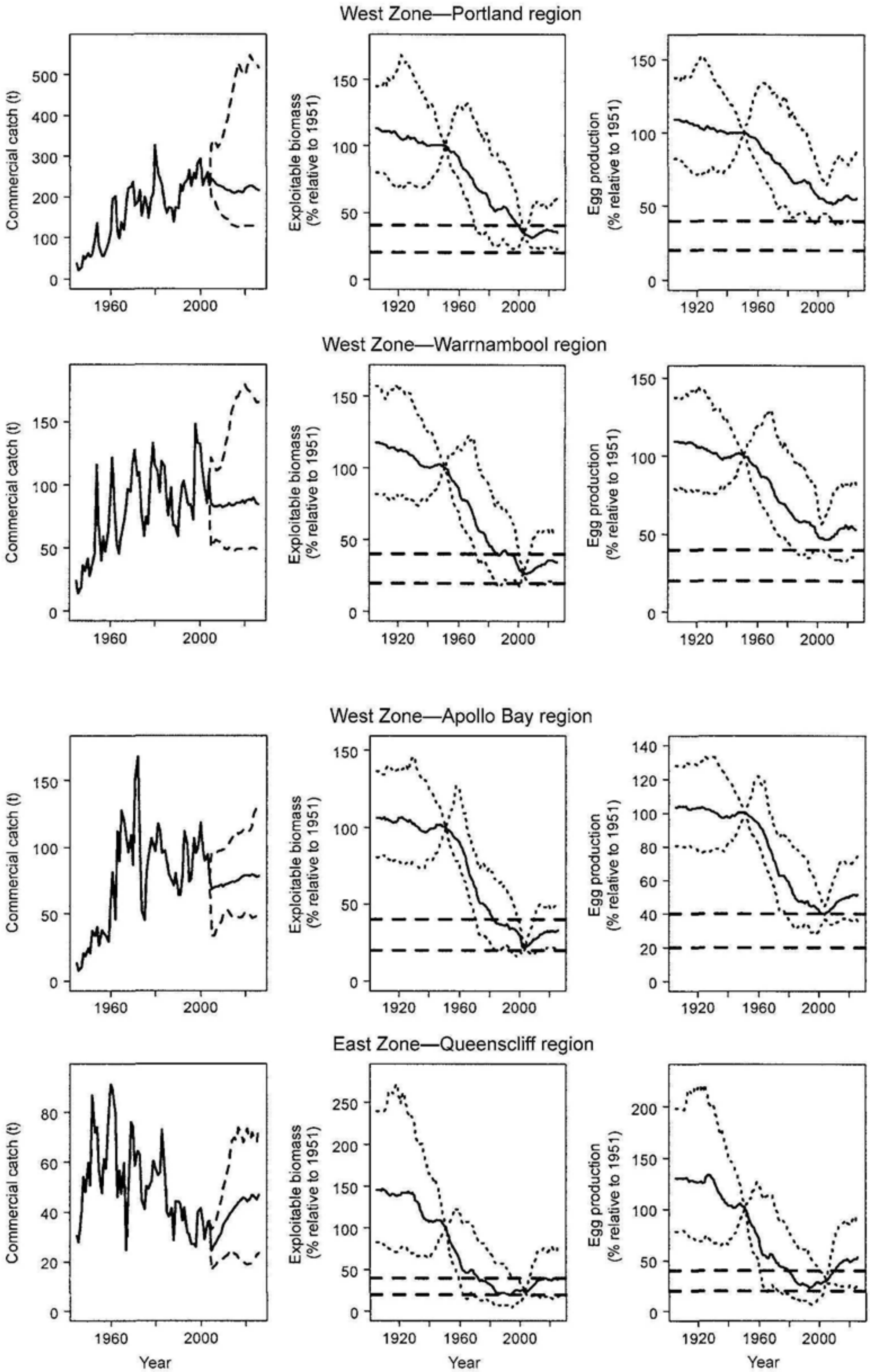
There was no strong relationship between poor estimation ability and poor management performance. Specifically, management performance was not notably poorer for the Apollo Bay and San Remo regions than for the remaining regions even though the estimates of abundance for Apollo Bay and Ran Remo were poor (Fig. 5). The lack of degradation in performance probably occurs because management strategy C sets TACs by zone, so imprecise estimates of abundance impact all of the regions in a zone in a relatively equal manner, and not just the region for which the estimates of abundance were poorly determined.

Sensitivity to alternative operating model specifications

The values for the performance measures for management strategy C were generally relatively insensitive to changing the specifications of the operating model (Table 7). The sensitivity tests that impacted performance to the greatest extent were: A-4 (more depleted stock initially), A-6 (smaller size classes), A-7 (lower rate of natural mortality), and A-8 (higher rate of natural mortality). Sensitivity test A-7 led to poorer conservation performance (a lower probability of leaving the exploitable biomass above 40% of the 1951 level) for both zones, whereas sensitivity tests A-6 and A-8 led to a higher probability of being above 40% of the 1951 level in 2025. The lower stock sizes for sensitivity test A-7 were expected as lower natural mortality leads to a less productive resource, whereas the opposite result for sensitivity test A-8 was also expected. The impact of sensitivity tests A-6 and A-4 on conservation performance was most marked for only one of the two zones (Table 7). Sensitivity tests A-4 and A-8 led to a marked reduction in the lower 5th percentile of the average catch from the western zone, whereas sensitivity test A-6 had a marked impact on the average catch in the eastern zone (Table 7). The sensitivity tests that led to the greatest amount of inter-annual variation in catches were A-4 (western zone) and A-6 (eastern zone).

The results were not particularly sensitive to how the data were generated, with two noteworthy exceptions, both of which relate to the relationship between catch-rate and abundance (see sensitivity tests B-1 and B-2 in Table 8). Specifically, conservation performance was markedly poorer if catch-rates were related non-linearly to abundance or catchability was increasing over time. This result was relatively intuitive, and highlights the importance of having a reliable index of relative abundance.

The results were not particularly sensitive to varying management-related assumptions (Table 9). It is noteworthy, however, that the probability of being above 40% of the 1951 egg production in 2025 was lower when there were no MPAs, but the opposite effect was evident for exploitable biomass (see sensitivity test C-3 in Table 9).


West Zone—Portland region
Commercial catch (t)
Exploitable biomass (% relative to 1951)
Egg production (% relative to 1951)
West Zone—Warrnambool region
Commercial catch (t)
Exploitable biomass (% relative to 1951)
Egg production (% relative to 1951)
West Zone—Apollo Bay region
Commercial catch (t)
Exploitable biomass (% relative to 1951)
Egg production (% relative to 1951)
East Zone—Queenscliff region
Commercial catch (t)
Exploitable biomass (% relative to 1951)
Egg production (% relative to 1951)
Year
Year
Year

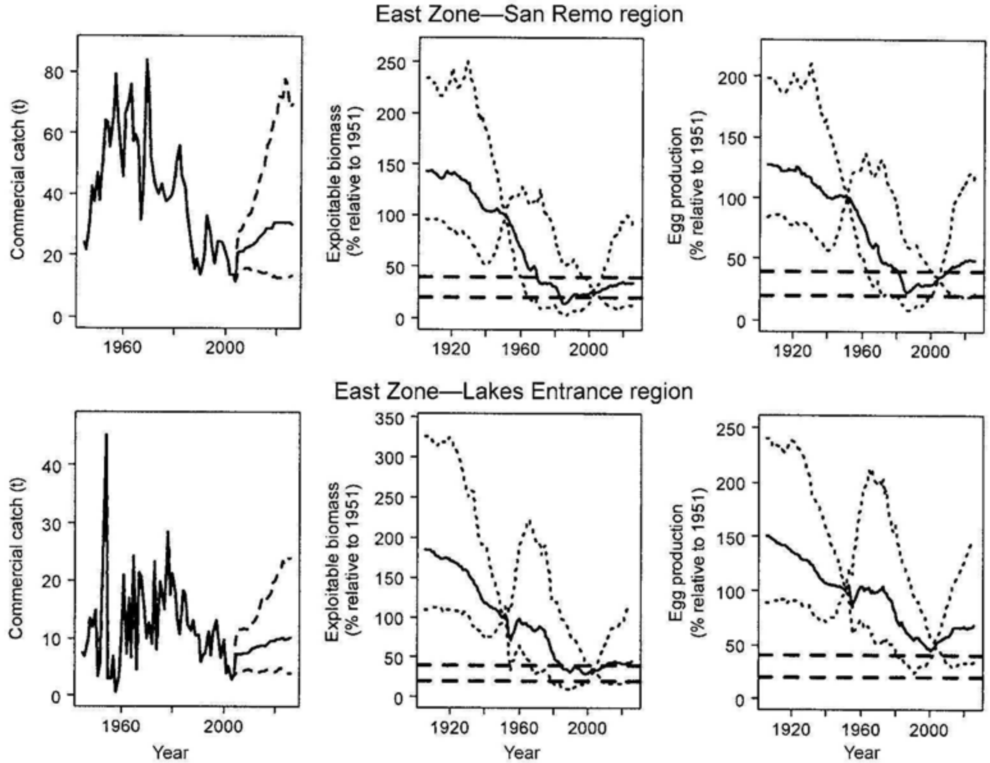


Fig. 4 (*opposite page and above*) Time-trajectories of exploitable biomass and egg production (expressed relative to 1951), and catch by the commercial fishery by region for management strategy C and operating model A-1. Horizontal lines denote the target and limit reference points.

Alternative management strategies

There was not much impact on the performance measures of increasing the value of the parameter that determines the extent to which catch limits may be varied from one year to the next, Δ, from 0.1 to 0.2 (comparing the results for management strategies A–C with those for management strategies D–F in Table 10).

Two variants of management strategy C with different decision rules were constructed to achieve a higher probability (preferably 0.5) of being above 40% of the 1951 exploitable biomass in 2025. Management strategy C-1 set the TAC for the western stock to that corresponding to having a probability of 0.5 of being above 40% of the 1951 exploitable biomass in 5 years and set the TAC for the eastern stock so that there was at least a 5% increase in exploitable biomass over the next 5 years, if the exploitable biomass was less than 40% of the 1951 level. It also set the TAC for this stock so that there was at least a 5% increase in egg production over the next 5 years if the egg production was less than 40% of the 1951 level, although the TAC set by this management strategy tended to be determined by the status of exploitable biomass relative to the target level. In contrast, management strategy C-2 applied the same decision rule to the two stocks. It set the TAC so that there was a 5% increase in exploitable biomass if the probability of being above 40% of the 1951 exploitable biomass was less than 0.5. It also reduced the TAC to that corresponding to a probability of 0.5 of being above the 1951 egg production in 5 years irrespective of whether or not it was predicted that there was expected to be a 5% increase in egg production over the next 5 years, if the probability of being above 40% of the 1951 egg production was less than 0.5.

The probabilities of being above 40% of the 1951 level were higher for these two variants of management strategy C (Table 10). Management strategy C-1 is perhaps too conservative; it achieved high probabilities of being above 40% of the 1951

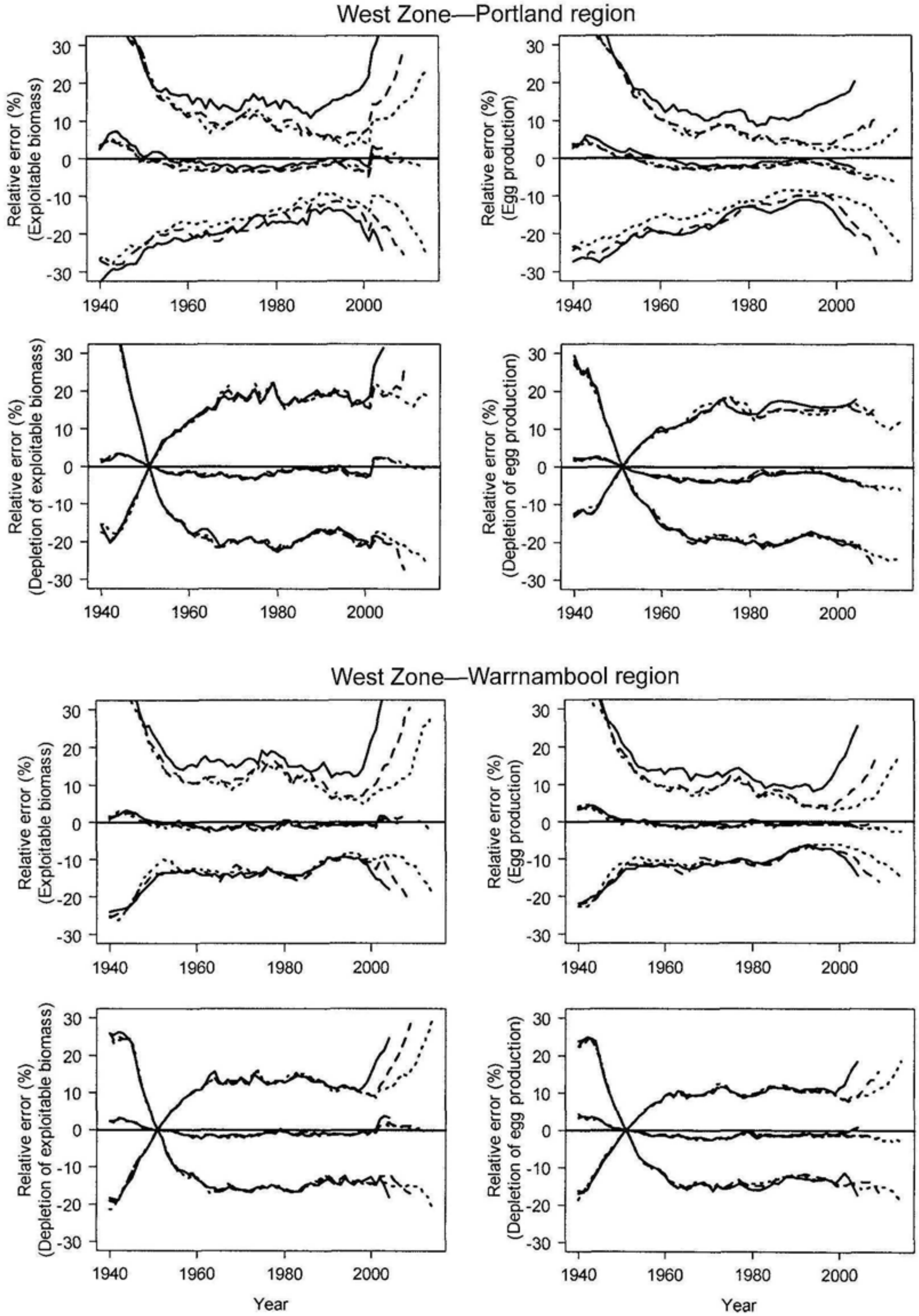


Fig. 5 Medians and 90% probability intervals for the relative errors (=100(estimated value – true value)/true value) for exploitable biomass and egg production (in absolute terms and relative to that in 1951). Results are shown for assessments conducted for 2004 (solid lines), 2009 (dashed lines) and 2014 (dotted lines).

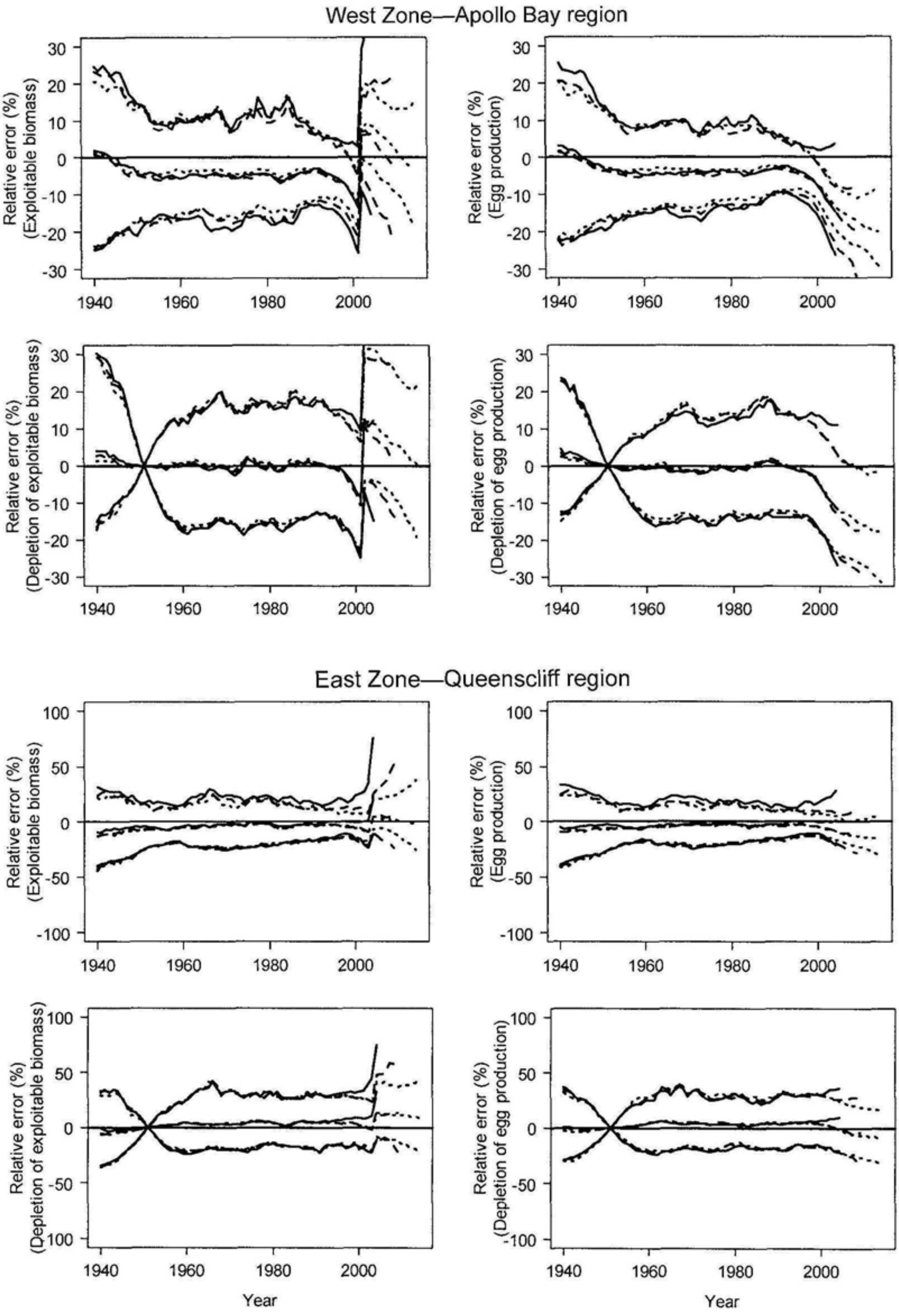


Fig. 5 (*continued*)

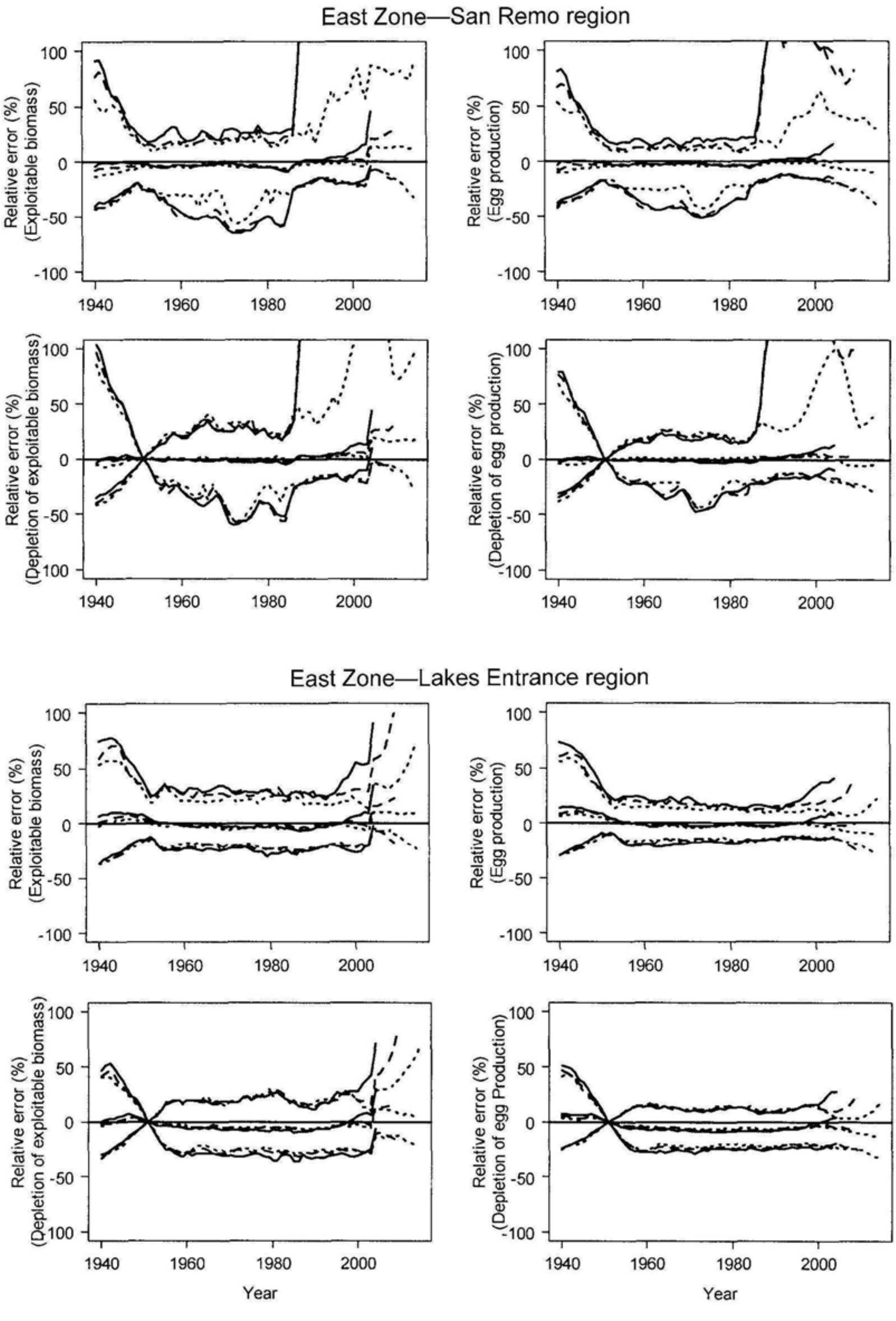


Fig. 5 (*continued*)

exploitable biomass, but at large cost in catches. In contrast, management strategy C-2 left the exploitable biomass close to the target level in 2025, but with much less impact on catches.

DISCUSSION

This study explored the performance of a variety of management strategies based on the current assessment method, with the aim of determining which of these strategies is able to satisfy the biological objectives of the rock lobster fishery management plan that stocks be above limit reference points with high probability (>75%) and be maintained above target reference points on average.

The results of this study highlight that there are several trade-offs that need to be taken into consideration when selecting a management strategy for rock lobster off Victoria, i.e., between yield and conservation status. There is also a trade-off between complexity (TACs and assessments by region) and simplicity (TACs and assessments by zone). The results show that the best performance, in maintaining stocks above the target reference point for exploitable biomass, occurred when assessments were conducted by region and TACs were set by region. However, the majority of the calculations of this study were based on a slightly less conservative management strategy in recognition that setting TACs by region is currently logistically infeasible. Improved performance could have been achieved by conducting assessments and setting TACs at spatial scales even finer than region, but these analyses were not conducted because it is infeasible at present to disaggregate the data needed to conduct stock assessments to much finer scales than region.

The management strategy can be modified to achieve a different trade-off between risk and reward (e.g., Table 10). In particular, it is possible to better

Table 7 Performance measures for management strategy C for the three baseline operating models and the sensitivity tests related to the biological specifications of the operating model. $P(>ySB_{1951})$ is the probability in 2025 of being above y times the 1951 egg production, $P(>yEB_{1951})$ is the probability in 2025 of being above y times the 1951 exploitable biomass, $\bar{C}_{2005–14}$ is the median average catch (t) over 2005–14, $\tilde{C}_{2005–14}$ is the lower 5th percentile of the average catch (t) over 2005–14, P_{cat} is the probability of a reduction in TAC between 2005 and 2014, and AAV is the absolute annual variation in catches (%) between 2005 and 2014.

Operating	Western zone				Eastern zone		
model	$P(>0.4SB_{1951})$	$P(>0.2EB_{1951})$	$P(>0.4EB_{1951})$		$P(>0.4SB_{1951})$	$P(>0.2EB_{1951})$	$P(>0.4EB_{1951})$
Conservation-related performance measures (%)							
A-1	93	98	26		74	95	47
A-2	93	97	25		76	92	50
A-3	97	98	31		74	93	41
A-4	95	100	44		72	93	45
A-5	92	98	28		73	93	47
A-6	74	77	26		93	98	81
A-7	88	99	13		74	91	33
A-8	97	100	51		82	89	56
A-9	96	100	27		80	95	47
A-10	85	98	29		70	94	47
A-11	89	99	25		78	94	48
	$\bar{C}_{2005–14}$	$\tilde{C}_{2005–14}$	AAV	P_{cat}	$\bar{C}_{2005–14}$	$\tilde{C}_{2005–14}$	AAV	P_{cat}
Utilisation-related performance measures								
A-1	381	304	2.55	54	65	49	5.37	14
A-2	396	309	2.30	52	60	50	4.30	19
A-3	390	301	2.48	52	58	47	3.70	23
A-4	313	255	5.10	76	59	45	3.91	16
A-5	438	340	2.35	35	68	52	5.92	21
A-6	413	373	0.00	20	30	30	10.82	73
A-7	394	310	2.92	59	63	52	4.70	16
A-8	376	279	3.30	47	61	49	4.89	19
A-9	376	315	2.03	60	65	55	5.16	14
A-10	389	292	2.83	55	63	49	4.78	19
A-11	383	289	2.45	58	63	50	4.54	17

achieve the intent of the rock lobster management plan by changing how TACs are set using the results of the stock assessment. This study focused on a relatively small number of management strategies, primarily because applying the assessment method can be time-consuming, particularly for years well into the future (because each additional year adds an extra estimable parameter to the stock assessment model). The calculations could have been based on a simpler assessment method, but doing so may have compromised the ability to draw conclusions pertinent to the situation of managing the rock lobster resource off Victoria.

The results of this study suggest that the assessment method is generally relatively accurate (correct on average) and relatively precise (estimates were generally within ±20% of the true values). However, estimation performance was poor/imprecise on occasion. Reasons for poor estimation performance include occasional very large estimated year-classes for the most-recent years of the assessment period. Some "learning" took place as additional data were added to the assessment (Fig. 5), but, as expected, the precision of estimates of cohort size for recent years is markedly poorer than for those cohorts that have been fished for several years. The learning is restricted to recent years—additional data are unlikely to lead to an improved understanding of the historical dynamics of the resource (Fig. 5). The common-held belief that the ratio of the current stock size to the stock size in some historical year is estimated more robustly than recent stock size in absolute terms (e.g., Punt 1989; Punt et al. 2002) was therefore not supported for rock lobster off Victoria. Similar conclusions were drawn by Punt et al. (2002) based on age-structured models and by Punt (2003) based on a size-structured model.

The results of MSE allow the key sources of uncertainty to be identified. For this study, and consistent with previous MSE studies (Butterworth & Punt 1999; Punt 2006), the reliability of catch rates as an index of relative abundance and whether

Table 8 Performance measures for management strategy C for the sensitivity tests related to the data used when conducting assessments and making management decisions. $P(> ySB_{1951})$ is the probability in 2025 of being above y times the 1951 egg production, $P(> yEB_{1951})$ is the probability in 2025 of being above y times the 1951 exploitable biomass, $\bar{C}_{2005-14}$ is the median average catch (t) over 2005–14, $\tilde{C}_{2005-14}$ is the lower 5th percentile of the average catch (t) over 2005–14, P_{cat} is the probability of a reduction in TAC between 2005 and 2014, and AAV is the absolute annual variation in catches (%) between 2005 and 2014.

Operating model	Western zone				Eastern zone			
	$P(> 0.4SB_{1951})$	$P(> 0.2EB_{1951})$	$P(> 0.4EB_{1951})$		$P(> 0.4SB_{1951})$	$P(> 0.2EB_{1951})$	$P(> 0.4EB_{1951})$	
Conservation-related performance measures (%)								
A-1	93	98	26		74	95	47	
B-1	21	13	1		53	63	28	
B-2	26	16	1		27	32	7	
B-3	97	100	26		73	95	46	
B-4	93	98	30		75	95	43	
B-5	94	99	24		77	95	47	
B-6	95	97	28		73	95	48	
B-7	94	99	26		75	95	48	
B-8	93	98	26		73	95	45	
B-9	95	100	35		80	95	45	
	$\bar{C}_{2005-14}$	$\tilde{C}_{2005-14}$	AAV	P_{cat}	$\bar{C}_{2005-14}$	$\tilde{C}_{2005-14}$	AAV	P_{cat}
Utilisation-related performance measures								
A-1	381	304	2.55	54	65	49	5.37	14
B-1	540	440	4.15	16	75	65	6.79	23
B-2	518	410	3.99	17	81	58	7.73	15
B-3	384	309	2.40	53	65	48	5.29	13
B-4	387	318	2.44	54	65	50	5.45	16
B-5	385	311	2.25	55	66	50	5.30	13
B-6	380	301	2.79	54	64	49	5.19	16
B-7	380	306	2.58	54	65	49	5.43	15
B-8	385	307	2.50	54	65	49	5.48	14
B-9	382	303	3.40	48	63	52	5.09	14

Table 9 Performance measures for management strategy C for two of the three baseline operating models and the sensitivity tests related to how management strategies are implemented. $P(> ySB_{1951})$ is the probability in 2025 of being above y times the 1951 egg production, $P(> yEB_{1951})$ is the probability in 2025 of being above y times the 1951 exploitable biomass, $\bar{C}_{2005\text{–}14}$ is the median average catch (t) over 2005–14, $\tilde{C}_{2005\text{–}14}$ is the lower 5th percentile of the average catch (t) over 2005–14, P_{cat} is the probability of a reduction in TAC between 2005 and 2014, and AAV is the absolute annual variation in catches (%) between 2005 and 2014.

Operating model	Western zone $P(> 0.4SB_{1951})$	Western zone $P(> 0.2EB_{1951})$	Western zone $P(> 0.4EB_{1951})$	Eastern zone $P(> 0.4SB_{1951})$	Eastern zone $P(> 0.2EB_{1951})$	Eastern zone $P(> 0.4EB_{1951})$
Conservation-related performance measures (%)						
A-1	93	98	26	74	95	47
A-2	93	97	25	76	92	50
C-1	92	98	29	79	92	43
C-2	91	96	23	82	95	39
C-3	87	100	28	68	94	57
C-4	93	98	24	74	94	43
C-5	92	98	23	76	96	43

Operating model	Western zone $\bar{C}_{2005\text{–}14}$	Western zone $\tilde{C}_{2005\text{–}14}$	Western zone AAV	Western zone P_{cat}	Eastern zone $\bar{C}_{2005\text{–}14}$	Eastern zone $\tilde{C}_{2005\text{–}14}$	Eastern zone AAV	Eastern zone P_{cat}
Utilisation-related performance measures								
A-1	381	304	2.55	54	65	49	5.37	14
A-2	396	309	2.30	52	60	50	4.30	19
C-1	385	308	2.67	56	61	51	4.37	19
C-2	379	290	2.69	63	62	52	4.52	16
C-3	382	303	2.37	50	65	51	5.15	11
C-4	384	313	2.45	52	65	50	5.06	14
C-5	386	312	2.25	53	66	52	5.18	15

Table 10 Performance measures for different management strategies for the baseline 6-stock operating model (A-1). $P(> ySB_{1951})$ is the probability in 2025 of being above y times the 1951 egg production, $P(> yEB_{1951})$ is the probability in 2025 of being above y times the 1951 exploitable biomass, $\bar{C}_{2005\text{–}14}$ is the median average catch (t) over 2005–14, $\tilde{C}_{2005\text{–}14}$ is the lower 5th percentile of the average catch (t) over 2005–14, P_{cat} is the probability of a reduction in TAC between 2005 and 2014, and AAV is the absolute annual variation in catches (%) between 2005 and 2014.

Operating model	Western zone $P(> 0.4SB_{1951})$	Western zone $P(> 0.2EB_{1951})$	Western zone $P(> 0.4EB_{1951})$	Eastern zone $P(> 0.4SB_{1951})$	Eastern zone $P(> 0.2EB_{1951})$	Eastern zone $P(> 0.4EB_{1951})$
Conservation-related performance measures (%)						
A	100	100	60	66	84	34
B	95	99	27	74	95	47
C	93	98	26	74	95	47
D	100	100	61	62	83	32
E	96	100	22	75	96	41
F	97	100	26	73	94	40
C-1	100	100	98	98	100	97
C-2	100	100	55	79	98	49

Operating model	Western zone $\bar{C}_{2005\text{–}14}$	Western zone $\tilde{C}_{2005\text{–}14}$	Western zone AAV	Western zone P_{cat}	Eastern zone $\bar{C}_{2005\text{–}14}$	Eastern zone $\tilde{C}_{2005\text{–}14}$	Eastern zone AAV	Eastern zone P_{cat}
Utilisation-related performance measures								
A	338	274	3.59	30	76	51	6.16	48
B	381	308	2.73	54	63	48	4.27	45
C	381	304	2.55	54	65	49	5.37	45
D	330	263	5.04	22	79	51	6.79	48
E	375	285	3.45	45	71	49	7.09	46
F	375	284	3.03	45	71	51	7.08	46
C-1	242	242	11.11	91	30	30	11.09	39
C-2	340	285	5.48	57	62	42	6.07	44

the correct value for natural mortality is being assumed are key uncertainties. In contrast, other factors, e.g., including the true number of stocks being managed, uncertainty in the model estimates owing to sampling variability, and the impact of MPAs, are less important in achieving management outcomes.

Only relatively few MSE studies have explored the implications of stock structure on the performance of management strategies (see review in Punt 2006). Within the context of whale management, IWC (1992) showed that unintended stock depletion was likely if assessments are conducted based on data for large areas, but catches are concentrated spatially, even when management is based on a feedback control management strategy, whereas Dichmont et al. (2006) highlighted the impact of the inability to spread removals spatially on conservation performance for a prawn fishery in northern Australia. The results of this study confirm those of these earlier studies and suggest that assessment and management based on areas that are larger than those in which individual stocks are found often lead to an inability to achieve conservation objectives. However, this study also shows that conservation objectives were achieved when, for example, catches were taken approximately in proportion to a stock's biomass.

Finally, the approach for modelling spatial structure outlined here could be applied to other situations in which there are hints of spatial variation in biological process such as growth, natural mortality and recruitment, but the impact of this variation on the ability to achieve conservation and utilisation objectives is unknown. The operating model of this study was based on the assumption that animals do not move after they settle, but it could be extended easily (given adequate data and/or appropriately constructed hypotheses) to species which do exhibit considerable post-recruitment movement.

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